INFORMATION VISUALIZATION AND INTERACTION IN MAP-BASED, MOBILE SHARED WORKSPACES

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CHAPTER I

Introduction

I.1 Problem Statement

Mobile shared workspaces (MSWs) are software applications that support loosely-coupled cooperative work in the mobile context (Rodríguez-Covili et al., 2011). MSWs facilitate collaboration between groups of spatially distributed users and are typically supported using mobile devices, such as tablets and smartphones. The design of MSW applications poses several unique challenges due to the distributed nature of collaborators and the computing devices used.

Collaborators in MSW scenarios are typically distributed throughout a specific geographic region performing tasks that are contingent upon knowledge of the region’s geography; therefore, digital maps are frequently utilized to support mobile collaboration. The current state of the art in MSW software applications is limited in the visualization of and interaction with information on a digital map. For example, single information entities are typically represented using a point of interest (POI) placed on the digital map. These POIs can lead to visual clutter and loss of information saliency. Furthermore, current mobile devices leverage novel input mechanisms, such as touch, that may not be leveraged to their full potential in current MSW software applications.

MSW software applications may be improved through developing novel techniques in two key areas: information visualization and information interaction. The objective of the proposed dissertation research is to develop and evaluate new methods of visualizing information on a digital map in order to benefit collaborators during MSW scenarios. In addition, compensatory input methods to facilitate efficient interaction with geospatial information within an MSW application will be developed.

Previous research has established the following general design requirements for MSW applications based on the results of observational field studies (Herskovic et al., 2011; Rodríguez-Covili et al., 2011):

- **Autonomy.** Users must be able to perform meaningful work, even if they are disconnected from the network and/or physically isolated from others.

- **Ad-hoc Communication.** Collaboration must be supported regardless of physical location.

- **Group Awareness.** Each user must be able to obtain an awareness of other group members and their reachability (e.g., online/offline status).

- **Messaging.** Collaborators must be able to contact each other, and communication should be facilitated
Figure I.1: A comparison of (a) POIs, and (b) a Feature Set covering the same geospatial area. Notice that Feature Sets do not occlude the underlying geography and provide a larger target area than a single POI.

by the MSW.

- **Information Sharing.** The MSW must integrate information to form a coherent picture of the world state and allow users to control information flow.

Visualization techniques can be utilized to support many of the above MSW design requirements, particularly *Information Sharing*. The primary contribution of this dissertation will be the design and implementation of Feature Sets, a technique for visualizing and interacting with geospatial information. Feature Sets will address the above design requirements for MSW applications, while attempting to overcome the shortcomings of POI-based data visualization.

POIs present numerous design and interaction issues when used on a mobile device. For example, POIs are typically interacted with by tapping on the mobile device’s touch screen using a finger. Since direct interaction with the POI is necessary, the POI’s icon must be large enough to select accurately. Ensuring that the direct selection of a POI is always possible requires thresholding the minimum size of the POI, such that it is always large enough to accurately select with a finger. At higher zoom levels, POIs that are large enough for selection may obstruct significant portions of the digital map on which they are overlayed (see Figure I.1). Methods to overcome the precise selection issue of POIs exist (e.g., Yatani et al. 2008), but these methods rely on an icon that must remain large enough to be salient at any zoom level, potentially causing map occlusion and contributing to visual clutter.

Visual clutter is a key design challenge in both map-based, mobile applications and in general, as it hinders perceptibility and understanding (Delort, 2010; Klippel et al., 2006). Prior research addresses visual clutter by focusing on three approaches: changing the appearance of data (e.g., Fredrikson et al. 1999; Humphrey and Adams 2010; Wu et al. 2009), spatially distorting the information (e.g., Fuchs and Schumann 2004), and temporally modifying the data by altering size and opacity (Ellis and Dix, 2007; Humphrey and Adams,
2010). These approaches mitigate visual clutter by employing grouping mechanisms that only group information of a single type (Delort, 2010; Fredrikson et al., 1999; Humphrey and Adams, 2010; Markerclusterer, 2009; Wu et al., 2009). Feature Sets attempt to mitigate visual clutter through domain-specific groupings, such as geospatial location. These groupings are not necessarily contingent upon the type of information being grouped, the information must simply possess a shared characteristic inherent to the domain.

The primary benefit of Feature Sets is providing a flexible grouping construct that can provide additional context to grouped information, while reducing visual clutter when compared to POIs. For example, a Feature Set may enclose a building, hence all generated information (e.g., status reports of personnel, structural integrity, etc.) pertaining to the building can be located within the Feature Set. A single POI typically represents a single item, leading to visual clutter if many POIs pertaining to the building are present on the map. Visual clutter is undesirable, especially on mobile devices, which typically have limited screen real estate (Burigat et al., 2008).

One of the primary purposes of Feature Sets is to abstract POIs to areas of interest (AOIs) and use these AOIs to categorize and visualize relevant information. The primary method of constructing a Feature Set on a mobile device is to draw an area on the map using either a finger or a stylus (see Figure I.2). Therefore, it is crucial to understand the impact of drawing as it pertains to Feature Set creation and, if necessary, provide methods to assist drawing as an interaction method.

Interacting with a mobile device while walking can provide a host of interaction challenges. For example, walking speed may dictate interaction difficulty (Bergstrom-Lehtovirta et al., 2011), a user’s attention may be divided between the device and navigation (Kane et al., 2008), and occlusion due to using a finger as an input
mechanism (Holz and Baudisch, 2010) (i.e., the “Fat Finger” problem) may lead to user input that lacks the user’s intended precision. Therefore, an offset will exist between the user’s supplied input and the intended line (see Figure I.3). If the intended line is known, the offset can be utilized as an error metric to gauge the precision of user input when performing a drawing task.

It is important to determine the precision with which a user can specify an area by drawing on a touch screen in order to support drawing as an interaction mechanism. Quantifying drawing precision can be considered the continuous case of precisely selecting single targets, which has been a popular area of research in seated (e.g., Dearman et al., 2007; Kown et al., 2009; Park et al., 2008), controlled walking (e.g., Lin et al., 2007; Schedlbauser and Heines, 2007; Schilbach and Rukzio, 2010), real-world walking (e.g., Bergstrom-Lehtovirta et al., 2011), and mass-distribution (e.g, (Henze et al., 2011)) scenarios. Drawing requires the accurate and continuous specification of many individual points (i.e., targets) that form a solid line. Each specified point may have some offset from the user’s intended point, resulting in error.

Wayfinding, determining a route from one location to another, is an important component of MSW scenarios, since MSW tasks are typically carried out in a real environment. MSW tasks may require users to traverse and navigate the real environment using a digital map. Prior research has demonstrated that visual clutter negatively impacts wayfinding ability, and users may be unable to ignore unwanted or irrelevant graphic information (Dobson, 1980). Visual clutter may also obscure paths that can otherwise be used to complete a wayfinding task. Wayfinding errors may also be introduced when a user leverages information that is outdated, or does not correctly discover new information. Therefore, by reducing visual clutter and improving information saliency, Feature Sets may also reduce wayfinding errors.

Prior research has identified the importance of information context in collaborative workspaces (Dourish and Bellotti, 1992). Supporting information context ensures that communicated content possesses the appropriate character to place the information within the context of the overall environment. Feature Sets can be used to provide context on the information that they contain. Three different types of context will be
supported by Feature Sets: *geospatial, temporal, and semantic*. *Geospatial* context is supported by providing geospatial containers for information (i.e., the AOI), the *semantic* context is supported through providing novel methods for filtering and sorting related information within a Feature Set, and the *temporal* context will be supported through providing mechanisms to obtain temporal information concerning when information is added to a Feature Set. Through supporting these contexts, Feature Sets may provide a usability benefit when compared to POI-based approaches.

### 1.1.1 Contributions

The contributions of the proposed research are two-fold. First, Feature Sets will be developed in order to reduce visual clutter, improve wayfinding performance, and increase the usability of map-based MSW applications. Second, methods of assisting the user during continuous precise selection tasks will be developed. These algorithms may be directly applicable to any work that relies on continuous precise selection, such as tasks requiring area or line specification (e.g., drawing, lasso-style selection, creating routes in a navigation application, etc).

Compensatory methods for assisting the user in performing continuous precise selection tasks will be developed. Much like the algorithms developed to determine error (Hooten, 2010), these assistive methods are directly applicable to any scenario where a user must provide precise, continuous input at a time when it may be difficult to do so, such as when a user is walking or when attention is divided between multiple tasks. Even though these assistive methods will be developed with mobile device interaction in mind, the developed techniques may also apply to mouse or stylus-based, continuous precise selection tasks.

Since Feature Sets have been designed to support MSW scenarios, the findings will be directly applicable to a number of domains. These domains include first response, firefighting, and medical staffing, among others. Feature Sets also have merit as a general visualization technique for information-dense interfaces, and may be applicable to any domain where a large amount of information is spatially displayed and that information can be grouped based on domain-relevant characteristics. Feature Sets will provide a novel approach to supporting collaborative work with large data sets on mobile devices by allowing groupings that can be based on domain-relevant characteristics, such as geospatial location.

Feature Sets are also the first visualization technique to be designed to specifically meet MSW design guidelines, while providing for the three types of information context. Demonstrating that Feature Sets result in improved user performance will indicate that, by designing visualization methods to meet MSW design guidelines, user performance can be improved versus approaches that do not take MSW design requirements into account. This outcome is a two-fold benefit, the link between MSW design requirements, visualization, and improved performance will be shown, and Feature Sets will be shown to be a beneficial visualization technique for assisting users during continuous precise selection tasks.
technique that results in improved user performance.

Feature Sets can also be applied to desktop computing scenarios. Even though desktop devices (e.g.,
desktop computers, laptops, etc.) typically have larger screens than mobile devices, visual clutter may still
be present with the POI approach, rendering Feature Sets beneficial. Feature Sets also provide other benefits,
such as organizing information into geospatial containers and supporting various types of information context,
which may provide additional meaning to the information presented to the user.
CHAPTER II

Background

II.1 General Requirements for Mobile Shared Workspace Design

Prior research has produced generalized requirements for the design of mobile shared workspace applications (Herskovic et al., 2011; Rodríguez-Covili et al., 2011). Rodríguez-Covili et al. decomposed MSW application design into a reference architecture through generalizing the results of MSW field studies in construction site management, fire emergency response, and hospital scenarios (Rodríguez-Covili et al., 2011). The resulting reference architecture was designed to address general MSW software requirements (see Section I.1 for these general requirements).

Visualization can play a large role in reinforcing all of Rodríguez-Covili et al.’s stated requirements except for Ad-hoc Communication, which must be facilitated in order for collaboration to take place. For example, visualization changes can indicate that a user’s connectivity to collaborators has been lost. Altering the visualization (see Figure II.1), allows the user to perform autonomous work with the knowledge that a portion of his or her on-screen information is potentially stale or outdated.

Figure II.1: An MSW visualization indicating a user’s connectivity status. Stale information is shown in grayscale. Current information (e.g., information added by the user) is shown in color. The user’s location (i.e., the icon labeled “Me” on the map) is shown as a red circle to indicate that he/she is offline.

MSW applications rely on standard widgets to fulfill MSW design requirements, and several widgets are needed to facilitate these requirements. For example, Group Awareness is provided through the use of a contact list that displays each collaborator’s connectivity status (i.e., online or offline). The positions of other collaborators, tasks to be performed, and points of interest are indicated by a POI placed on a digital map.
Figure II.2: (a) A mobile device visualization using a digital map. The map representation provides connectivity information and the offline user’s (i.e., Susan’s) last known location. (b) A standard online/offline collaborator list (e.g., Buszko et al., 2001; Meyer et al., 2011; Monares et al., 2011), where green indicates online and red offline.

A text-based chat widget fulfills the *Messaging* requirement. A file browser is used to share certain types of information. Many collaboration applications use a multiple widget approach, both in the MSW domain (Buszko et al., 2001; Meyer et al., 2011; Monares et al., 2011; Velde et al., 2005) and otherwise (Convertino et al., 2005, 2009; Fredrikson et al., 1999; Wu et al., 2009).

The multiple widget approach utilized by MSW frameworks presents a host of interaction difficulties. For example, numerous widgets can be difficult to manage on a mobile device, since multiple widget changes may be required in order to accomplish a single task or access required information (Rashid et al., 2012). For example, if a user wishes to discuss the contents of a POI with the collaborator that created it, the user must change to a buddy list widget to find the appropriate collaborator, switch to a text messaging widget to send the collaborator a message, and then switch back to the digital map to continue performing work. Changing focus to each new widget may incur additional cognitive load, since the user has to remember the item’s description, creator, and his/her reason for wanting to discuss the item at each step in the process.

Requiring multiple widgets to complete a single task may be problematic on a mobile device, since widgets typically have to be displayed full screen so that components are large enough for selection. Therefore, with existing MSW applications, interaction on a mobile device can be difficult. Utilizing a single widget that encompasses the needed functionality may be more useful, since attention will not be diverted between multiple widgets. Such a widget can allow information about an on-screen item, its creator, and the means of messaging the creator to be easily accessed. Single widgets that aggregate the functionality and information necessary to complete relevant tasks is an approach that is not seen in current MSW applications, and may provide a usability benefit. Aggregation can synthesize multiple data sources to reduce the total number
of widgets required to support the MSW. For example, a listing of collaborators’ connectivity status can be included in the MSW, and the information can also be aggregated into a combined visualization (see Figure II.2).

The “Iceberg Effect” explains the MSW design requirements that many developers may ignore, since the requirements are typically obscured from the developer and client (Herskovic et al., 2011). Herskovic et al. introduce the user interface as the tip of the iceberg (see Figure II.3), but neglect to discuss the user interface’s importance in MSW design. If the application’s usability is hindered due to a poor user interface, the implementation of the remainder of the design concerns (e.g., connectivity, interoperability, etc.) is irrelevant. If visualization techniques reinforce MSW design guidelines, developers can integrate concerns into the visualization, ensuring the inclusion of hidden requirements into the final design.

Information context within a collaborative setting is also important. Dourish and Bellotti (1992) determined that information must possess both content and character in order to provide meaning in a collaborative scenario. Previous MSW frameworks provide avenues to efficiently communicate content; the ability to place POIs on a digital map represents one example. Character places communicated content within the context of the present information body, and is generally much more difficult to support within a MSW application. For example, if two POIs are placed near to one another on a map, it may be difficult to quickly determine whether or not the two POIs are related if no additional information concerning the POIs’ character is provided.

MSW design requirements illustrate key concerns that must be addressed when designing MSW applica-
tions. However, the lack of emphasis on the user interface and visualization aspects provides an open research question for improving the MSW user experience.

II.1.1 Current MSW Visualization Techniques

Many MSW applications leverage a digital map to display relevant information (e.g., Buszko et al., 2001; Löffler et al., 2007; Meyer et al., 2011; Monares et al., 2011; Nivala and Sarjakoski, 2003). The digital map coordinates and displays information, and is a logical MSW interface component, since individuals are inherently distributed throughout a geographic region and information can possess geospatial components. Digital maps visualize the environment occupied by the user and can assist with wayfinding and orientation (Cheverst et al., 2000; Darken and Cevik, 1999; Delort, 2010; Klippel et al., 2006; Nivala and Sarjakoski, 2003; Sarjakoski and Nivala, 2005). Digital maps can assist in providing common ground in terms of the content being displayed and processes that must be performed by users (Convertino et al., 2009). When individuals collaborate using a digital map, the map can provide shared objects that facilitate communication and coordination (MacEachren and Brewer, 2007).

Many map-based MSW applications typically facilitate Information Sharing through annotation drawing on the map, referred to as “sketching” (e.g., Convertino et al., 2005; Ens et al., 2011; Meyer et al., 2011; Monares et al., 2011; Ochoa et al., 2011). Sketches can be input into a mobile device using either a finger or stylus as the primary input method. Sketching support in many MSW applications is rudimentary, providing a simplistic means for a user to sketch words or indicate AOIs on a map (e.g., Ens et al., 2011; Meyer et al., 2011; Monares et al., 2011). Previous work has shown that, when coupled with strong visualization support, sketching can also be used to specify tasks (Hooten et al., 2011).

Information Sharing is also accomplished on a digital map through creating POIs. POI specification requires a user to place an icon on the map at a particular location and, in some cases, provide additional information (e.g., text, multimedia, etc.). POIs have been utilized in both two-dimensional and three-dimensional digital maps (Löffler et al., 2007; Velde et al., 2005). Domain-specific iconography may also be used to provide meaning to the POI (e.g., Humphrey and Adams, 2010; Löffler et al., 2007; Velde et al., 2005; Zhang and Adams, 2011). POIs are a nearly ubiquitous tool for information communication in mobile, map-based collaboration software applications (Buszko et al., 2001; Herskovic et al., 2011; Meyer et al., 2011; Rodríguez-Covili et al., 2011; Velde et al., 2005), and are the de facto standard method for visualizing data in many web-based mapping frameworks (Google, 2012; Microsoft, 2012; OpenLayers, 2012).

Context-awareness provides a fine-grained and shared synergistic group behavior (Dourish and Bellotti, 1992). MSW applications are no exception to the need for context-awareness; therefore, it is important to provide context-awareness within the digital map. Three types of context awareness may be beneficial
when applied to digital maps in MSW scenarios: geospatial, temporal, and semantic. The geospatial context involves leveraging the position of an item in order to obtain greater meaning, and is inherent to digital map displays. The temporal context requires leveraging time-based information in order to provide additional meaning to information on the map, such as through altering the display properties of information over time (Ellis and Dix, 2007). The semantic context exploits the relatedness between items in order to provide greater meaning to each of the related items (Dourish and Chalmers, 1994). POIs support the geospatial context to a limited degree. For example, if a POI is placed over a building, there is a relatively good chance that the POI is geospatially related to the building. The temporal context can be used to quickly provide a time-based ordering of events, and has been leveraged by previous visualization techniques (e.g., Humphrey and Adams 2010). For example, in a first response scenario, a POI representing a fire may have very different meaning to a user if the POI was created five minutes ago versus five hours ago. A limited semantic context can be supported through type-based groupings of information (e.g., POIs representing similar information can be grouped together).

Even though POIs can provide some information context, POIs are not without flaws. For example, POIs can cause visual clutter (Fredrikson et al., 1999; Humphrey and Adams, 2010; Rinner et al., 2005; Velde et al., 2005; Wu et al., 2009), which results in interaction difficulties, hinders understanding, and lowers perceptibility of information (Klippel et al., 2006). Visual clutter is either mentioned as a design problem (Velde et al., 2005; Wu et al., 2009) or ignored altogether (e.g., Löffler et al., 2007; Meyer et al., 2011; Rodríguez-Covili et al., 2011) in much of the MSW literature.

General techniques have been developed to minimize visual clutter outside of the MSW domain. These techniques typically fall into three categories: appearance, which alters the look of the data; spatial distortion (e.g., the cartographic lens method developed by Fuchs and Schumann, 2004), which displaces data; and temporal, which uses techniques like animation to distort the appearance of data (Ellis and Dix, 2007). Specific visual clutter reduction methods include heat maps (Fisher, 2007; Wu and Zhang, 2011), aggregation (Fredrikson et al., 1999; Markerclusterer, 2009), modified Voronoi diagrams (Delort, 2010), and the General Visual Abstraction algorithm (Humphrey and Adams, 2009). Spatial distortion techniques are not applicable to map-based interfaces, since spatial location of information with regard to the digital map is typically very important. However, appearance altering and temporal techniques are applicable.

Many of the appearance altering techniques mitigate visual clutter by providing an aggregated visualization of on-screen information. The construction of this visualization is usually contingent on a type-based grouping mechanism. For example, heat maps reduce visual clutter by exploiting semantic context through type-based groupings. Wu and Zhang used heat maps to display check-in information from Foursquare, a location-based social networking website (Foursquare, 2011), on a digital map (Wu and Zhang, 2011).
Figure II.4: A visualization of (a) heat maps (Wu and Zhang, 2011) and (b) aggregates (Fredrikson et al., 1999). Both demonstrate a frequency visualization based on item type, where color denotes the frequency of the item’s occurrence in a particular geographic region.

A heat map showed the frequency of Foursquare check-ins at various locations as an indicator of a location’s popularity (see Figure II.4a). Another type-based grouping method, aggregates, was used in a manner similar to heat maps to display frequency information of car accidents on a digital map (Fredrikson et al., 1999) (see Figure II.4b).

Heat maps and aggregates reduce visual clutter caused by large groups of similarly-typed POIs that occur in close proximity. Aggregates go a step farther by allowing user-specified groupings, but, like heat maps, these groupings are based on item type. Neither approach accounts for a densely packed arrangement of differently typed items. For example, if heat maps were used to overlay check-ins from Foursquare and Yelp (Yelp!, 2011), overlapping heat maps may result, leading to visual clutter. Toggle functionality can be implemented, such that a user can enable/disable specific heat maps (or aggregates), but this approach restricts the user to only viewing single item distributions clearly on the map at any given time.

Another type-based grouping mechanism, the General Visual Abstraction algorithm (Humphrey and Adams, 2010), utilizes temporal modification to mitigate visual clutter. The General Visual Abstraction algorithm extends the functionality of the basic POI, by incorporating temporal adjustments (i.e., altering scale and opacity of the POI), along with a type-based grouping mechanism. The algorithm calculates a POI’s visual score to form type-based groupings and uses animation to alter the size and transparency values of on-screen information based on the visual score (Humphrey and Adams, 2010). Several factors affect an
Figure II.5: The General Visual Abstraction algorithm’s type-based grouping of triaged victims in an incident response scenario. The black squares indicate the locations of individual POIs within the group.

item’s visual score, with the most influential being whether or not the user has recently interacted with the item. Interaction occurs when the mouse cursor hovers over a POI. If POIs are not interacted with for an extended period of time, their visual representation reduces in size and lowers in opacity, entering a visual state known as Residue. If many identically-typed POIs are collocated and are in the Residue state, then the POIs group (see Figure II.5). The General Visual Abstraction augments type-based grouping through exploiting the temporal context. Despite the algorithm’s temporal context reflecting interaction and enabling grouping, it is still difficult to place items into a chronological ordering, which may improve temporal understanding of a scenario.

The General Visual Abstraction algorithm has similar issues to heat maps and aggregates. Visual clutter is reduced through type-based grouping, but clutter can result if many differently typed POIs occupy the same region. The General Visual Abstraction algorithm may not be applicable to the MSW domain, since hovering is not supported by default on mobile devices. However, the General Visual Abstraction algorithm, heat maps, and aggregates may provide adequate test cases with which to compare new visual clutter reduction methods.

Visualization support for public and private data sharing is a concept identified in the shared workspaces literature (Convertino et al., 2005; Herskovic et al., 2011; Rodríguez-Covili et al., 2011; Wu et al., 2009), and provides a form of semantic context to information. Users create public and private information in different ways; taking more time to construct public information to ensure that collaborators fully understand the information’s meaning (Greenberg et al., 1999). Public and private data spaces support this creation behavior by allowing users to easily dichotomize created information as either public or private. Visualizing private and public information on a digital map has been supported through three methods: providing multiple map
Figure II.6: Convertino et al.’s multiple viewport application, with a public viewport (left) and a private viewport (right). The public map is densely cluttered with POIs, whereas the private map has relatively few POIs.

viewports (Convertino et al., 2005, 2009; Wu et al., 2009), using zoom levels to limit the granularity of what is seen (Löffler et al., 2007; Velde et al., 2005), and restricting what can be viewed based on group membership and/or permissions (Herskovic et al., 2011; Meyer et al., 2011).

Wu et al.’s (2009) geo-Collaboration through Information Visualization system utilizes multiple map viewports to facilitate information sharing. A similar approach has been used by others (Convertino et al., 2005, 2009). Each collaborator can see a public view of the digital map in one interface panel and a private view in the other (see Figure II.6). A user can create information in the private map that is only viewable by his-or-herself, while simultaneously viewing and contributing to a public map. Private views can be shared, such that if a user requires that a collaborator view his or her map, the user can invite the collaborator to do so. Multiple viewports provide a clear distinction between public and private data; however, two map views can be space intensive. Due to limited screen real estate on mobile devices, multiple viewports may be inappropriate for the MSW domain. Other issues, such as contention for the control of the shared public viewport (Wu et al., 2009), may also be problematic in MSW scenarios.

Multiple views provide a coarse-grained semantic context by separating public and private information. The public view can also provide Group Awareness by displaying information created by other collaborators. Convertino et al.’s (2009) shared viewport approach provides a buddy list and chat tool to support Group Awareness and Messaging. Wu et al.’s system provides a separate Aggregation Chart widget and an Annotation Browser that aggregates similar information into type-based and chronological groupings. However,
Wu et al.’s approach does not integrate this information into a single visualization, and multiple widgets will likely be cumbersome on a mobile device.

Zoom levels can be used to facilitate the public/private sharing of data (Velde et al., 2005). Information sharing through zooming assumes that mobile collaborators will work in very specific regions of the map; therefore, each user’s visualization is limited to the user’s work area. This approach is utilized by the SHARE system (Velde et al., 2005), which ensures privacy, to an extent, by limiting data access and visualization based on the geospatial distribution of the collaborators. Higher-ranking group members can view more of the map and, as such, can access more data than lower-ranking collaborators. Zooming is more space efficient than multiple map views, but may be too limited of an approach. For example, a user may lose context of the overall scenario by being unable to view information that is added to other portions of the map. Also, true privacy does not exist, since privacy is influenced solely by user location and rank.

SHARE’s zoom-based approach to information communication provides Group Awareness. SHARE also utilizes a Push-to-Share system that allows users to broadcast information in order to meet the Messaging MSW design requirement. SHARE proposes, but does not implement, an Ontology database for providing the semantic context between information. This Ontology database allows SHARE to make logical connections between pieces of information and present those connections to the user.

Data access can be restricted based on permissions and group memberships. Herskovic et al. (2011) mention restricting data access based on permissions, but they do not design a system that utilizes this concept. The Collaborative Map system developed by Meyer et al. (2011) allows collaborators to form and manage workgroups. Meyer et al.’s system does not appear to facilitate multiple groups simultaneously or support permissions. The flexibility of group permissions may provide a finer-grained approach to information control than systems based solely on private/public data sharing, since information access can be controlled ad-hoc at the group level.

Layers overlayed on top of the digital map can implement a permissions-based approach to information control, and can improve usability by expressing relationships between displayed information (Chi, 2000; Hooten et al., 2011; Kimelman et al., 1994; Viljoen, 1997). A single layer can represent the information provided by a single group or user. Individuals of higher permission levels can view more layers, and users with multiple group memberships can access each group’s layer. Privacy can be obtained by reserving a single private layer per user that is only accessible by that user. Layers can facilitate fine-grained information sharing by allowing a user to share information with a single member, a group, a number of groups, or everyone. A potential downside is that layers may become difficult to manage if a user is involved in multiple groups. Layers can provide support for the semantic context by grouping related information into individual layers whose visibility can be toggled by the user.
II.1.2 Mobile Map-Based Interfaces and Wayfinding

MSW scenarios are typically undertaken in real-world environments, where collaborators may have a need to determine routes between various locations within the environment by wayfinding. Wayfinding is defined as the process of determining and following a path or route between an origin and a destination (Golledge, 1999). Wayfinding is the purposeful navigation between geospatial locations and is a prominent application of spatial cognition.

Wayfinding is subdivided into two categories: unaided wayfinding, which is navigation without the use of a map or other assistive device; and aided wayfinding, which comprises the use of maps, signs, and navigation assistants (Wiener et al., 2009). Maps are intended to provide survey knowledge and facilitate the creation of mental representations of an environment (Montello and Freundschuh, 1995). Survey knowledge provides the spatial awareness necessary to plan new routes, shortcuts, and detours (Klippel et al., 2010). The ability to bolster survey knowledge is crucial to MSW scenarios, especially those occurring in highly dynamic environments, where external factors may cause survey information to change over time.

Prior wayfinding research has determined that it is beneficial to make users aware of their location through a mobile interface (e.g., Klippel et al., 2006, 2010; Nivala and Sarjakoski, 2003). This awareness can be facilitated via an icon on the interface’s map that updates to reflect the changing position of the user (Darken and Cevik, 1999). A user’s location can be determined easily through the use of a global positioning system, WIFI networks (Sammarco et al., 2008), accelerometers (Bylemans et al., 2009), and radio frequency identification tags (Hekimian-Williams et al., 2010).

Digital maps that reflect the user’s current location are generally referred to as You-Are-Here (YAH) maps (Levine, 1982). YAH maps are intended to provide assistance with route planning, navigation, and orientation by allowing a user to instantly determine his or her location with respect to the environment (see Figure II.7). YAH maps can also be used to indicate the position of other agents in virtual and real worlds. For example, in robot control scenarios, it is common to display a YAH map that indicates the current position of the robot in relation to the mapped area (e.g., Drury et al., 2007; Hayes et al., 2010; Nielsen and Goodrich, 2006). While not explicitly stated in the literature, numerous MSW applications utilize the YAH map to provide survey knowledge to mobile, distributed users (e.g., Buszko et al., 2001; Löffler et al., 2007; Monares et al., 2011; Rodríguez-Covili et al., 2011).

Previous work has developed the following design criteria for effective YAH map design (Klippel et al., 2006):

- **Completeness:** All information that is necessary to complete the given task must be presented on the map.
Figure II.7: A digital YAH map showing the user’s position and orientation as an arrow. The circle around the arrow indicates uncertainty in the location measurement.

- **Perceptibility, syntactic clarity, visual clutter**: All task-relevant items on the map must be easily perceptible and identifiable, with visual clutter being the biggest threat to perceptibility.

- **Semantic clarity**: All symbols must be imbued with meaning, and all symbols should be self-explanatory.

- **Pragmatics**: A good design should take into account how, when, and where information is used.

These criteria can, at times, conflict with one another and result in usability problems. For example, completeness and perceptibility may not be possible if a large quantity of information must be displayed to ensure completeness, since a large amount of displayed information may result in visual clutter. Achieving full semantic clarity can also be a hindrance, since providing unique symbols for a multitude of information types may result in information overload.

The link between visual clutter and wayfinding is important, and previous research has shown that map readers may be unable to ignore unwanted or irrelevant graphic information (Dobson, 1980). Therefore, MSW applications that display large amounts of information on the digital map may hinder a user’s ability to wayfind. It is important to provide methods to reduce visual clutter, such that wayfinding can be improved in dynamic scenarios (e.g., disaster first response, construction management, etc.).

Designing YAH maps for mobile devices can result in even greater design challenges. Early YAH maps
were typically large stationary maps that displayed relevant information from the perspective of the particular map’s location in the environment (Levine, 1982). Static YAH maps may only need to provide for a small subset of possible tasks that are achievable with respect to the user’s current location. YAH maps utilized on mobile devices are carried with the user and are subject to the changing goals of users and the conditions of the environment. Therefore, mobile YAH maps must account for a larger possibility of use cases.

Prior research developed navigation tasks that can be used to quantitatively evaluate a user’s level of survey knowledge, both when using a map and when navigating an environment unassisted. These tasks fall into two distinct categories: searching and exploration, and example tasks include (Darken and Cevik, 1999):

- **Targeted Search**: A search task where the desired target is indicated on a map.

- **Primed Search**: A search task where the target’s location is given, but the target is not shown on the map. The search is presumed to be non-exhaustive.

- **Naive Search**: A search task where no knowledge of the target’s location is provided, implying an exhaustive search.

- **Exploration**: A general wayfinding task in which there is no specific target. A user may be asked to explore an area and report any interesting items that were found.

These task types provide an adequate starting point for defining domain-specific search and wayfinding tasks when using digital maps. Darken and Cevik (1999) designed tasks of each of the four types to compare forward-up and north-up virtual map displays. These task types were also used effectively to study wayfinding in large virtual worlds (Darken and Cevik, 1999; Darken and Sibert, 1996), and can be modified for MSW scenarios. For example, primed search can be accomplished by tasking the user with finding an item on the map within an indicated region (e.g., a city block, a large structure, etc.). Naive search can be accomplished by tasking a user with finding a particular named target on a map (e.g., a particular building or a POI representing a particular event). An exploration task can ask the user to scan a certain area and report any items of interest that may be indicated by POIs on the map. Targeted search is unnecessary, since all other tasks require finding a target on the map. Wayfinding can augment these tasks by requiring users to navigate to particular items of interest in the real world, or guide simulated agents to destinations via the mobile interface.

Prior research has developed general strategies for testing map reading comprehension under the effects of visual clutter. Phillips and Noyez (1982) conducted one of the first map-based visual clutter evaluations using geological survey maps, and developed several questions to evaluate the effect of visual clutter. These questions can be categorized into two basic types: pointed questions and general questions. Pointed questions related to satisfying specific queries, such as determining the location of rivers and roads on the map. General
questions were phrased as timed true/false questions that required a general survey of the map. For example, a general question asked participants to determine whether or not limestone rock formations ever occurred at greater than 305 meters on the presented map. General questions require a more exhaustive search of the map in order to determine general environmental characteristics. Pointed questions typically involve finding a number of a particular type of item. Many of the questions asked by Phillips and Noyez were timed; however, the authors did not provide a justification of the time intervals used, indicating that the intervals were perhaps chosen by experimentation and were task specific.

General and pointed questions can be adapted to a mobile YAH map used in an MSW scenario. Pointed questions can ask about items of importance on the map. General questions can task the user with developing a higher-level understanding of the scenario by making connections between items present on the map. For example, in a first response scenario, a general question may ask if a building is likely to catch fire in the future. The participant must determine if items representing fire reports are in close proximity to the building in order to determine if a fire may spread to the particular building. Such a question may require more cognitive effort than simply finding a particular piece of information on the map.

Prior research has classified the wayfinding challenges that occur when performing assisted navigation (Owens and Brewster, 2011). Owens and Brewster’s wayfinding classification categorizes errors into three broad sources: the map being used, the navigator, and the environment. Map errors are typically related to misrepresentations of information on the map (e.g., a path being omitted, obscured, or misrepresented). Navigation errors are typically related to miscues in judgment, hesitation, or disorientation. Environmental errors arise when the environment has changed and the map no longer reflects the current environmental state.

A mobile YAH map can remedy environmental errors by providing updated information concerning the environment (e.g., indicating closed roads, blocked paths, etc.). However, care must be taken to prevent map errors when using a digital YAH map on a mobile device. For example, information items placed on the screen may obscure relevant paths. Information relevant to a path (e.g., indication that a path is blocked or inaccessible) may also be obscured by other information. If added information is not salient enough, navigation errors may lead to reduced wayfinding performance. Therefore, methods that reduce visual clutter on a digital map may also improve wayfinding ability by reducing navigation errors.

Many MSW applications and frameworks implement YAH maps to provide localization information to the user and to other collaborators (e.g., Buszko et al., 2001; Löfler et al., 2007; Monares et al., 2011; Rodríguez-Covili et al., 2011). Previous research in the design of mobile guides also emphasizes the importance of location awareness in mobile map-based applications (Nivala and Sarjakoski, 2003); however, conflicting opinions exist as to whether or not localization information is beneficial in mobile collaboration scenarios. Nova et al. (2006) utilized location awareness in a collaborative game and determined that when sharing
location information between users, task performance did not improve. The authors also stated that users became much more passive when localization information was provided. Ultimately, the authors concluded that by not broadcasting location information, participants were forced to communicate more often, leading to greater communication of relevant information.

Prior research has determined that the use of a mobile device for navigation can discourage engagement and degrade spatial knowledge acquisition, thus hindering the development of survey knowledge necessary for wayfinding (Parush et al., 2007). Mobile navigation systems can excel at providing route knowledge between distinct locations, but may fail at effectively developing survey knowledge (Parush et al., 2007). Mobile navigation systems may remove humans from the loop, providing an automated means of route discovery that requires little cognitive effort. Map-based MSW applications often attempt to develop a user’s survey knowledge and spatial awareness; therefore, a higher level of user engagement may be necessary than that which is typically utilized in mobile navigation systems.

Despite the findings of Nova et al. (2006) and Parush et al. (2007), the pervasive use of YAH maps in other MSW applications supports the notion that YAH maps are generally beneficial for mobile collaboration. However, the benefits of utilizing location awareness and the YAH map may be domain dependent. For example, the task devised by Nova et al. was a relatively straightforward search-based task, and may not have required location awareness to be carried out successfully. As task difficulty increases, however, the need for location awareness may increase, lending validity of the use of the YAH map in more dynamic domains. A highly dynamic scenario may also increase user engagement, mitigating one of the key issues in developing survey knowledge (Parush et al., 2007).

II.1.3 Precise Selection with Mobile Devices

Mobile device interaction while walking can provide a host of interaction challenges. For example, walking speed may dictate interaction difficulty (Bergstrom-Lehtovirta et al., 2011), a user’s attention may be divided between the device and navigation (Kane et al., 2008), and occlusion due to using a finger with the screen as an input mechanism (Holz and Baudisch, 2010) may lead to user input that lacks the user’s intended precision, resulting in error. Additionally, imprecise selection can result as the finger’s contact area with the screen changes during finger movement. The changing contact area results in a non-uniform mapping between the fingertip and the screen’s interaction point, which causes input error (Forlines et al., 2007). Unlike a mouse, which can accurately select a single pixel, a finger’s contact area is much larger, resulting in imprecise mappings to a single pixel (Benko et al., 2006).

Target selection tasks are often used for evaluating mobile device usability. The target selection task places targets on the screen and requires the user to select the targets. Targets can be static in nature or change.
position relative to the screen (e.g., Hajri et al., 2011). Target selection evaluations have been performed in
seated (Dearman et al., 2007; Kown et al., 2009; Park et al., 2008), controlled walking (Bergstrom-Lehtovirta
et al., 2011; Lin et al., 2007; Schedlbauer and Heines, 2007; Schildbach and Rukzio, 2010), and real-world
(Henze et al., 2011) scenarios.

While target selection is important, mobile devices are not solely used for selecting static targets. For
example, continuous precise selection tasks such as performing gestures (e.g., Bragdon et al. 2011; Findlater
et al. 2012) and annotating and drawing (e.g., Convertino et al., 2005; Ens et al., 2011; Meyer et al., 2011;
Monares et al., 2011; Ochoa et al., 2011), are also frequently utilized when interacting with touch screens.
Continuous precise selection requires the accurate specification of many individual points (i.e., targets) that
form a solid line. Each specified point may have some offset from the user’s intended point, resulting in error
(see Figure I.3).

Pixel-precise specification is important in some domains, such as those that map pixel locations to precise
geospatial coordinates. Prior research has shown that drawing on a touch screen to specify geospatial coor-
dinates is preferred to selecting each point individually (Hayes and Hooten, 2010). If drawing is to be used
as a specification mechanism in software applications where continuous precise selection is necessary, it is
important to quantify the error generated due to a user’s continuous imprecise selection (see Figure I.3). If
one knows quantitatively how much drawn input deviates from a particular shape, then the user’s error may
be corrected.

Previously Hooten and Adams (2011) developed a preliminary algorithm for determining the error that
exists between a user’s drawn input and an on-screen object the user attempted to trace. The algorithm solves
the nearest-point-on-a-curve problem iteratively (Glassner, 1993); where each point is a single point in the
user’s supplied input and the curve is the intended object the user attempts to trace. This algorithm does not
provide the true error, rather an approximate error is calculated based on the sum of distance measurements
from each input point to the curve being traced (see Figure I.3). Hooten and Adams’s algorithm is provided
as Algorithm 1.

Algorithm 1 Error calculation algorithm for the nearest-point-on-curve problem.

| Input: The number of discrete parameters, $n$, input point $p_I$, and curve $C$ |
| Output: The shortest distance from $p_I$ to $C$, $d_{pc}$ |
| 1: $d_{pc} \leftarrow \infty$ |
| 2: for all $p_C \in C$ do |
| 3: $d \leftarrow (p_C, x - p_I, x)^2 + (p_C, y - p_I, y)^2$ |
| 4: if $d < d_{pc}$ then |
| 5: $d_{pc} \leftarrow d$ |
| 6: end if |
| 7: end for |

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Curve $C$ represents the parameterized form of the curve to be matched, and $P_C$ returns a point on the parameterized curve $C$. Since $n$ is the number of discrete parameters, it is an application-dependent parameter specified by the implementer. A lower $n$ value results in a faster algorithm, albeit with potentially lower precision, since there are fewer points on $C$ to match to $P$. Algorithm 1 runs in $O(nm)$ when $m$ input points are used.

Hooten and Adams used Algorithm 1 to determine the performance differences between drawing tasks using touch input and mouse input (Hooten and Adams, 2011). Later work has confirmed Hooten and Adams’ findings using an unpublished algorithm (Zabramska and Stuerzlinger, 2012). Both works indicate that drawing using a finger is faster, but results in more error, than when drawing with a mouse. Therefore, it is important to support finger-based drawing on mobile devices since more precise methods (e.g., a mouse or stylus) are not always available or practical.

Algorithm 1 is analogous to dynamic time warping, which is an algorithm for measuring the similarity between two sequences of data (Sakoe and Chiba, 1978). Dynamic time warping was initially developed to determine differences between data sequences that may vary in time, but remain similar (e.g., speech, written words, gestures, etc.). Dynamic time warping has been applied to a number of other fields, such as gesture recognition (Gavrila and Davis, 1996), signature recognition (Munich and Perona, 1999), and data mining (Keogh and Pazzani, 2000).

Dynamic time warping typically excels at determining the similarity between one dimensional data sets; however, research in signature recognition has attempted to apply dynamic time warping to two dimensional data sets, such as drawn figures. Dynamic time warping-based signature recognition algorithms typically fall into two basic categories, those that use the dynamic information of a signature (Bashir and Kempf, 2008; Faundez-Zanuy, 2007) and those that attempt to match the entire signature as it is drawn (Efrat et al., 2007; Munich and Perona, 1999).

The dynamic information approach extracts key biometric information (e.g., velocity of drawing, pen position, amplitude, etc.) from the process of creating the signature. The biometric information is represented as a set of time-series data that is subjected to dynamic time warping-based algorithms. These algorithms operate with complexity similar to, or worse than, traditional dynamic time warping algorithms, $O(nm)$. Since dynamic information based approaches provide measures of similarity on biometric information, they cannot generate a concrete metric for how much two signatures, as written, may vary. Signatures are matched based on the biometric input that was used to create them, not the physical characteristics of the signatures themselves.

Dynamic time warping-based algorithms that attempt to match entire signatures do so using continuous, or near continuous, representations of the input data. Continuous data is obtained through parameterization
of the input and/or the curve to be matched. Parameterization adds a large enough number of points to the data, such that matchings can occur at resolutions far finer than the sampling resolution, therefore simulating continuity. A similar parameterization approach is leveraged by Algorithm 1, and is controlled by the algorithm’s \( n \) parameter. Continuous dynamic time warping-based signature recognition algorithms have been developed that possess exponential time complexities (Munich and Perona, 1999). Approximation-based approaches have been known to achieve \( O(nmr^2) \) time complexity, where \( r^2 \) is the discretization parameter (Efrat et al., 2007).

Algorithm 1 provides an adequate and realistic error measurement in most cases. However, since the algorithm simply matches each input point to the closest point on a given curve, the algorithm may provide an inadequate error measurement when the input deviates greatly from the curve being matched (see Figure II.8). The error shown in Figure II.8 illustrates the key flaw of the algorithm. Rather than match the right side of the user’s drawn input (shown in blue) to the right side of the rectangle (shown in black), each input point is matched to the left side of the rectangle. The algorithm does not account for user intent. The dynamic time warping algorithm applied to the same data will exhibit similar flaws. The reported error for this particular input is artificial and does not provide an accurate estimate of the true error of the drawn shape.

II.1.4 Summary

Unique visualization techniques may be utilized to reinforce MSW design guidelines. Section II.1 discussed the MSW design guidelines and how combined visualizations may reduce the need for multiple widgets (see Figure II.2), which may simplify performing tasks within the user interface.

POIs are ubiquitous in map-based software applications, including MSW applications. However, when POIs are leveraged, visual clutter can result. Grouping mechanisms have been developed to cope with clutter, but these mechanisms rely strongly on the type of the POIs being grouped and may not be effective when
MSW design requirements include Autonomy, Group Awareness, Messaging, and Information Sharing. Convertino et al. (Buddy List / Multiple View) and Wu et al. (* Multi-View Chat) include POIs, Sketching, text editor, Layers. Meyer et al. (P2P) and Rodriguez-Covili et al. (Yes, P2P) use Buddy List and Chat Tool for Private/Public Chat. Velde et al. (SHARE) use hierarchies and Push-To-Share, while Meyer et al. use POI, Sketching, widgets.

Table II.1: Summary of each discussed method’s approach to meeting MSW design requirements. (* Indicates that visualization support was not explicitly stated.)

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<tr>
<th>Design</th>
<th>Geospatial</th>
<th>Context</th>
<th>Semantic</th>
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<tbody>
<tr>
<td>Convertino et al</td>
<td>POIs, Sketching</td>
<td>* Sketching, perspectives</td>
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<td>Meyer et al.</td>
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</tr>
<tr>
<td>Velde et al. (SHARE)</td>
<td>POIs, 3D</td>
<td>Ontology</td>
<td>Ontology</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>POIs, Sketching</td>
<td>Annotation Browser</td>
<td>Sketching, Aggregation Chart</td>
</tr>
</tbody>
</table>

Table II.2: Summary of each discussed method’s approach to providing information context. (* Indicates that visualization support was not explicitly stated.)

Many POIs of different types are collocated.

Prior research has identified the importance of public and private data sharing (Convertino et al., 2005; Wu et al., 2009) as a form of semantic context; however, on a mobile device, visualization techniques to support private/public data sharing are limited. The multiple map view approach may be too space intensive. Zooming can be leveraged, but it does not provide true privacy. Layers can implement permissions and may facilitate private/public data sharing. Layers also facilitate multiple group memberships, which may allow for fine-grained information sharing. However, layer management may be difficult if many layers are required.

MSW frameworks typically utilize common interface components to provide information context and meet MSW requirements. These common interface components include: POIs, layers, chat, and buddy lists. Table II.1 summarizes how these common components are used to meet MSW design requirements in previously developed shared workspace systems. Note that the MSW frameworks (i.e., Meyer et al.’s system, SHARE, Rodriguez-Covili et al.’s MSW framework) share many of the same widgets utilized by the desktop-based shared workspace software (i.e., Wu et al.’s and Convertino et al.’s systems).

Each of the systems shown in Table II.1 implements methods to support context awareness through the geospatial, temporal, and semantic contexts. The methods to satisfy the three semantic contexts for each system are summarized in Table II.2.

Feature Sets are designed to address each of the MSW Design Requirements shown in Table II.1, and to provide information context. Chapter III will return to Tables II.1 and II.2 in order to illustrate how Feature Sets compare to these previously developed methods.
The YAH map is used to coordinate the position of a user within an environment, and is frequently used in MSW applications. Prior research has shown the connection between visual clutter and reduced wayfinding capability when using YAH maps. It is believed that by developing visualization methods to reduce visual clutter on a YAH map, wayfinding performance may be improved. Therefore, Feature Sets may improve wayfinding performance when using a digital YAH map.

Specific tasks can be utilized to assess the impact of visual clutter, such as the pointed and general question technique (Phillips and Noyez, 1982). The effectiveness of the YAH map for displaying information can be evaluated by modifying the task types described by Darken and Cevik (1999). Prior research (e.g., Owens and Brewster) can be used to inform evaluations concerned with the effects of visual clutter on wayfinding. Feature Sets will be evaluated using modified versions of these techniques in order to assess Feature Sets’ effect on visual clutter and wayfinding performance.

Drawing can be facilitated on a mobile device touch screen by using the finger. However, when a user attempts to draw, error may occur due to the physiology of the finger and the resolution of the mobile device’s touch screen (i.e., the “fat finger” problem). Prior research has resulted in algorithms that can quantify this drawing error (Hooten and Adams, 2011). Dynamic time warping-based algorithms have also been developed that can determine if two data sets correspond to one another. When applied to signature recognition, the results of dynamic time warping-based algorithms are analogous (although with potentially higher algorithmic complexity) to those obtained by Algorithm 1.

The background provided in this section discusses the current state of the art in MSW research and indicates the shortcomings of previous approaches in terms of visualization techniques. The remainder of this report discusses Feature Sets and how Feature Sets can be used to address these shortcomings. Additionally, previous methods of evaluating YAH maps, wayfinding, and visual clutter have been discussed. These methods will be utilized to design the user evaluations that will scientifically validate Feature Sets. Since drawing is the interaction technique most leveraged by Feature Sets, the presented background has also discussed precise selection and techniques for quantifying user error when drawing. These techniques may be improved or used outright within Feature Sets to assist in the specification of Feature Sets on a digital map.
CHAPTER III

System Description

III.1 Introduction

Feature Sets are abstract containers that group information based on geospatial information. Feature Sets were designed upon the core visualization concepts of providing information overviews, filtered information, and in-depth details on demand (Shneiderman, 1996). Feature Sets integrate multiple levels of detail within the same representation, which may be beneficial to user understanding (Keahey, 1998). Feature Sets aggregate information of multiple types into a single visualization, providing additional context that may be unavailable when viewing information of a single type. Feature Sets’ primary focus is to reduce visual clutter when displaying information on a digital map; however, additional characteristics of Feature Sets described in Sections III.2 and III.3 will show that Feature Sets also support salient notification of new information and more robust grouping and information display mechanisms.

This chapter will discuss the design and implementation of Feature Sets in two sections. Section III.2 discusses the design of Feature Sets as evaluated by a user study described in Chapter IV. Section III.3 proposes extensions to Feature Sets that will be developed and evaluated for completion of the dissertation.

III.2 The Developed System

Feature Sets support MSW design requirements while addressing deficiencies in current data visualization techniques for mobile devices. A Feature Set is a geospatial map region (e.g., a building, a road, a portion of wilderness, etc.) that can be used as a container to store information relevant to that region. A Feature Set abstracts the notion of POIs to AOIs and can store information of different types related to the area. Since information added to a Feature Set can encompass more than a single POI (i.e., the information can be pertinent to the entire area), added information is referred to as an information item or simply an item.

III.2.1 Information Grouping and Display

Feature Sets provide overview knowledge by placing information into geospatially-related groups. Detailed information is accessed by tapping or clicking on the Feature Set (see Figure III.1). The shape of the Feature Set indicates the geospatial region to which information within the Feature Set pertains. The geospatial context for information is supported by providing a geospatial container with which to store information. When a Feature Set is selected (i.e., it is tapped or clicked) it enters the expanded state, which displays a listing of the items contained within the Feature Set (see Figure III.1b). The Feature Set displays a detail
Figure III.1: The three visualization states of a Feature Sets when placed on a digital map.

view of information on demand by allowing the selection of individual items from the expanded view. The Feature Set enters the details state when an item is selected from the expanded view’s item list. The details state provides detailed information for the selected item (see Figure III.1c).

Information items are displayed in a chronologically ordered list in a Feature Set’s expanded state; with the newest item appearing at the top of the list. Users can scroll through the list to see items that have been added to the particular Feature Set over the course of the Feature Set’s existence. Chronological ordering provides a temporal context to the created information; users can browse the item list to gain a temporal understanding of events that have occurred within the Feature Set. POI-based approaches by default do not support the temporal context, since no chronological ordering is used. POI-based approaches may also add information to the map directly on top of or nearby other information items, causing visual clutter. The expanded Feature Sets view prevents visual clutter by categorizing collocated information into an ordered list.

The details state of a Feature Set provides detailed information for a single information item within the Feature Set (see Figure III.1c). The details state can display an image or other media, such as video thumbnails, associated with the information item along with an accompanying text description of the item. Information regarding the creator of the item, such as the creator’s name and connectivity status, is also displayed (see Figure III.1c). The details state also displays tags that provide classification for the information item and are beneficial for use as search keywords (see Section III.3 for a discussion of information tags).

Feature Sets’ three information views are designed to explicitly reinforce many of the previously mentioned MSW design requirements (see Section II.1). For example, Messaging can be provided by allowing the user to message the creator of the item through a shortcut within the item view (see Figure III.1c). Group
Awareness is supported by displaying the item creator’s connectivity status within the item view. Information Sharing is facilitated by aggregating collocated information from multiple collaborators and providing a meaningful summary of the information in one convenient location, the Feature Set. Also, since information items and Feature Sets can be created by a single user, Autonomy is supported as the user can continue to add information items and Feature Sets even if network connectivity to the rest of the group is lost. If network connectivity is lost, Feature Sets can become gray in color, to indicate a network connection is not present and displayed information may be stale (see Figure II.1).

III.2.2 Salient Notification

Feature Sets provide salient information updates to the user at the overview and expanded visualization states, through the use of notification indicators. Notification indicators are icons associated with each Feature Set that clearly display the number of items within the Feature Set the user has yet to view (see Figure III.1a). A notification indicator’s count increases as items are added or modified within the Feature Set, and decreases as items are viewed. The expanded view displays unviewed information using boldface text in the Feature Set’s information items list (see Figure III.1b). The use of boldface text alerts users to new information in a manner similar to the appearance of new e-mail indicators in an e-mail inbox. Boldface text alerts users to new or altered information by visually distinguishing these information items from others that have been previously viewed.

Notification indicators are used to support Information Sharing in collaborative scenarios by alerting users to information that has been added or modified by other collaborators. Using notification indicators, users do not have to search for new information within Feature Sets without first knowing whether or not information has been updated within a Feature Set. Notification indicators have been designed to increase the discoverability of newly added information.

Compared to POIs, notification indicators provide a more salient alternative to representing new information. When using a POI-based approach, new information is added to the map via adding a new POI or altering a POI that currently exists. Even if the POI is altered (e.g., highlighted, increased in size, etc.) such that the new information is more apparent, the POI can still be difficult to find if an area is visually cluttered. Feature Sets reduce visual clutter and provide information update knowledge via the notification indicator.

III.2.3 Feature Set Creation and Interaction

Feature Set creation is facilitated through sketching, which allows the user to draw any abstract shape to represent a Feature Set (see Figure III.2). Sketching is particularly useful for Feature Sets that represent abstract ideas or locations. For example, if a collaborator in an emergency response scenario finds a number
of victims at the site of an explosion, the collaborator can draw a Feature Set that roughly encompasses the encountered victims. If a single item is created in an area with no Feature Sets nearby, a Feature Set can be automatically created to encompass it, and the user can be prompted to provide a geospatial area for the item via sketching. If an item is created that happens to be near more than one Feature Set, the user can select the Feature Set to which the newly created item should belong, or create a new Feature Set altogether. Utilizing drawing for Feature Set creation leverages a common touch input mechanism (i.e., the finger) and provides the ability to create complex shapes quickly.

Feature Sets are designed to support unimanual interaction. Since users are intended to be active in an environment while participating in a MSW scenario, bimanual interaction is not practical because one hand may be dedicated to supporting the mobile device. Therefore, Feature Set creation and visual state changes are accomplished using a single finger. A user taps a Feature Set to enter its expanded state. Users can revert an expanded Feature Set to the overview state by tapping on the expanded Feature Set. Selection of individual information items in the expanded view is facilitated via tapping on the item of interest. A user can transition from the details state to the expanded state via a single tap on a back button that is displayed while in the details state (see Figure III.1c), and the overview state can be accessed by closing and reopening the Feature Set. The interaction design of Feature Sets ensures that all levels of information (e.g., overview, expanded, details) are no more than two tap interactions from any other level.

Feature Sets are at a disadvantage from an interaction standpoint when compared to viewing the information of a single POI, since the information contained by a single POI can be accessed via a single tap. However, when a group of POIs are present, as many selections as POIs in the group may be required to find a particular item. Feature Sets, on the other hand, impose a much smaller upper limit on the number of
interactions required to find a particular item by providing information in a sorted list and clearly indicating the presence of new information to the user.

Another interaction disadvantage for Feature Sets is that they are inherently tied to the geography of the map. Therefore, the size of a Feature Set will change as a user alters the zoom level of the map, unlike POIs which typically retain the same size regardless of zoom level. This disadvantage is particularly problematic if the user zooms out a large distance, since a Feature Set may become too small to reliably select with a finger (see Figure III.3). Feature Sets’ reliance on the underlying geography to form their shape results in reduced visual clutter, but can introduce selection difficulties at higher zoom levels where Feature Sets may become too small to accurately select.

III.3 Proposed System Developments

Three key features are proposed to extend and enhance the functionality of Feature Sets. These features are proposed to address current deficiencies in the design of Feature Sets. The first improvement is Feature Set abstraction. Abstraction will alter the current design of Feature Sets, such that a Feature Set can contain Feature Sets, as opposed to simply containing information items. Abstraction was developed to further reduce visual clutter, provide a grouping mechanism internal to the Feature Set that may be beneficial in large or complex geospatial areas, and to provide the possibility for Feature Sets with a larger hit area at higher zoom levels. The second improvement is to add the ability to tag information and Feature Sets with relevant keywords to facilitate searching and filtering of Feature Sets. Tagging functionality is external to the Feature Sets visualization, but works alongside Feature Sets to reduce visual clutter and assist the user when searching for information. The third improvement is the addition of layers to Feature Sets. Layers will provide coarse grained methods to limit the number of displayed Feature Sets, and facilitate separate private, public, and group-centric workspaces.
The proposed work also includes integrating drawing more effectively with Feature Sets to assist in the Feature Set creation process. The developed system allows a user to draw an arbitrary shape to represent the contained area of a Feature Set; however, it may be difficult with the current approach to accurately specify more complex geometry. For example, a mobile user may intend to define a single building as a Feature Set and instead, due to the imprecision inherent to touch-based interaction, the building and its surrounding areas may be included in the Feature Set. Therefore, a proposed system development is to remove the need for precise drawing when creating a Feature Set.

III.3.1 Feature Set Abstraction

Feature Set abstraction facilitates the development of geospatial information hierarchies by allowing Feature Sets to be nested within encompassing Feature Sets (see Figure III.4). Feature Set abstraction is intended to work closely with zooming to provide ideal visual representations of Feature Sets depending on the current zoom level of the digital map. For example, on the Vanderbilt University campus (see Figure III.4), a Feature Set may exist for the Divinity School and Garland Hall. At a high zoom level, a single, geospatially larger Feature Set representing the Vanderbilt University campus, can contain both Feature Sets.

This example demonstrates the benefits of Feature Set abstraction. First, by utilizing larger Feature Sets at higher zoom levels, it is ensured that Feature Sets will remain large enough to select with a finger. Second, the contained Feature Sets represent a logical sub-grouping of information with the Vanderbilt University Feature Set, and form a geospatially-related hierarchy of information. Feature Set abstraction can segment the Vanderbilt Campus area, which is comprised of numerous structures and landmarks, into a series of nested
geospatial containers, allowing for a hierarchical visualization of a potentially complex area. More importantly, this hierarchy can be viewed and utilized without concrete knowledge of the area, which is beneficial at higher zoom levels where important areas on the map may be too small to be adequately visualized. Abstraction may also be beneficial for gaining survey knowledge of the map, since the approximate location of pertinent landmarks and locations (e.g., Garland Hall in Figure III.4) can be determined without an exhaustive search of the map at lower zoom levels. Feature Set abstraction can be used to convey geographical information to the user at high zoom levels that may, by necessity, obscure and hide important map details.

Feature Set abstraction has also been designed to work effectively with notification indicators to provide salient information updates at every abstraction level. The number of new and changed items in a nested Feature Set are propagated up to the highest level Feature Set, adding to the parent Feature Set’s notification count. An example is provided in Figure III.4, where the highest level Feature Set has two unviewed items and a contained Feature Set, the Divinity School, has two unviewed items, leading to a count of four appearing on the highest level notification indicator. Effectively coupling Feature Set abstraction with notification indicators will be a significant improvement that further reduces visual clutter, while continuing to provide overview information. Coupling notification and abstraction is a novel approach for saliently visualizing information on a digital map.

Feature Set abstraction is a repeatable concept that can nest Feature Sets to any number of levels. The core Feature Set concepts: container shape, overview information, and detailed views on demand can be preserved and repeated at all abstraction levels. A limitation of abstraction is that information retrieval may become confusing if Feature Sets are nested too deeply, similar to deeply nested context menus in traditional desktop user interfaces (Jacko and Salvendy, 1996). Notification indicators can help mitigate this issue by directing users to new information (see Figure III.4), but it is expected that design guidelines will be needed to address the appropriate depth to nest abstracted information in Feature Sets.

Shortcomings may also exist with notification indicators when coupled with abstraction. For example, notification indicators are limited by the simplicity of their visualization. User evaluations may determine that the simple increase/decrease count on the notification indicator is too simplistic and does not communicate enough overview knowledge. Abstraction further complicates the issue, since at a top level Feature Set, a user cannot tell which nested Feature Set has been updated without first expanding the top level Feature Set. This issue can be addressed through a more complex implementation (e.g., indicators that take the shape of the modified nested Feature Set, highlighting the nested Feature Set in the overview state, etc.). Despite their simplistic design, notification indicators improve saliency by propagating notification information to top level Feature Sets. This propagation increases the effectiveness of abstraction, while providing salient notification at all abstraction levels.
III.3.2 Filtering Methods

Even though Feature Sets have been designed to reduce visual clutter, the presence of many Feature Sets on the map may increase the difficulty of finding individual information items or Feature Sets of interest. Therefore, it is beneficial to couple Feature Sets with filtering mechanisms, such that the visible set of Feature Sets can be reduced based on filtering criteria.

Items can be supplied with tags during creation to facilitate searching and filtering. For example, in Figure III.1c the displayed tag is Framing. This tag, supplied by the collaborator that created the information item, can be used as a search term to filter the number of Feature Sets visible on the screen or indicate Feature Sets that contain the searched items (see Figure III.5a). A user can select a highlighted feature to see a list sorted with the searched items at the top of the list (see Figure III.5b). Searching via tags can circumvent visual clutter by minimizing the need to search the digital map’s entire contents. Tags also provide an extensible method by which to organize data, and in appropriate domains, applicable tags can be provided by default, to minimize the user’s need to type new tags for common, domain-specific nomenclature. A potential limitation of tags is user frustration that may occur when a user must memorize tags or search for relevant tags using trial and error methods. A list of available tags can be provided (see Figure III.5a) and predictive text used when entering tag search terms to alleviate this issue.

Tags can provide a semantic context to information items and Feature Sets. For example, if a user searches for the “fire” tag, all Feature Sets containing items tagged with the word fire are displayed. Such a display can give the user an idea of how a fire has propagated throughout an area. From conducting a search of the fire tag, the user can discover associations (e.g., geospatial proximity) between Feature Sets that share related information items.
III.3.3 Information Layering

Feature Sets can be used with layers to support the public and private creation of data, group memberships, and permissions. The visibility of layers can be toggled in order to reduce the number of visible Feature Sets on the map. Group-specific Feature Sets can be stored in separate layers that users can toggle to view more or less information as necessary. If a user determines that a Feature Set in one layer is pertinent to another group, the Feature Set can be shared with that group and, thus, visible in both layers. Feature Sets can also be color coded by layer or colored using patterned fills (e.g., crosshatching, dots, etc.), such that users can quickly recognize what Feature Sets belong to which group. Promoting Feature Sets from the user’s private layer to a group layer or a public layer can also be supported. Like tags, layers provide a semantic context to Feature Sets by representing all of the Feature Sets created by a single group or user on one layer. Hiding and showing other users’ layers allows users to quickly determine which users added particular content, assisting in collaboration between multiple users.

Feature Sets combined with layers provide a coarse-grained method of Information Sharing, since Feature Sets can be promoted to relevant layers and their visibility restricted based on extensible criteria (e.g, group membership, privacy, etc). When a user promotes a Feature Set from his/her private layer to the public layer, fellow collaborators gain access to a large amount of information in a compact visualization. Layers also reduce visual clutter by allowing for the toggling of visibility of a potentially large number of Feature Sets at once.

Layers possess design challenges and limitations. A potential limitation is that too many layers may lead to confusion, especially if a user is unaware of which layers are currently hidden versus those that are shown. This issue can be mitigated through providing knowledge of layers’ state, such as with a list displaying hidden and shown layers. Sharing Feature Sets between layers is a design challenge. For example, overlap will occur if a Feature Set is shared with a group that already has a Feature Set placed at the location of the Feature Set being shared. Overlap must be avoided, since it can lead to visual clutter and limit the ability to easily select the overlapping Feature Sets. One solution may be to incorporate the overlapping Features into an abstract Feature Set; however, Feature Set combination must occur in a salient way to prevent confusion.

III.3.4 Feature Set Creation

Precise selection using a finger as the input mechanism is difficult; therefore, it is expected that as users draw to specify Feature Sets, errors will be unavoidable. It is necessary to develop methods that assist the user in the process of creating Feature Sets to mitigate these errors. For example, if a user specifies a region on the map through drawing (see Figure III.6a), landmarks encompassed within that region can be automatically highlighted and shown in a list that can be utilized to create a Feature Set. The created Feature Set can consist
of one or many of the landmarks encompassed in the drawn region (see Figure III.6b).

The use of landmarks can be beneficial in Feature Set creation; however, user-created Feature Sets may not always enclose landmarks. Therefore, additional methods will be implemented that can determine what is enclosed in a user’s drawn areas. For example, if a user draws around a parking lot and section of road (see Figure III.7), the interface can make suggestions as to what landmarks may be of interest within the user’s drawn area (i.e., the road and parking lot).

Preliminary work using map geography to influence the outcomes of user drawings was implemented for the Dynamic Information Evaluation to assist in the drawing of routes (see Section IV.5.1). The Dynamic Information Evaluation assisted users in drawing paths by causing drawn lines to automatically snap to the nearest street. This preliminary work indicates that utilizing map geography to impact drawing performance is possible.

Several methods exist for determining the potential Feature Sets within a user’s drawn shape. If a mapping service such as Google Maps is used, the locations of roadways and many structures can be known ahead of time; therefore, providing suggested Feature Sets that are comprised of these landmarks is relatively simple (see Figure III.7). A drawback to this approach is that, when no landmark information exists, Feature Sets cannot be suggested to the user. Therefore, some locations, such as parking lots and miscellaneous small buildings, cannot be suggested as Feature Sets.

III.4 Summary

Feature Sets are geospatial containers intended to reduce visual clutter, support MSW design requirements, and provide context to displayed information. Feature Sets have been designed to fulfill MSW design require-
Figure III.7: A user’s original drawn area (shown in red), and the recommended Feature Sets that have been suggested by the interface, shown in blue. In this case, the recommended Feature Sets are a section of roadway and a parking lot.

Table III.1: Summary of previous methods’ and Feature Sets’ approaches to meeting MSW design requirements. (* Indicates that visualization support was not explicitly stated.)

<table>
<thead>
<tr>
<th>Design</th>
<th>Autonomy</th>
<th>Group Awareness</th>
<th>MSW Design Requirement</th>
<th>Information Sharing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convertino et al.</td>
<td>Gray out</td>
<td>Integrated Connectivity Information</td>
<td>Integrated Communications Chat Tool</td>
<td>AOIs, Notification Indicators, Layers, Tags</td>
</tr>
<tr>
<td>Meyer et al. (CoMA)</td>
<td><em>(P2P)</em></td>
<td>Buddy List / Multiple View</td>
<td>Chat Tool</td>
<td>POI, Sketching, text editor, Layers</td>
</tr>
<tr>
<td>Rodriguez-Covili et al</td>
<td>Yes (P2P)</td>
<td>Buddy List</td>
<td>Private/Public Chat</td>
<td>POI, Layers</td>
</tr>
<tr>
<td>Velda et al. (SHARE)</td>
<td>*</td>
<td>Hierarchies</td>
<td>Chat Tool</td>
<td>POI, Sketching, widgets</td>
</tr>
<tr>
<td>Wu et al. (CIVIL)</td>
<td>*</td>
<td>Multiple View</td>
<td>Push-To-Share</td>
<td>POI, line/region, voice, Layers</td>
</tr>
</tbody>
</table>

Tables III.1 and III.2 show that Feature Sets have been designed to meet many MSW design requirements and provide all levels of information context. Feature Sets also meet the general requirements of an effective visualization technique by providing overview information, filtered information, and in-depth details on demand. The proposed research will attempt to extend Feature Sets by implementing Feature Set abstraction, tagging, and layers. Abstraction will allow Feature Sets to contain Feature Sets, supporting geospatial information hierarchies, reducing visual clutter, and ensuring that Feature Sets are large enough to be selected at high zoom levels. Tagging will allow users to filter the displayed Feature Sets by providing relevant search criteria. Tagging will be useful in the event that a user is searching for specific types of information on the digital map. Layering will be implemented to support the private/public classification of data and group and user specific displays of information.
Table III.2: Summary of previous methods’ and Feature Sets’ approaches to providing information context. (* Indicates that visualization support was not explicitly stated.)

<table>
<thead>
<tr>
<th>Design</th>
<th>Geospatial</th>
<th>Context</th>
<th>Temporal</th>
<th>Semantic</th>
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</thead>
<tbody>
<tr>
<td>Feature Sets</td>
<td>AOIs, Sketching</td>
<td>chronological item ordering</td>
<td>Layers, Tags</td>
<td></td>
</tr>
<tr>
<td>Convertino et al.</td>
<td>POIs, Sketching</td>
<td>*</td>
<td>Sketching, perspectives</td>
<td></td>
</tr>
<tr>
<td>Meyer et al. (CoMA)</td>
<td>POIs</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Rodriguez-Covili et al.</td>
<td>POIs, Sketching</td>
<td>Time stamps</td>
<td>Sketching, Related Information</td>
<td></td>
</tr>
<tr>
<td>Velda et al. (SHARE)</td>
<td>POIs, 3D</td>
<td>Ontology</td>
<td>Ontology</td>
<td></td>
</tr>
<tr>
<td>Wu et al. (CIVIL)</td>
<td>POIs, Sketching</td>
<td>Annotation Browser</td>
<td>Sketching, Aggregation Chart</td>
<td></td>
</tr>
</tbody>
</table>

Drawing is an interaction mechanism that is crucial to the creation of Feature Sets. The current implementation of Feature Sets utilizes drawing in a rudimentary way that may be insufficient for Feature Set creation. Therefore, the proposed research will integrate drawing more closely with Feature Sets and attempt to provide suggestions of appropriate Feature Sets to create when the user draws arbitrary shapes on the digital map.
CHAPTER IV

Preliminary Feature Sets Evaluation

IV.1 Introduction
A preliminary user evaluation was conducted to assess the benefits of Feature Sets as compared to POIs. Since POIs are a common visualization method to display information on digital maps, a comparison study of POIs and Feature Sets is a logical first step in evaluating the effectiveness of Feature Sets. The evaluation comprised two experiments, the Static Information Evaluation and the Dynamic Information Evaluation.

The Static Information Evaluation verified the applicability of Feature Sets to a task typically performed by POIs: presenting static information on a digital map. The Static Information Evaluation presented information at varying levels of information density. Both Feature Sets and POIs were used to visualize the same information at three levels of information density. Participants used POIs and Feature Sets to answer questions that were constructed in accordance with prior literature (e.g., Darken and Cevik 1999). The Static Information Evaluation also tasked participants with finding particular locations on a digital map.

The Dynamic Information Evaluation compared Feature Sets and POIs by using a wayfinding task that supplied new information to the digital map dynamically throughout the duration of the experiment. The main purpose of the Dynamic Information Evaluation was to determine if Feature Sets provided better information discovery and salience than POIs when information is dynamically added to the digital map. The Dynamic Information Evaluation primarily tests each visualization conditions’ ability to inform users of new information.

Both evaluations were primarily concerned with Feature Sets’ ability to visualize and interact with information. Therefore, users were not required to create Feature Sets or add new information items to existing Feature Sets. Testing such functionality will be a focus of the proposed research.

The remainder of this chapter will describe the experimental methodology, test apparatus, hypotheses, and outcomes of each experiment.

IV.2 Participants
Both evaluations were performed sequentially by all participants. Participants were convenience subjects drawn from the population in and around the Vanderbilt University campus. 30 participants performed the evaluations. A Shapiro-Wilk test determined that participant age deviated from a normal distribution ($W(30) = 0.87, p < 0.01$). The participant median age was 20.5 years, the minimum reported age was 18 years and the maximum reported age was 30 years. 27 participants performed each experiment using the
Participants were administered a demographic survey to subjectively assess computer usage experience, touch device experience, and experience level with using digital maps. All participants reported a basic understanding of digital maps, with 50% reporting Good-to-Expert understanding of digital maps. Participants’ digital map, computer usage, and touch device experience had no effect on results.

IV.3 Test Apparatus
The same test apparatus was used for both evaluations and consisted of a web application, a web browser, and a tablet personal computer. The web application was designed using Ruby on Rails, JavaScript, and HTML 5. The web application presented a digital map encompassing the leftmost three quarters of the user interface and a panel for questions and instructions, the Questions Panel, on the rightmost quarter of the interface, as shown in Figure IV.1. The application was presented on an ASUS EP121 slate personal computer running Windows 7. Since the interface was developed using web technologies, it can be displayed correctly by any modern web browser; however, in order to remove potentially distracting aspects of most modern web browsers (e.g., navigation buttons, text fields, etc.), and to provide more robust touch interaction support, a simplistic web browser, known as SimpleBrowser (Hooten and Hayes, 2012), was developed using C++ with the Qt toolkit and released into the open source.

The digital map was provided via the Google Maps JavaScript API (Google, 2012), and Google Maps’ road map display view was utilized at all times. Participants panned the map using a single finger and zoomed the map using a two-finger pinch gesture. The minimum zoom level was thresholded to prevent participants from zooming out too far and potentially losing focus on the locations of interest. All questions presented to the participants were multiple choice, with answers being provided through the use of radio buttons. Previous and Next buttons were located at the bottom of the Questions Panel to allow users to navigate the questions; however, participants were unable to proceed to subsequent questions without first providing an answer to the question being displayed. Upon providing an answer to the displayed question, tapping the next button caused a new question to be displayed. The Previous button allowed users to revisit previous questions if desired; however, no participant utilized this functionality in either evaluation.

Both evaluations utilized a first response scenario as the testing domain. Information was provided in the form of reports, and a single report represented a single information item. These reports represented information that may be supplied by a team of first responders deployed in the field. For example, a fire report indicates the detection of a fire at a specific location. An example of a fire report, as visualized by both techniques (i.e., Feature Sets and POIs) is shown in Figure IV.2.

Reports contain detail views that display more information about a specific report. The detail view was
Figure IV.1: The web application used to evaluate Feature Sets in the evaluations. The map is displaying an
the Static Information Evaluation Feature Sets condition. The Dynamic Information Evaluation utilized the
Navigation and Guide buttons at the top to toggle between map navigation and path drawing, respectively.

Figure IV.2: A Fire Report as visualized using Feature Sets in the (a) expanded and (b) detail states. (c) A
Fire Report as visualized using POIs.
Thirteen report types were used for both evaluations (see Figure IV.3). Each report type used a unique icon, such that each report was more easily identifiable. Several of the report types were adapted from scenarios that typically fall under the Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) event domain. Some report types not encountered in the CBRNE domain, such as the laser report, were added to introduce additional variety.

IV.4 The Static Information Evaluation

IV.4.1 Experimental Design

A user evaluation was designed to determine the benefits and shortcomings of Feature Sets when compared to POIs for presenting static information on a digital map. The Vanderbilt University campus was used as the setting for the Static Information Evaluation. Reports were localized around seven areas on the map, as shown in Figure IV.4. These seven locations were chosen because they represented varying sizes and shapes, while still remaining closely coupled to the underlying geography.

Three information densities were tested: Low, Medium, and High. Each density level comprised five clusters of information on the digital map. The Low density used 20 discrete information items per cluster, Medium used 35 information items per cluster, and the High density used 50 information items per cluster. An example of a cluster of reports at each information density for POIs and Feature Sets is shown in Figure IV.5. Each density was performed using both visualization presentations, Feature Sets and POIs. One information density and visualization presentation pair formed a single trial. There were six trials in total representing all information density and visualization combinations. The participants performed all six trials in a fully
Both visualization methods displayed the same quantity of information distributed in the same manner on the map; however, report types differed between visualization methods to mitigate learning effects. For example, a fire report located at the (-36.4532, 86.6543) coordinate in the POI visualization condition was replaced by a report of a different type (e.g., a suspicious person report) at the same location in the Feature Sets visualization condition.

Participants were tasked with using the map and the information on it to answer six questions. Each question was one of the following three types:

- **Primed.** Users were provided with an initial search area on the map and asked to perform a task within the given search area.

- **Naive.** Users were asked to perform a task without being provided an initial search location. Naive tasks required an exhaustive search of the map.

- **Exploration.** Users were given information about a particular location on the map and asked to determine the impact of such information.

Question types were designed based on prior research discussed in Section II. The format of each question is given in Table IV.1. Questions were presented in the same order for each trial, and only the report types and locations were altered to prevent learning effects across trials. The provided answers were also the same.
Figure IV.5: Report visualizations for Featheringill Hall at each information density using Feature Sets and POIs. (a) The visualization for Feature Sets at all information densities. Note that the notification indicator reflects the High density trial. POIs are shown at the (b) Low, (c) Medium, and (d) High information densities.

<table>
<thead>
<tr>
<th>Category</th>
<th>Code</th>
<th>Question Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primed</td>
<td>Primed How Many</td>
<td>How many reports of type X exist at location Y?</td>
</tr>
<tr>
<td></td>
<td>Primed Exist</td>
<td>Does report type X exist at location Y?</td>
</tr>
<tr>
<td>Naive</td>
<td>Naive How Many</td>
<td>How many reports of type X exist on the map?</td>
</tr>
<tr>
<td></td>
<td>Naive Exist</td>
<td>Does report type X exist on the map?</td>
</tr>
<tr>
<td>Exploration</td>
<td>Exploration Action</td>
<td>Should action X be taken at location Y due to the existence of report type Z?</td>
</tr>
<tr>
<td></td>
<td>Exploration Affected</td>
<td>Is location X affected by the existence of report type Y at location Z?</td>
</tr>
</tbody>
</table>

Table IV.1: The type and format of each of the questions asked to participants in the Static Information Evaluation. Codes will be used when discussing objective results.

for the visualization conditions at the same information density. In other words, the answers to the Feature Sets High information density trial were the same as the answers to the POI High information density trial. Identical question answers and report locations ensured that participants performed tasks between visualization methods in the same manner. Full randomization and differing report types between visualization trials was implemented to mitigate learning effects. Each of the 30 participants was asked two questions of each type, resulting in sixty total responses per question type.

A “Do not know” response was offered for each question. Participants were encouraged to choose the “Do not know” response, as opposed to guessing, if they did not know the answer to a particular question. The “Do not know” response was provided to mitigate the occurrence of lucky guesses by participants.

Questions were designed to promote different types of search behavior. The Primed How Many and Naive
How Many questions were designed to require an exhaustive search of a particular region and the entire map, respectively. Participants were asked to count the occurrence of a specific type of report, requiring participants to view each report. These two questions were designed to leverage the inherent benefits of Feature Sets, which provides a chronological ordering of reports within a list, leveraging temporal context.

The Primed Exist and Naive Exist questions were designed to promote “at a glance” behavior. The Primed Exist and Naive Exist questions can be answered by finding a single specific item in a region and on the entire map, respectively. These questions were designed to leverage the inherent benefits of POIs, which display all information without any additional effort (e.g., tapping, scrolling, etc.) on behalf of the participant. Exploration questions were designed to require additional effort (i.e., determining the impact and meaning of report types in addition to simply finding and/or counting them) on behalf of the participant.

Participants were also asked to perform Find Tasks. These Find Tasks occurred before any question that required the user to find a specific location on the map (i.e., the Primed and Exploration question types). The intent of the Find Tasks was to decouple search time from the time taken to answer the Primed and Exploration questions. Naive questions required an exhaustive search of the entire map; therefore, search time was inherent to the task itself. Four Find Tasks were performed for each trial, and always occurred before each of the Primed and Exploration questions.

Each Find Task presented the participant with a location on the map to find, the location was always one of the seven used in the evaluation (see Figure IV.4). The location was designated as found after the user tapped the map location. Upon tapping the appropriate location, the AOI changed color indicating a success and the user was allowed to proceed to the next question. The next question presented to the participant involved the area found during the Find Task. For example, if a Find Task requires a participant to locate the Library Lawn, the following question asked the participant to perform a task at the Library Lawn. A participant was unable to proceed to the next question before first successfully completing the Find Task.

The map’s position and zoom level was reset to a default value after completing each question, and the default map orientation can be seen in Figure IV.1. After answering each location question, the zoom level and position of the map was centered to the location of interest in the map. Re-centering the map after location questions ensured that each participant attempted Primed and Exploration type questions from the same starting map position and zoom level. The map position and zoom level was set to the default values for Naive questions, ensuring participants began Naive questions from the same starting map position and zoom level.

Participants underwent a training exercise prior to performing the Static Information Evaluation. The training required participants to answer questions similar to those used in the Static Information Evaluation using both Feature Sets and POIs at a very low information density (i.e., five items per region). Participants
were allowed to ask questions and receive assistance from evaluators during the training exercise. The training task occurred in the same map region as the Static Information Evaluation, but utilized different information located in different regions than those used in the Static Information Evaluation. The training exercise took approximately ten minutes to complete.

Participants were exposed to each of the different report types during the training evaluation. Participants were instructed that all of the report types seen in training were utilized during the evaluation, and that it may be beneficial to remember the icon that was associated with each report type. Leveraging iconography is an essential part of using POI-based approaches on a digital map. Therefore, some memorization is inherent to the usage of POIs in order to remember what icon type corresponds to a certain report type. The Static Information Evaluation viewed this memorization process as an inherent design flaw of POIs; therefore, when performing the evaluation using POIs, participants were forced to either remember the icon that was associated with each report type, or rediscover the association between icon and report type through interacting with the on-screen POIs. This approach may be seen as a limitation of the study, and can be easily overcome by displaying a picture of the desired icon alongside each question being asked. However, this experiment treated the need for memorization as something inherent to POI usage.

IV.4.2 Hypotheses

POIs represent information “at a glance” on a digital map. When the information density is low, POIs can usually easily represent all information without visual clutter or additional work (e.g., selecting items for more information, panning, zooming, etc.) on behalf of the participant. A low information density also ensures that the potential for information overload is minimized, since an overwhelming number of POIs are not displayed on the map. Since Feature Sets inherently require an additional interaction (i.e., tapping on the Feature Set) before information regarding specific reports can be seen, Feature Sets are at a disadvantage when compared to POIs in low information density situations. Therefore, it was hypothesized, $H_1$, that at the Low information density, POIs will result in faster task completion times than Feature Sets.

As information density increases, it is believed that the need to excessively manipulate the map to see individual POIs will become detrimental and result in increased task completion times. However, at all information densities, Feature Sets are interacted with in essentially the same way. Therefore, with Feature Sets, there is less need to adjust the map in order to see and interact with individual reports. It was hypothesized, $H_2$, that Feature Sets will result in faster task completion times than POIs at the Medium and High densities.

Increasing information density may also make questions more difficult to answer correctly. In the High density trials, information overload may lead to increased incorrect answers for POIs. Therefore, it was hypothesized, $H_3$, that Feature Sets will result in more correct questions answered than POIs at the High density.
Due to the nature of POIs to overlap, cause visual clutter, and obscure one another when placed close together, participants may perform additional map panning and zooming when completing trials using the POI visualization method. Therefore, it was hypothesized, $H_4$, that more pans and zooms will be performed and more time will be spent panning and zooming when using the POI visualization method.

POIs can also obscure underlying map geography. Feature Sets are semi-transparent, allowing the underlying geography to remain visible. Therefore, it was hypothesized, $H_5$, that search time will be lower when using Feature Sets at all information densities. It is expected, but not hypothesized, that search time for the POI visualization condition will increase with increasing information density, but will remain relatively constant at all information densities when using Feature Sets.

IV.4.3 Metrics

All the Static Information Evaluation metrics were obtained on a per-trial basis, where a single trial consisted of performing tasks using a single information density with a single visualization method. Objective metrics were obtained through aggregating the correct answers reported for each of the six questions and four location tasks. Pan and zoom counts and durations, measured in seconds, were logged by the interface. Subjective metrics were obtained via a Likert scale rating survey administered after each trial and a visualization method comparison survey administered upon the completion of the experiment.

IV.4.3.1 Objective Metrics

The objective metrics for the Static Information Evaluation include:

- Correct Answer Percentage. The percentage of correct answers for each question type. Since two questions of each type were asked per participant per trial, sixty total responses exist for each question type per trial.

- Correct Answer Duration. The time required to achieve a correct answer, measured in seconds. Reported per question.

- Find Duration. The time taken to find a particular location on the map, measured in seconds. Reported as the median duration of all find tasks performed for a particular trial.

- Map Interaction metrics. These metrics include pan counts, zoom counts, pan durations, and zoom durations. Durations are measured in seconds.
Determining how many reports of a specific type were in one location was...
Finding how many of a specific report occurred on the entire map was...
Determining the effects of reports on neighboring geography was...
Finding one specific report in a given location was...
Finding one specific report on the entire map was...
Overall, interacting with reports was...
Selecting reports using a single finger was...
Determining the meaning of a single report was...

Table IV.2: Codes used for the subjective metrics and their corresponding questions from the Condition Rating Survey.

The Correct Answer Percentage was used as a measure of effectiveness for both visualization methods. The purpose of the Correct Answer Duration was to determine, in the case of a correct answer, which visualization method resulted in a shorter average time to achieve the correct answer. Since the average duration for each question type may vary greatly (e.g., finding a single report of a certain type on a map may be performed significantly faster than counting every report type occurrence on the map), Correct Answer Duration results are reported per question.

Map interaction statistics are intended to determine the amount of manipulations of the map needed to perform tasks. A single zoom count or pan count is defined as the entire duration of the gesture. Pan duration and zoom duration is the time measured in seconds of an entire pan or zoom gesture. These four metrics compose the Map Interaction metrics. The Map Interaction metrics will be reported in two sets: those that occurred during Find Tasks and those that occurred during questions. Pan and zoom durations are calculated by summing the individual pan and zoom durations per participant. Summing pan and zoom durations results in one pan and zoom duration value per participant. Pan and zoom counts are treated similarly.

IV.4.3.2 Subjective Metrics

A Condition Rating Survey was administered upon the completion of each trial to subjectively rate the performance of both visualization techniques at each information density. The Condition Rating Survey was a Likert scale survey that utilized nine levels, with 1 being the lowest and 9 the highest. The Condition Rating Survey contained eight questions (see Table IV.2) and subjectively assessed participant preference for performing each of the tasks.

A Comparison Ranking Survey was administered upon the completion of the evaluation. The purpose of the survey was to subjectively rank Feature Sets and POIs across seven factors (see Table IV.3). Each question required the participant to specify which visualization condition was easier to use. The Comparison Ranking Survey provided three options for each question: Feature Sets, POIs, or Both were equally easy.
Table IV.3: Question codes and their corresponding questions as asked in the Comparison Ranking Survey.

<table>
<thead>
<tr>
<th>Question Code</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counting Reports</td>
<td>Counting occurrences of a specific report type was easier using...</td>
</tr>
<tr>
<td>Determining Report Effect</td>
<td>Determining report effect on neighboring geography was easier using...</td>
</tr>
<tr>
<td>Finding Reports</td>
<td>Finding specific reports was easier using...</td>
</tr>
<tr>
<td>Interacting Reports</td>
<td>Interacting with reports was easier using...</td>
</tr>
<tr>
<td>Overall Preference</td>
<td>Overall, I preferred to use...</td>
</tr>
<tr>
<td>Selecting Reports Finger</td>
<td>Selecting reports using a finger was easier using...</td>
</tr>
<tr>
<td>Understanding Reports</td>
<td>Understanding the meaning of a report was easier using...</td>
</tr>
</tbody>
</table>

Table IV.4: Descriptive statistics for the Correct Answer Percentage metric. The maximum number of correct answers for any single condition is 60.

<table>
<thead>
<tr>
<th></th>
<th>Low Exploration</th>
<th>Medium Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature Sets</td>
<td>Primed</td>
<td>Naive</td>
</tr>
<tr>
<td>POIs</td>
<td>90.00</td>
<td>96.67</td>
</tr>
<tr>
<td>POIs</td>
<td>76.67</td>
<td>81.67</td>
</tr>
</tbody>
</table>

IV.4.4 Results

Hypothesis testing for all metrics was conducted using non-parametric statistics. A Shapiro-Wilk test determined if a given metric’s results adhered to a normal distribution. In many cases, data deviated significantly from a normal distribution; therefore, the Wilcoxon signed-rank test was used. No multiple comparisons were performed on single data sets; therefore, no omnibus testing was used and there was no requirement to adjust for familywise error. Non-parametric descriptive statistics (e.g., medians, ranges, etc.) are reported in accordance with the statistical analysis performed.

IV.4.4.1 Objective Metrics

The descriptive statistics for the Correct Answer Percentage by visualization condition, question type, and information density are shown in Table IV.4. Feature Sets result in a higher Correct Answer Percentage for all question categories except the Exploration type at the Low information density. A two-tailed paired, Wilcoxon signed-rank test found significant difference for the Correct Answer Percentage metrics for the Primed tasks at the Low \((W(29) = 65, z = -1.77, p = 0.038)\) and High \((W(29) = 126, z = -2.23, p = 0.013)\) information densities, and for Naive tasks at the Low \((W(29) = 60, z = -2.16, p = 0.018)\) and High \((W(29) = 221, z = -4.12, p < 0.001)\) information densities. These results indicate that, in cases where the exact location of information is not needed, Feature Sets outperform POIs even when the information density is low.

Feature Sets were expected to outperform POIs at higher information densities and significantly higher results for Feature Sets for the Correct Answer Percentage metric are not surprising. As information density
increases, the inherent benefits of Feature Sets, in terms of resulting in tasks being performed correctly, become realized. However, no significance was found for any question type at the Medium information density. This outcome is surprising, since Feature Sets outperformed POIs for many of the tasks performed in both the Low and High densities. Despite the lack of significance, descriptive statistics do show higher Correct Answer Percentages for Feature Sets for all cases in the Medium information density.

![Descriptive statistics for Correct Answer Duration](image)

**Figure IV.6:** Descriptive statistics for the Correct Answer Duration metric for all participants. All durations are reported in seconds. Outliers are represented by an ×.

The descriptive statistics for the Correct Answer Duration metric are shown in Figure IV.6. Feature Sets result in lower Correct Answer Durations for questions that require counting (i.e., *Naive How Many* and *Primed How Many*) at all information densities. A paired, two-tailed Wilcoxon signed-rank test showed that the differences between the Correct Answer Duration for Feature Sets and POIs was significant for the *Primed How Many* question at the Low density only ($W(29) = 124.5, z = -1.72, p < 0.05$), and no significant difference was found for the *Naive How Many* question at any density. Therefore, it is not conclusively proven that Feature Sets possess lower task durations than POIs at higher densities. However, the descriptive statistics do indicate a widening performance gap between Feature Sets and POIs for counting questions as information density increases.
Figure IV.6 indicates that for existence questions (i.e., Primed Exist and Naive Exist), POIs outperform Feature Sets at the Low and Medium densities, with Feature Sets performing as well as or better than POIs at the High density. A paired, two-tailed Wilcoxon signed-rank test showed that the difference between Feature Sets and POIs for the Correct Answer Duration metric is significant for the Primed Exist question at the Low ($W(29) = 704.5, z = -4.12, p < 0.01$) and Medium ($W(29) = 659, z = -2.94, p < 0.01$) densities; and for the Naive Exist question at the Low density ($W(29) = 804.5, z = -5.59, p < 0.01$). These results indicate that, in terms of Correct Answer Duration, POIs are better at supporting “at a glance” behavior than Feature Sets. However, as information density increases, this advantage has less impact on task duration, with Feature Sets showing signs of outperforming POIs at the High information density.

The Correct Answer Durations were similar for Feature Sets and POIs at the Medium and High densities for the Exploration Affected question, and POIs possessed a lower Correct Answer Duration at the Low density. A paired, two-tailed Wilcoxon signed-rank test showed that the differences between the Correct Answer Duration for Feature Sets and POIs was significant for the Exploration Affected question at the Low density ($W(29) = 124.5, z = -1.72, p < 0.05$). Participants reported difficulty determining if areas on the map were affected by information items when using Feature Sets to answer Exploration Affected questions. This difficulty may be due to Feature Sets not displaying the exact location of reports on the map, and can be easily remedied by providing the exact location of an item on the map when its detail information is displayed. Despite the difficulty; however, Feature Sets possessed Correct Answer Durations that were as good as or better than POIs for the Exploration Affected question at the Medium and High density; further proof of a widening performance gap between Feature Sets and POIs as information density increases.

Feature Sets performed better than POIs at the Medium information density for the Exploration Action question. A paired, two-tailed Wilcoxon signed-rank test showed that the differences between Correct Answer Duration was significant at the Medium ($W(29) = 33, z = -6.14, p < 0.001$) and High ($W(29) = 562.5, z = -3.33, p < 0.001$) information densities. The Exploration Action results do not demonstrate the pattern of Feature Sets outperforming POIs as information density increases. This inconsistency may be due to the lack of knowledge of items’ exact locations. The relatively high duration for POIs during the Exploration Action Medium information density trial are also puzzling; and may indicate that the Exploration Action task in the Medium density was much more difficult when using POIs than intended by experimenters.

The descriptive statistics for the Find Duration metric are shown in Table IV.5, and show that at all densities, Feature Sets resulted in a lower and consistent Find Duration. A two-tailed, paired Wilcoxon signed-rank test showed a significant difference between Feature Sets and POIs for the Find Duration metric at the Low ($W(29) = 212.5, z = -3.13, p < 0.001$), Medium ($W(29) = 147.5, z = -4.33, p < 0.001$), and High ($W(29) = 141, z = -4.44, p < 0.01$) densities, as well as the Total for both visualization conditions.
### Table IV.5: Descriptive statistics for the Find Duration metric. All durations are reported in seconds.

<table>
<thead>
<tr>
<th>Density</th>
<th>Condition</th>
<th>median</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>MapFeatures</td>
<td>5</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>POIs</td>
<td>7</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Medium</td>
<td>MapFeatures</td>
<td>5</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>POIs</td>
<td>7</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>High</td>
<td>MapFeatures</td>
<td>5</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>POIs</td>
<td>8</td>
<td>4</td>
<td>62</td>
</tr>
<tr>
<td>Total</td>
<td>MapFeatures</td>
<td>5</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>POIs</td>
<td>7</td>
<td>2</td>
<td>62</td>
</tr>
</tbody>
</table>

(W(29) = 210, z = -3.45, p < 0.001). This result indicates that, at all densities, finding locations on the map occurred more quickly when using Feature Sets.

The Find Duration metric was also calculated by presentation order to determine if presentation order had any affect on a participant’s ability to find locations on the map. A significant difference for Find Duration on presentation order indicates a potential confound on the previous finding that Feature Sets result in significantly lower Find Duration. However, a paired, two-tailed Wilcoxon test revealed no significant difference on Find Duration when compared by presentation order at each information density. Therefore, the significant difference in Find Duration can be attributed solely to the visualization method.

The descriptive statistics for the Map Interaction metrics for Find Tasks are shown in Figure IV.7, there were no zooms reported for Feature Sets at the Medium information density. The application automatically adjusted the map to center locations pertinent to the questions being asked. Naive question types displayed the entire map; therefore, zooming was typically unnecessary for completing tasks when using Feature Sets.

At every information density there were fewer pan counts and zoom counts reported for Feature Sets. The median Pan and Zoom Durations were also lower for Feature Sets at all information densities. A two-tailed paired Wilcoxon found significant differences between Feature Sets and POIs for Zoom Count, Pan Count, Zoom Duration, and Pan Duration at all densities where data was available to perform a comparison (see Table IV.6). This result indicates that for Find Tasks, at all densities, Feature Sets require fewer Map...
Figure IV.7: Descriptive statistics for the Map Interaction metrics for Find Tasks shown by information density. A single count corresponds to a single interaction; durations are measured in seconds.

Interactions. Such an outcome is attributed to the design of Feature Sets, which allowed participants to “see underneath” the Feature Set and easily interpret map geography.

Descriptive statistics for the Map Interaction Pan Duration and Zoom Duration metrics are shown by question type in Figure IV.8. Feature Sets, in many cases, resulted in no zooms being performed by participants. For example, no participants performed any zooming for the Primed question type when using Feature Sets. The same is true for Zoom Duration when performing Exploration type questions. However, in cases where multiple participants zoomed when using Feature Sets (e.g., the Naive question type), Zoom Duration medians were lower for Feature Sets. A two-tailed Wilcoxon signed-rank test comparing the Zoom Duration differences between Feature Sets and POIs determined significant differences for each question type at every information density (see Table IV.7). For cases where no interactions were performed using Feature Sets, the
Figure IV.8: Descriptive statistics for the Map Interaction Pan Duration and Zoom Duration metrics for each of the three question types.

POI results were compared to a median of zero.

The Pan Duration results shown in Figure IV.8 indicate that for all question types and at every information density, Feature Sets result in lower median Pan Durations. A two-tailed Wilcoxon signed-rank test comparing the Pan Duration differences between Feature Sets and POIs determined significant differences for each question type at every information density (see Table IV.7). The Pan and Zoom Duration results indicate that at all information densities and for all question types, Feature Sets result in lower interaction times. This result is due to the design of Feature Sets, which mitigates the need to frequently adjust the map in order to search for information.

Results for Pan and Zoom Counts (see Figure IV.9) are similar to those seen for Pan and Zoom Durations (see Figure IV.8). Feature Sets result in lower medium Pan and Zoom Counts for every case of question type and information density. The Zoom Count results for Feature Sets also indicate that, in many cases, participants did not perform any zooms. The POI Zoom Count data were compared against a median of zero for comparison testing purposes. A paired, two-tailed Wilcoxon signed-rank test showed that, for both Pan Count and Zoom Count at every information density, Feature Sets possessed significantly lower counts and
durations (see Table IV.7).

The Pan Duration, Zoom Duration, Pan Count, and Zoom Count findings show that for all question types and for all information densities, participants spent less time manipulating the map when using Feature Sets. This result supports the finding that Feature Sets require less map manipulation in order to access desired information. When taken together, the Map Interaction metrics provide strong evidence that fewer map interactions are necessary to locate required information on the map when using Feature Sets.

### IV.4.4.2 Subjective Metrics

The descriptive statistics for the Condition Rating survey are shown in Figure IV.10 (see Table IV.2 for question code definitions). Rating levels for the Condition Rating Survey ranged from 1 to 9 with higher ratings being better. Feature Sets rank higher than or equivalent to POIs for all categories, excluding the Effect Reports question in the Low information density and the Find One Report Map question in the Low information density. The Effect Reports question specifically tasks participants with determining whether or not a report at one location on the map will have an effect on another location on the map. Participants
Table IV.7: Paired, two-tailed Wilcoxon signed-rank test results comparing the Map Interaction metrics of Feature Sets and POIs for questions ($d f = 29$). A significant difference exists between Feature Sets and POIs for every metric at every information density.
Figure IV.10: Descriptive statistics for the Condition Rating survey shown by information density. Rating levels ranged from 1 to 9 with higher ratings being better.
commented that when using Feature Sets, the exact locations of reports was unknown, leading to confusion when answering the **Effect Reports** question. Such comments are reflected in the subjective Condition Rating Survey results for the **Effect Reports** question. POIs higher ranking for the **Find One Report Map** question is expected, since at the low density it is very easy to find single reports at a glance on the map using POIs.

A two-tailed paired Wilcoxon signed-rank test was performed for each question in the Condition Rating survey at each information density. A significant difference was determined between Feature Sets and POIs for the **Count Report Location** question at the Low ($W(29) = 590, z = -1.833, p = 0.034$), Medium ($W(29) = 616.5, z = -2.26, p = 0.012$), and High ($W(29) = 639.5, z = -2.64, p < 0.005$) densities. This result indicates that Feature Sets are subjectively preferred at all densities for counting reports at one particular location on the map. The difference between ratings for the **Count Report Map** category was significant in the Medium ($W(29) = 701.5, z = -3.72, p < 0.001$) and High ($W(29) = 629.5, z = -2.54, p < 0.010$) densities. This outcome is surprising, as POIs were expected to rate higher at lower information densities, since relatively little visual clutter was present at the Low information density.

No significant differences were determined for the **Find One Report Location** and **Find One Report Map** questions. Feature Sets rated higher or equal to POIs except for the Low density condition for the **Find One Report Map** question. Once again, this is a surprising outcome as POIs were expected to rate higher, since these questions promoted “at a glance” search behavior. POIs are more suited to “at a glance” search behavior, since the type and location of an information item can be known by directly observing at the item. These results indicate that Feature Sets may not be less preferred than POIs, despite not promoting “at a glance” search behavior.

Participants rated POIs and Feature Sets similarly for the **One Report Meaning** and **Effect Reports** questions. Feature Sets are ranked equal to or higher than POIs for the **One Report Meaning** question, and a two-tailed paired Wilcoxon determined the difference between the medians to be significant at the Medium ($W(29) = 617, z = -2.33, p < 0.010$) and High ($W(29) = 639.5, z = -1.74, p = 0.042$) densities. This result indicates that, as information density increases, participants prefer Feature Sets for determining the meaning of single reports, perhaps because these reports are easier to find and interact with when using Feature Sets. POIs rated higher than Feature sets in the Low density for the **Effect Reports** question, and a significant difference was determined between Feature Sets and POIs in the Low density ($W(29) = 296, z = -2.07, p = 0.019$). This question required exact knowledge of an information item’s location, which Feature Sets did not display; therefore, this outcome is not surprising.

Participants rated Feature Sets equal to or higher than POIs at every density for the **Interacting Reports** and **Selecting Reports** questions. A paired, two-tailed Wilcoxon determined significant differences between the medians of POIs and Feature Sets for the **Interacting Reports** question at the Medium density only ($W(29) =$
<table>
<thead>
<tr>
<th>Question Code</th>
<th>Feature Sets</th>
<th>POIs</th>
<th>Equally Easy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counting Reports</td>
<td>21</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Determining Report Effect</td>
<td>3</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Finding Reports</td>
<td>12</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Interacting Reports</td>
<td>22</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Overall Preference</td>
<td>23</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Selecting Reports Finger</td>
<td>17</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Understanding Reports</td>
<td>18</td>
<td>3</td>
<td>9</td>
</tr>
</tbody>
</table>

Table IV.8: Descriptive statistics for the Condition Ranking survey. Statistics represent counts for each question that a particular option was chosen.

$611, z = -2.16, p = 0.015)$. This outcome is unexpected, but may be attributed to the number of interactions required at the High information density. Both Feature Set and POI conditions required a large number of interactions to find information at the High density. The relatively large number of interactions may have frustrated participants and resulted in the somewhat low, a value of 6, identical median ratings. Significant differences were found at the Medium ($W(29) = 586.5, z = -1.82, p = 0.036$) and High ($W(29) = 609.5, z = -2.18, p = 0.015$) densities for the Selecting Reports question, indicating that Feature Sets become more preferred for selecting items as information density increases; a predicted outcome.

The descriptive statistics for the Comparison Ranking survey are shown in Table IV.8 (see Table IV.3 for a full description of the questions asked). The descriptive statistics show that in all cases except the Determining Report Effect and Finding Reports questions, Feature Sets was chosen more times as the preferred method. A test of equal proportions determined a significant difference for the Determining Report Effect question (POIs: CI(0.5166, 0.7892), $p < 0.050$), indicating that participants preferred POIs to Feature Sets when determining the effect of reports on nearby portions of the map. This result reinforces the finding determined when analyzing responses for the Effect Reports question of the Condition Rating Survey.

A test of equal proportions found significant differences for the Counting Reports (Feature Sets: CI(0.5506, 0.8163), $p < 0.050$), Interacting Reports (Feature Sets: CI(0.5854, 0.8427), $p < 0.050$), and Overall Preference (Feature Sets: CI(0.6210, 0.8682), $p < 0.050$) questions. These results indicate that Feature Sets are subjectively preferred over POIs for counting tasks, interacting with reports on the map, and that Feature Sets are preferred overall to POIs.

**IV.4.5 Discussion**

Hypothesis $H_1$ states that POIs will result in faster task completion times than Feature Sets at the Low information density. The findings for the Correct Answer metric do not support or refute this hypothesis. POIs possessed significantly lower Correct Answer Durations for the Primed Exist and Naive Exist questions, an
expected outcome, since these questions are designed to promote “at-a-glance” analysis of the map. However, in the case of counting tasks at the Low information density, Feature Sets outperformed POIs, and the difference in Correct Answer Durations was significant for the Primed How Many question type. POIs did possess lower Correct Answer Durations for the Exploration Action and Exploration Affected questions. Therefore, at the Low information density, POIs are faster to use than Feature Sets for the “at-a-glance” tasks; however, for tasks that require a more thorough analysis of the map, such as counting reports, Feature Sets outperform POIs even at the Low information density.

$H_2$ states that as information density increases, Feature Sets will result in faster task completion times than POIs at the Medium and High densities. The findings indicate that, in the Medium information density, POIs possess lower Correct Answer Durations than Feature Sets for the Primed Exist and Naive Exist questions. The Primed Exist question and Naive Exist questions at the High density show that the difference in Correct Answer Duration between the two visualization conditions narrows to two seconds. Feature Sets result in lower Correct Answer Durations in all other cases at the High density. When taken together, the Correct Answer Durations at the Medium and High information densities indicate a trend in Feature Sets either possessing lower Correct Answer Durations or at least approaching the Correct Answer Durations reported by POIs. Therefore, as information density increases, Feature Sets may begin to perform faster than POIs for all question types tested. Thus, while $H_2$ was not fully supported, the results indicate that if information density continues to increase, Feature Sets will eventually overtake and outperform POIs.

$H_3$ states that Feature Sets will result in more correct answers than POIs at the High information density. Feature Sets were determined to result in a higher Correct Answer Percentage for all question types, except the Exploration question type at the Low density. A significant difference was determined at the High information density for the Primed and Naive question types; and Feature Sets possessed a higher Correct Answer Percentage at the High information density. These results indicate that $H_3$ is proven. More interesting is that Feature Sets resulted in higher Correct Answer Percentages than POIs in many cases at the Low and Medium information densities. These results indicate that, in many cases, Feature Sets result in as many or more correct answers than POIs regardless of information density.

Hypothesis $H_4$ states that more pans, zooms and more time spent panning and zooming will occur when using POIs. This hypothesis is supported by the findings from the Map Interaction metrics. Feature Sets resulted in significantly less time spent panning and zooming the map in all cases except the Exploration question type. Participants also performed significantly fewer pans and zooms in many cases when using Feature Sets. The discrepancy with the Exploration question type is more than likely due to the absence of the exact location of reports being shown on the map when using Feature Sets. Future improvements to Feature Sets will work to rectify this issue.
$H_5$ states that search time will be lower when using Feature Sets at all information densities. Find Duration results indicate that, at all densities, Feature Sets resulted in significantly lower Find Durations, supporting $H_5$. The reduced Find Durations were also shown to be independent of presentation order; therefore, this finding cannot be attributed to participant familiarity with the map. Find Durations were also constant for Feature Sets regardless of the information density. The lower Find Durations for Feature Sets is more than likely attributed to removing the need for participants to “look behind” reports being displayed on the map. Therefore, less interaction with the map is needed to find locations on the map, resulting in lower overall Find Durations and Map Interactions for Feature Sets.

Subjective results indicated that in Feature Sets were ranked equivalently or better than POIs in many cases. Participants reported a preference in the Low density for POIs when answering questions that required finding a single report on the entire map and questions that determined finding the exact locations of reports. The subjective results show a pattern of Feature Sets being more highly ranked than POIs as information density increases. The objective results echo this sentiment, with a widening performance gap exhibited between Feature Sets and POIs as information density increased. Participants also indicated preference for Feature Sets when performing counting tasks, interacting with individual reports, and overall when compared to POIs.

The results indicate that Feature Sets, in many cases, meet the design goals. The design of Feature Sets renders the visualization technique more useful for obtaining information from multiple information items, such as when counting the occurrence of specific information items on the map. Objective and subjective results showed that, for these counting-type tasks, Feature Sets outperformed POIs and were preferred by participants. Results also showed that Feature Sets were not completely outperformed by POIs for questions that leveraged “at a glance” behavior, such as determining the location of a single item on the map when many of those items are present. When Feature Sets are outperformed by POIs for these “at a glance” question types, it is at lower information densities. Subjective and objective results show, in many cases, that as information density increases Feature Sets outperform POIs for nearly all questions. The exception is questions that require exact knowledge of an item’s location, which can be easily supported in Feature Sets by adding the item’s location to its detail information (e.g., by placing a marker on the map showing exact location within a Feature Set for a particular item when that item is selected by the user).

The Static Information Evaluation validated Feature Sets as an interaction and data visualization technique for presenting data on digital maps. Feature Sets were shown to outperform POIs in many cases and, in cases where POIs performed better, the performance was not significantly better, except when the participant required exact knowledge of an item’s location. Once Feature Sets are improved to show the exact location of information, it is believed that Feature Sets will be a worthwhile visualization method regardless
Figure IV.11: The distribution of information items using each visualization condition. Figure IV.11a shows the test region for the Dynamic Information Evaluation encompassed by a black dashed line.

of information density.

The results indicate the importance of supporting the *geospatial* information context. Feature Sets allowed for geospatial groupings of information, which reduced visual clutter and provided an overview level of information, features that were absent from the POI visualization method. The Static Information Evaluation demonstrates that by leveraging the *geospatial* information context to provide overview information, user performance can be improved when using digital maps.

**IV.5 The Dynamic Information Evaluation**

**IV.5.1 Experimental Design**

A user evaluation was designed to determine the benefits and shortcomings of Feature Sets as compared to POIs for presenting dynamic information on a digital map. The Dynamic Information Evaluation was always performed immediately after the Static Information Evaluation, and participants were given the option of taking a ten minute break between evaluations, if necessary. The evaluation was presented to participants in the form of a wayfinding task that required participants to determine a path between two points presented on the map. The Fisk University area of Nashville, TN was used, with information confined to a rectangular area formed by Jefferson Street, Dr D.B. Todd Jr. Blvd., Charlotte Ave., and Interstate 65 (see Figure IV.11a). This area was chosen because it contained a variety of streets to facilitate the wayfinding tasks.

The independent variable tested was the visualization condition, POIs or Feature Sets. The visualization condition presentation order was randomized for each participant. Both conditions visualized the same distribution of information items. Information was centered around five locations, with 20 information items clustered around each point (see Figure IV.11). A single cluster was represented by a single Feature Set in
the Feature Sets condition, and as a closely packed group of 20 POIs for the POI condition. The type of the information items was altered between visualization conditions to mitigate learning effects.

Each condition required the participant to perform five wayfinding tasks. A wayfinding task displayed two markers on the map, labeled A and B, respectively (see Figure IV.12). The participants were tasked with drawing the shortest route between markers A and B. The shortest route always required participants to draw through one of the five clusters of items on the map. Before drawing through a cluster of items; however, participants were required to determine if the cluster of items was “unsafe”. A cluster was determined to be unsafe if it contained any item that contained the word “unsafe” in the item’s description. When using Feature Sets, the “unsafe” designation was visible in the expanded Feature Sets’ view (see Figure IV.13a). When using POIs, the “unsafe” designation was visible after clicking on a POI to display its detail information (see Figure IV.13b). The participant was instructed not to draw a path through a cluster, if it contained an unsafe item, even if the resulting path was the shortest path from marker A to marker B.

Path drawing was facilitated using a single finger. A button labeled “Guide” was located at the top of the interface (see Figure IV.1), and users selected this button to activate the path drawing functionality. Users were unable to pan or zoom the map while path drawing was active. Once activated, the entire path was drawn using a single stroke. Upon releasing the stroke, the path drawing functionality was automatically disabled, such that participants were able to pan and zoom the map. Once a path was drawn a green marker, the movement indicator, appeared on screen and transversed the path from marker A to marker B (see Figure IV.12). Participants were able to tap on the movement indicator to pause and resume its movement. The movement indicator’s color changed from green to orange when paused.

Participants were able to pause the movement indicator and draw a new path, if desired. The movement indicator moved from marker A to marker B at a fixed time interval; therefore, regardless of the length of
the drawn path, the movement indicator transversed the path in the same amount of time. This movement behavior was intentional, as it ensured that participants had the same amount of time per wayfinding task to adjust a drawn path, if necessary.

Participants were required to redraw a path in some cases, as an “unsafe” item would be placed along the drawn path, rendering the path “unsafe”. Unsafe items were added after a path was drawn to provide dynamic information to the task. Participants were required to redraw paths to avoid unsafe items, which ensured that participants must take action and leverage new information in order to successfully complete tasks.

All drawn paths automatically snapped to the nearest road or street, to assist the participant in path drawing. Assistive drawing methods were developed, such that the participant did not have to focus on perfectly specifying drawn paths (i.e., ensure that drawn paths perfectly followed streets). An example of a participant's drawn input and the generated path is shown in Figure IV.14.

A task was considered complete when the movement indicator finished moving from marker A to marker B. Once movement was completed, participants were able to select a Next button to proceed to the next task. A Previous button also allowed participants to repeat previously completed tasks; however, no participant utilized this functionality. Upon clicking the Next button, the A and B markers for the next task were displayed, and the map view adjusted to place these markers within the view, such that participants did not have to search for the next path to draw.

Four task types were utilized for each visualization condition. The first, *Appear Group Unsafe*, caused an unsafe item to appear in a cluster of information items after the participant had drawn a path through the items. This task required the participant to pause the movement indicator, search the cluster of items for the
Figure IV.14: A participant’s drawn path (red) and the adjusted path (blue) used for transversal by the movement indicator.

newly added item, determine whether or not the added item was unsafe, and then draw a new path that avoided the cluster of items. Both visualization conditions supported this task differently. The Feature Sets condition incremented the notification indicator of the Feature Set representing the cluster. The POI visualization condition added a new POI to the cluster to represent the newly added information. The new item appeared three seconds after the path was drawn for both visualization conditions, ensuring that participants had the same amount of time to react to newly added information regardless of the visualization. The *Appear Group Unsafe* task was correctly performed if the participant determined the added item was unsafe and drew a new path to avoid the item.

The second task type was the *Appear Solo Unsafe* task. This task added a new information item along a drawn path, but not within a cluster of information items. The intent was to add information to the map without the influence of visual clutter. Both visualization conditions support this task differently. The Feature Sets condition creates an entirely new Feature Set to encompass the single information item that is added to the map. The POI condition simply adds a new item to the map. The new item appeared three seconds after the path was drawn for both visualization conditions, ensuring that participants had the same amount of time to react to newly added information regardless of the visualization. The *Appear Solo Unsafe* task was correctly performed if the participant determined the added item was unsafe and drew a new path to avoid the item.

The third task type is the *No Appear Group Unsafe* task. This task places an unsafe item within a cluster of information items before the participant draws a path. A participant must search through the cluster of information to find any unsafe items and, upon finding an unsafe item, the participant must draw a path that avoids the cluster of items. This task requires an exhaustive search of the information items within a clus-
Table IV.9: Order of the presented tasks for the Feature Sets and POI conditions in the Dynamic Information Evaluation.

<table>
<thead>
<tr>
<th>Task</th>
<th>Feature Sets</th>
<th>POIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distractor</td>
<td>No Appear Group Unsafe</td>
</tr>
<tr>
<td>2</td>
<td>No Appear Group Unsafe</td>
<td>Distractor</td>
</tr>
<tr>
<td>3</td>
<td>Appear Group Unsafe</td>
<td>Appear Group Unsafe</td>
</tr>
<tr>
<td>4</td>
<td>Distractor</td>
<td>Appear Solo Unsafe</td>
</tr>
<tr>
<td>5</td>
<td>Appear Solo Unsafe</td>
<td>Distractor</td>
</tr>
</tbody>
</table>

Therefore, the intent was to determine which visualization condition more easily facilitated exhaustive search. Note that the exhaustive search required for the Dynamic Information Evaluation is different than that required in the Static Information Evaluation. Participants were required to interact (i.e., tap on each POI to see its details view and page through all the items in a Feature Set’s expanded view) with each item in the Dynamic Information Evaluation to determine if an unsafe item existed.

The fourth task was a distractor task, and did not add any new information to the map. The intent of this task was to signal to participants that, upon drawing a path, a change in the map was not to be expected. Two instances of the distractor task were used in each condition. Performance on the distractor task is not reported. Non-distractor tasks were presented in the same order for both visualization conditions, but the distractor task was introduced at different times in each visualization condition to mitigate learning effects. Tasks of the same type were designed to be identical in duration between the two visualization conditions. For example, the Appear Solo Unsafe task requires the same amount of time to complete, excluding the time necessary to inspect the newly added item. The ordering of each task type is reported per visualization condition in Table IV.9.

Participants underwent a ten minute training exercise prior to performing the Dynamic Information Evaluation. The training required participants to perform each of the four task types once using both Feature Sets and POIs. Participants were allowed to ask questions and receive assistance from evaluators during the training exercise. The training task occurred in the same map region as the Dynamic Information Evaluation, but utilized different information and routes than those used in the Dynamic Information Evaluation.

IV.5.2 Hypothesis

Feature Sets’ notification indicators provide instant notification concerning when new information has been added to a Feature Set. Therefore, participants may be able to more quickly identify the presence of new information when using Feature Sets, as opposed to POIs. It was hypothesized, $H_1$, that Feature Sets will result in lower times needed to determine that new information has been added to the map.
When new information is added to a Feature Set, the temporal context is leveraged by adding the new item to the top of a Feature Set’s item list in the Feature Set’s expanded view. POIs do not leverage the temporal context as new POIs are simply added to the map, regardless of the level of POIs present in the area. This process may result in new information that is extremely difficult for participants to find. Therefore, it is hypothesis $H_2$ that Feature Sets will result in more occurrences of new information being found by participants when that information is added to the map.

Feature Sets make new information more salient than POIs. As a result, participants may need to perform fewer interactions with the map in order to find new information when using Feature Sets. Therefore, it is hypothesis $H_3$ that Feature Sets will result in fewer map interactions (i.e., pans and zooms), and that users will spend less time performing map interactions when using Feature Sets.

It is anticipated that Feature Sets will be subjectively preferred by users for the discovery of and interaction with new information on the map. Since Feature Sets have been designed to saliently notify the user of new information, it is expected that users will prefer Feature Sets to using POIs. Therefore, it is hypothesis $H_4$ that Feature Sets will be subjectively preferred for both interacting with and discovering new information on the digital map.

**IV.5.3 Metrics**

All metrics were obtained on a per-condition basis, where a single condition consisted of performing tasks using a single visualization method. Objective metrics were obtained through aggregating the successful performance for each of the three task types, the distractor task was excluded. The time taken to perform each task, both correctly and incorrectly, is also reported as measured in seconds. Pan and zoom counts and durations, measured in seconds, were logged by the interface. Subjective metrics were obtained via a Likert scale survey administered after each visualization condition and a comparison survey administered at the end of the Dynamic Information Evaluation.

**IV.5.3.1 Objective Metrics**

The ratio of tasks performed correctly to the number of tasks performed, the Correct Task Percentage is an objective metric. Thirty total tasks of each type were performed per condition, since each participant performed each task one time per visualization condition.

The amount of time required to perform a task correctly, the Correct Task Duration, was measured in seconds. The purpose of the Correct Task Duration is to determine, in the case of a task being performed correctly, the visualization method that results in the shorter average time. Correct Task Duration is reported per task type.
Pan counts, zoom counts, pan durations, and zoom durations were logged. A single zoom count and pan count is defined as the entire duration of the gesture, from its start to its finish. Pan duration and zoom duration is the time measured in seconds of an entire pan or zoom gesture. These four metrics compose the Map Interaction metrics. Pan and zoom durations are calculated by summing the individual pan and zoom durations per participant. Summing pan and zoom durations results in one pan and zoom duration value per participant. Pan and zoom counts are treated similarly.

### IV.5.3.2 Subjective Metrics

A Condition Rating Survey was administered upon the completion of each condition to subjectively rate the performance of both visualization techniques. The Condition Rating Survey was a Likert scale survey where a rating of 1 was the lowest and 9 the highest. The Condition Rating Survey contained five questions and subjectively assessed participant preference for each of the questions listed in Table IV.10.

A Comparison Ranking Survey was administered upon the completion of all conditions. Whose purpose was to subjectively rank Feature Sets and POIs for each of the questions in Table IV.11. Each question required the participant to specify which visualization condition was easier to use. The Comparison Ranking Survey provided three options for each question: Feature Sets, POIs, or “Both were equally easy”.

### IV.5.4 Results

All hypothesis testing was conducted using non-parametric tests for each of the metrics reported. A Shapiro-Wilk test determined that the data deviated significantly from a normal distribution, in many cases; therefore,
the Wilcoxon signed-rank test was utilized for comparison tests. No multiple-comparison tests were performed on single data sets; therefore, no omnibus testing was used and there was no requirement to adjust for familywise error. Non-parametric descriptive statistics (e.g., medians, ranges, etc.) are also reported in accordance with the statistical analysis performed.

### IV.5.4.1 Objective Metrics

The descriptive statistics for the Correct Task Percentage metric are shown in Table IV.12. The descriptive statistics show that, for all task types, Feature Sets result in more tasks performed correctly than when using POIs. A two-tailed, paired Wilcoxon signed-rank test found a significant difference in Correct Answer Percentage for the *Appear Group Unsafe* task type ($W(29) = 231, z = -4.76, p < 0.0001$), indicating that Feature Sets result in more tasks being performed correctly when task completion is contingent upon recognizing the arrival of new information in visually cluttered areas of the map. This finding is supported by the similarity in Correct Task Percentage for the *Appear Solo Unsafe* task type. When information is added in areas that contain no previous information, the addition is salient, regardless of the visualization method; however, when the area is visually cluttered, Feature Sets provide a salient means of alerting the user to new information.

The descriptive statistics for the Correct Task Duration metric are shown in Table IV.13. The descriptive statistics show that, for all task types, Feature Sets result in lower durations required to complete tasks correctly. An unpaired Wilcoxon signed-rank test determined a significant difference in the Correct Task Duration metric for the *Appear Group Unsafe* ($W(45) = 389, z = -2.68, p < 0.005$), *Appear Solo Unsafe* ($W(45) = 117, z = -2.67, p < 0.005$), and *No Appear Group Unsafe* ($W(54) = 102.5, z = -4.811, p < 0.0001$) task types. These results indicate that, in all task types, Feature Sets result in significantly faster task performance than POIs. A significant difference for the *No Appear Group Unsafe* supports results from
Figure IV.15: Map Interaction descriptive statistics for the Dynamic Information Evaluation.

The Static Information Evaluation (see Section IV.4) that indicated Feature Sets resulted in faster task performance when searching static information for specific information items.

The Map Interaction statistics are summarized in Figure IV.15 and show that, for all question types, Feature Sets results in fewer Pan and Zoom Counts and lower Pan and Zoom Durations than POIs. A two-tailed, paired Wilcoxon signed-rank test determined that, for each metric and task type, excluding Zoom Duration for the Appear group Unsafe and Appear Solo Unsafe, the difference between Feature Sets and POIs is significant (see Table IV.14). The Zoom Duration result is likely due to participant behavior when searching for new information. Oftentimes, participants performed one or two zoom gestures to reach a specific zoom level that was comfortable for viewing individual information. Once the zoom level was determined, the participant did not alter it when searching through information. This behavior was particularly true for POIs. However, the results for the Zoom Count metric may indicate that participants performed more zoom gestures when using POIs to reach the preferred zoom level for viewing information. These results indicate that
participants required less interaction with the map to perform tasks using Feature Sets, demonstrating that Feature Sets are more efficient for interacting with information on the digital map, and reaffirming findings from the Static Information Evaluation (see Section IV.4).

### IV.5.4.2 Subjective Metrics

The descriptive statistics for the Condition Rating survey are shown in Table IV.16 (see Table IV.10 for a description of each question code). The descriptive statistics show that Feature Sets rate as good as or better than POIs for each question category. It is expected that the drawing-based categories (i.e., Creating Paths and Modifying Paths) will be rated similarly, since drawing was implemented identically for both conditions. Categories concerned with the presentation and interaction of information; however, clearly show a difference in favor of Feature Sets. A two-tailed, paired Wilcoxon signed-rank test determined a significant difference between Feature Sets and POIs for the Find New Info \( (W(29) = 777, z = -5.106, p < 0.001) \) and Interact New Info \( (W(29) = 734.5, z = -4.35, p < 0.001) \) categories, which indicates that participants preferred to use Feature Sets over POIs when finding and interacting with new information on the digital map. Despite a higher rating for Feature Sets in the Determine Path Correct category, this difference was not significant.

The comparable ratings for Feature Sets and POIs for the Determine Path Correct category is puzzling, since determining the correctness of a drawn path requires finding and interacting with new information; two aspects of the evaluation for which participants clearly preferred Feature Sets.

The descriptive statistics for the Comparison Questionnaire are shown in Table IV.15 (see Table IV.11 for a description of each question code). These results indicate preference for Feature Sets for the Determine Path Correct, Find New Info, Interact New Info, and Determine Path Needs Modification categories. A test of equal proportion was used to determine that significant differences for the Find New Info (Feature Sets: CI(0.6210,
Figure IV.16: Condition Rating Survey descriptive statistics for the Dynamic Information Evaluation.

<table>
<thead>
<tr>
<th>Map Features</th>
<th>POIs</th>
<th>Equally Easy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creating Paths</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Determine Path Correct</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Find New Info</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Interact New Info</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>Modifying Paths</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Determine Path Needs Modification</td>
<td>22</td>
<td>2</td>
</tr>
</tbody>
</table>

Table IV.15: Condition Rating Survey descriptive statistics for the Dynamic Information Evaluation.

$0.8682, p < 0.050$, $Interact New Info$ (Feature Sets: CI$(0.5506, 0.8163), p < 0.050$), and $Determine Path Needs Modification$ (Feature Sets: CI$(0.5854, 0.8427), p < 0.050$) categories. These results reinforce the findings of the Condition Rating Survey. Participants prefer Feature Sets for both discovering and interacting with new information on the digital map. A significant difference for the $Determine Path Needs Modification$ category also supports the claim that Feature Sets are preferred for discovering and interacting with new information. Once again, the lack of a significant difference for the $Determine Path Correct$ category is puzzling. Participants may have indicated their preference for determining the drawn path was correct in terms of direction and orientation (i.e., the path correctly moved from marker A to marker B), rather than the determining whether or not the path correctly avoided unsafe items.
IV.5.5 Discussion

The Dynamic Information Evaluation results support each of the stated hypotheses. The significantly higher values for the Task Correct Percentage and Correct Task Duration metrics show that Feature Sets result in more tasks performed correctly and in less time than when using POIs. Since performing tasks correctly required participants to find new information as it was added to the map, these results confirm $H_1$ and $H_2$. Feature Sets provide a more efficient and effective way of interacting with new information on a digital map than POI-based approaches.

The objective results for map interaction indicate that participants did not need to perform as many pans or zooms to find newly added information and confirm $H_3$. The design of Feature Sets lends itself to this result. Participants do not need to manipulate the map as frequently when using Feature Sets, since new information is more salient when using Feature Sets. Results for the Map Interaction metrics also confirm previous Static Information Evaluation findings that, in general, Feature Sets results in less overall necessary map interaction than POIs.

Responses on the Condition Rating survey and Comparison Questionnaire indicate that Feature Sets are subjectively preferred to POIs for finding and interacting with new information, and support hypothesis $H_4$. User preference for Feature Sets is likely due to the inherent design aspects (e.g., notification indicators and chronological ordering in a Feature Set’s expanded view) of Feature Sets that provide temporal context to information and provide users with salient information updates.

It is important to note that the Dynamic Information Evaluation was conducted using a relatively low information density, 20 information items per cluster, on the digital map. Compared to the Static Information Evaluation, this information density falls between the Low and Medium classifications. The Dynamic Information Evaluation demonstrated that, even at relatively low information densities, Feature Sets are still superior to POIs for discovering and interacting with new information. Therefore, it is expected that with greater information density, the benefits of Feature Sets versus POIs for new information discovery and interaction will become even more apparent.

The Dynamic Information Evaluation demonstrated Feature Sets’ superiority to POIs for the discovery of and interaction with dynamic information. The superiority of Feature Sets for presenting new information can be directly attributed to notification indicators and the chronological ordering of information in a Feature Sets’ expanded view. Notification indicators greatly increase the discoverability of new information, and objective findings show that this increase in discoverability results in improved performance. Chronological ordering of information within a Feature Sets’ expanded view ensures that participants will always know exactly where to look for new information; new information was always found in the same location, the top of the item
list. The design of the Feature Sets’ expanded view provides a strong argument for supporting the temporal information context when designing visualizations for digital map-based interfaces. Through providing a chronological ordering of information, and providing a salient means of discovering new information, Feature Sets leverage the temporal context to improve user performance.

IV.6 Conclusions

This chapter described two evaluations that demonstrate the superiority of Feature Sets over POIs, the currently accepted standard for displaying information on a digital map. The Static Information Evaluation compared Feature Sets to POIs for the display of and interaction with static information on a digital map at increasing information densities. The Dynamic Information Evaluation compared Feature Sets to POIs for the display of and interaction with dynamic information on the digital map by requiring participants to perform simulated wayfinding tasks. Both evaluations resulted in findings that are favorable for Feature Sets and indicate that Feature Sets outperform POIs for displaying information on a digital map in most cases.

The Static Information Evaluation validated Feature Sets as an interaction and data visualization technique for presenting static data on digital maps, and showed that, in many cases Feature Sets are actually superior to POIs for presenting static information. The results of the Static Information Evaluation show, overall, that Feature Sets are a better alternative to POIs at higher information densities, and Feature Sets are not a detriment to performance at lower information densities. The Static Information Evaluation leveraged the geospatial information context to improve user performance by providing sufficient and useful overview information. The Dynamic Information Evaluation demonstrated that Feature Sets outperform POIs for discovering and interacting with dynamic information on a digital map, and showed the importance of leveraging the temporal context for improving user performance. The performed evaluations have shown that, in many cases, for displaying and interacting with information on a digital map, Feature Sets are a more effective and preferred method than POIs.

The findings from both evaluations show that by designing visualization techniques that support the Information Sharing MSW design requirements, such techniques result in improved performance as compared to visualization techniques that do not. The outcomes of both evaluations not only support Feature Sets, but also quantitatively show the link between the Information Sharing MSW design requirement, the temporal and geospatial information contexts, and user performance. Feature Sets directly and effectively support information contexts and MSW design requirements, improving user performance within digital map-based applications. The link between MSW design requirements, information context, and user performance is important, and both evaluations serve as the first occurrence of MSW design requirements being objectively validated by a highly-controlled laboratory study, as opposed to field trails and observation.
CHAPTER V

Conclusions and Contributions

V.1 Conclusions

This report introduces and validates the initial design of Feature Sets. Feature Sets are geospatial containers that allow for non-type based groupings of information on a digital map. Feature Sets are designed to provide overview information, filtered information, and details on demand. Further extensions to Feature Sets will extend the functionality of the visualization technique, while still providing sufficient overview, filtered, and detail information. Feature Sets are also designed to support MSW design requirements. These requirements provide general guidelines that dictate the overall design of MSW systems, and Feature Sets are the first known attempt to apply these guidelines solely to a visualization technique. Feature Sets also support three types of information context to enhance and support the meaning of presented information. These contexts are: geospatial, the location of information on the map; temporal, time-based knowledge related to presented information; and semantic, knowledge concerning the relatedness between items (e.g., similarity, creator, etc.).

Two Evaluations were conducted to assess Feature Sets. The Static Information Evaluation compared Feature Sets to POIs for the presentation of static information at increasing levels of information density. Feature Sets were proven to perform as well as, or better than POIs for all cases except those that required exact location knowledge of an item on the map. Feature Sets can be easily extended to display the exact location of information items on the map as part of that item’s detail information. Subjective results from Static Information Evaluation also showed that Feature Sets are preferred overall versus POIs, and Feature Sets tended to be rated more highly as information density increased.

The Dynamic Information Evaluation compared Feature Sets to POIs for the presentation of dynamic information and required participants to perform wayfinding tasks. Objective results indicate that Feature Sets result in more tasks performed correctly with a lower needed duration than when using POIs. Subjective results indicate that Feature Sets are also subjectively preferred over POIs for the discovery of and interaction with new information on the digital map.

Research findings indicate that Feature Sets increase user performance and efficiency compared to POIs for tasks that leverage both static and dynamic information on a digital map. Feature Sets’ superior performance is attributed to several key factors. First, Feature Sets reduce visual clutter by leveraging geospatial context and providing overview, filtered, and detail knowledge based upon the needs of the user. This reduc-
tion in visual clutter directly attributes to the superior performance of Feature Sets compared to POIs at higher information densities. Second, Feature Sets provide notification information to the user as overview information. This notification information was shown to improve task performance and lower task completion times as compared to a POI-based approach, which did not use notification indicators to indicate new information on the map. Third, Feature Sets leveraged the *temporal* context by displaying new information at the top of the information item list in a Feature Set’s expanded view. This design decision ensured that new information was located at the same place each time (i.e., the top of the item list), such that users know directly where to find new information. The combination of notification indicators and chronological information ordering provided support for information discovery and interaction; reducing task completion times and improving task performance.

Feature Sets are a novel visualization technique for presenting data on digital maps. Research findings have determined that Feature Sets are superior to POIs, a standard digital map visualization method, for displaying information on a digital map. Results indicate that by supporting *geospatial* and *temporal* context within the data visualization, user performance is improved. Results indicate that supporting these contexts may be considered a guideline for the effective design of visualization techniques intended to be used with digital maps. Future work, which implements layers and tagging, will attempt to achieve the same result for the *semantic* context. Supporting the MSW Information Sharing design requirement was shown to improve performance as well. The results obtained from both evaluations are the first example of the link between user performance and MSW design guidelines demonstrated in a controlled laboratory evaluation.

V.2 Contributions
The primary contribution of this research is the introduction of a novel visualization technique that improves performance when interacting with data on mobile devices. Feature Sets provide an efficient and effective means of discovering, interacting with, and communicating information on digital maps. Feature Sets are also generalizable in their design, rendering them effective in any domain where data can be spatially organized. Additional contributions of this research are:

1. Feature Sets are the first known attempt to apply MSW design guidelines solely to a visualization technique and produce favorable results. Feature Sets have been shown to offer superior performance as compared to POIs and offer an attractive alternative to POIs when presenting data on a digital map, particularly at high information densities. Feature Sets also represent one of the first attempts to group information using non type-based groupings.

2. The importance of the *geospatial* and *temporal* context for displaying information on a digital map has
been shown. Results indicate that, for visualization techniques intended to be used with digital maps, supporting the geospatial and temporal context may be considered a relevant design guideline. The proposed research will show a similar outcome for the semantic information context.

3. The impact of utilizing notification to alert users to the presence of new information on a digital map has been shown. Results indicate that by providing this information in the form of a notification indicator, performance can be improved when compared to a visualization technique that does not possess a means of salient notification.

4. Design guidelines regarding Feature Sets and visualization methods for digital maps in general will be developed. Research findings have shown that by supporting information context and the MSW Information Sharing requirement through visualization user performance is improved. The proposed research will expand upon and reinforce these findings, resulting in design guidelines dictating the appropriate design and use of Feature Sets, and visualization methods for mobile devices in general.

5. Assistive drawing techniques will be developed for mobile touch-enabled devices. It is expected that these techniques will allow a user to specify correct input without the need for precise continuous selection.

Feature Sets and the proposed assistive drawing techniques are being developed primarily to support touch interaction on a mobile device. However, the Feature Sets design is easily generalizable to any domain that can represent data spatially. Abstraction will allow Feature Sets to represent information in a spatial hierarchy, providing value to domains that may require more complex information categorization. The developed assistive drawing techniques are expected to be applicable to other domains (e.g., image manipulation, gesture recognition, etc.) as well. Therefore, despite the firm grounding in MSW application that utilize digital maps, research findings may be applicable to a far wider application space.

Feature Sets are a transformative concept for visualizing information within a digital map on a mobile device. Results have shown that Feature Sets perform as well as or better than POIs, the currently accepted standard for visualizing data on digital maps, and Feature Sets do not suffer from the issues of visual clutter that can adversely effect POIs. The design of Feature Sets has also shown the importance of supporting information context within the visualization itself. This outcome may have a large impact on visualization design in general; rather than placing emphasis on the particular design of a visualization method, designers can focus on whether or not developed techniques provide for the appropriate context. Such an approach can help to ensure the effectiveness of a proposed visualization technique before the prototyping stage, decreasing the time spent pursuing ineffective designs.
BIBLIOGRAPHY


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