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PEER-REVIEWED ARTICLE

User-centered Design and Evaluation of a Geovisualization Application Leveraging Aggregated Quantified-Self Data

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Individual movement traces recorded by users of activity tracking applications such as Strava provide opportunities that extend beyond delivering personal value or insight to the individual who engages in these "quantified-self" (QS) activities. The large volumes of data generated by these individuals, when aggregated and anonymized, can be used by city planners, Departments of Transportation, advocacy groups, and researchers to help make cities safer and more efficient. This opportunity, however, is constrained by the technical skills and resources available to those tasked with assessing bicycling behavior in urban centers. This paper aims to address the question of how to design cartographic interfaces to serve as mediated platforms for making large amounts of individual bicycling data more accessible, usable, and actionable. Principles of cartographic representation, geovisual analytics techniques, and best practices in user interface/experience design are employed to arrive at an effective visualization tool for a broad urban planning audience. We use scenario-based design methods to encapsulate knowledge of map use practice gleaned from the development process, and conduct a post-implementation, two-part user study with seven domain experts to further assess the usability and utility of the interactive mapping tool.

KEYWORDS: cartographic design study; user-centered design; movement data; quantified-self (QS); urban planning

INTRODUCTION

Advancements in global navigation satellite and positioning systems, together with the subsequent increase in use of geo-enabled tracking devices, have resulted in unprecedented amounts of individual movement data (Swan 2012; Laube 2015). These data are increasingly being generated using personal devices, such as smartphones and other wearables (e.g., augmented eyewear, pedometers, smartwatches, textiles, wristbands, etc.). At the most ambitious end of the self-tracking spectrum is the Quantified Self (QS) community, which is composed of individuals who believe in "self-knowledge through numbers" and who use these devices to track biological, physical, behavioral, environmental, and/or other information about themselves (Swan 2013).

The movement data generated by quantified-selfers can offer more than just direct personal insight to the individual who engages in QS activities. The large volumes of data generated by these individuals, when aggregated and anonymized, can also be used to inform city safety (Zeile et al. 2015), preferential route choices (Baker et al. 2017), and air pollution exposure (Sun and Mobasheri 2017). Ubiquitous computing and Internet of Things (IoT) technologies create further potential for integrating individual movement data into smart city initiatives, such as traffic congestion monitoring (Zanella et al. 2014). This can result in a more humanized, bottom-up approach to city planning (Smyth et al. 2013). The opportunity, however, is constrained by the technical skills and resources available to those tasked with assessing bicyclist or pedestrian behavior in urban centers. This paper aims to address the question of *how to design interactive mapping tools that can help urban and transportation planners leverage personal fitness data to better inform infrastructure decisions that aid in the safe and efficient movement of bicyclists?*

More specifically, in this problem-driven research, we examine the design of a commercial interactive cartographic application intended to support urban and regional planning. The interactive mapping tools considered in this design study are focused on utilizing large volumes of individual movement data contributed voluntarily by users of an activity tracking application, Strava. *Metro* is a small division of Strava (the company, which shares a name with its application) that aggregates and anonymizes data on bicycling activities recorded on the platform, and licenses these data to a variety of organizations that are taking data-driven approaches to city planning. Based on a needs assessment and work domain analysis carried out by the first author while employed by Strava, the following insights emerged:

- There existed a disconnect between what Strava Metro assumed data users were capable of (in terms of big data management, analysis, and visualization), and the reality of their time, resources, and abilities.

- Data users faced significant challenges with data size/complexity, resulting in frustration, confusion, and limited ability to extract value from the data.

- Most data users aimed to accomplish some variant of the following tasks: quantify/qualify ridership; distinguish between commute and recreational bicycling corridors; and identify candidate areas for modifying or creating new bicycle facilities.

Thus, we set out to develop a partnership with data users to alleviate their frustration and help address their needs. More specifically, we initiated a multi-year, user-centered design study to develop a geovisualization tool to make Metro data more accessible to stakeholders in the city planning process. These stakeholders may possess limited, or even no experience with geographic information systems (GIS) or spatial analysis. However, the tool should also support more advanced analysts, and offer immediate insights into the fundamental tasks outlined above. A major contribution of our work is the methodological framework we present for evaluating the extent to which the proposed design solution addresses the needs outlined above.

In the following sections, we first ground our design framework in relevant literature on cartographic approaches to mapping movement, geovisual analytics techniques for interacting with complex representations of movement, and urban interfaces (or city dashboards). Next, we introduce *Metro DataView*, an interactive network flow map designed to make data on bicycle activity more accessible, usable, and useful to decision makers, stakeholders, and researchers in the urban planning domain. A simplified approach to visualizing individual movement traces is then considered, followed by a presentation of a three-stage user-centered design and evaluation model employed to both formatively and summatively assess the cartographic tools presented in this work. That model combines a hypothetical use case scenario and claims analysis with a post-implementation user study to (1) characterize the domain problem, (2) synthesize knowledge of map use practice gleaned from the development process, (3) assess the extent to which the geovisualization tools support insight discovery, and (4) evaluate interface usability and utility. The paper concludes with a discussion of tool adoption and impact, major contributions, design limitations, and opportunities for future research and development.

BACKGROUND

This section provides background on cartographic approaches relevant to mapping individual activity traces; highlights ongoing research in the geovisual analytics community focused on exploring and making sense of complex movement data with an emphasis on transportation applications; and concludes with an overview on urban interfaces and their relevance to the visual communication of movement for an urban planning audience.

CARTOGRAPHIC APPROACHES TO FLOW MAPPING

Individual movement data are commonly structured as series (or trajectories) of point records, each composed of a latitude/longitude coordinate pair and a timestamp. Mapping these points directly is the simplest approach to visualizing and attempting to make sense of data in this form (Andrienko et al. 2008). Mapped depictions of raw GPS point data, however, become less feasible if the number of trajectories is large, if they reveal personally identifiable information, or if the analytical goal is to detect group—rather than individual—movement behavior. One, if not all, of these conditions will likely be met when engaging with individual movement data. In these cases, data aggregation becomes a viable strategy for preserving individual privacy while also making analytical tasks computationally tractable and mapped results visually meaningful (Rinzivillo et al. 2008).

Approaches to representing the spatial flow of objects in aggregate form have existed since at least 1845 (Robinson 1967). Effective flow maps are difficult to create, and have traditionally been drawn carefully by hand. Tobler (1987) introduced the challenges of migration flow mapping by computer, and, despite decades of advancement in GIS technology, creating effective digital flow maps remains difficult today (Rae 2011; Zhu and Guo 2014; Zhou et al. 2019). Connecting straight lines between locations on a map is inadequate, because the map quickly becomes cluttered and illegible. More sophisticated approaches to creating flow maps involve algorithm-driven line bundling and aggregation (e.g., Phan et al. 2005; Buchin, Speckmann, and Verbeek 2011; Debiasi et al. 2014). Such approaches have the advantage of reducing visual clutter through the offsetting or merging of lines. However, they become increasingly ineffective as data size and dimensionality increase, as well as when locations for origins and destinations and the arbitrary lines between them disguise the underlying patterns of the spatial phenomenon under study (Guo 2009).

GEOVISUAL ANALYTICS APPROACHES TO MAKING SENSE OF FLOWS

Interactive geovisual analytics approaches allow us to move beyond messy cartographic representations of movement into an environment that lets users filter, analyze, and more effectively make sense of large, complex flow data. These approaches oftentimes leverage computational data summarization, pattern extraction techniques, and linked views (Andrienko et al. 2008). For example, Boyandin et al. (2011) proposed linking two separated origin and destination maps with a non-spatial temporal heatmap to represent change in movement flows over time more effectively. Other notable works include those of Wood, Dykes, and Slingsby (2010), and Wood, Slingsby, and Dykes (2011). These authors explored the benefits and shortcomings of representing flows with curved symbols in comparison to other, more novel, approaches such as gridded views and origin-destination (OD) maps (i.e., an origin-destination matrix overlaid on geography). With respect to computational pattern extraction, Guo (2009) introduced a methodological framework that combined hierarchical and multivariate clustering, together with interactive flow maps, and demonstrated the value of that framework in the context of migration mapping. This work was later extended to more effectively support multi-resolution flow clustering on large datasets (Zhu and Guo 2014), and to develop a multi-scale flow density estimation and selection methodology for visualizing patterns in complex OD pairs (Zhu et al. 2019).

Transportation, in particular, is an active research area in the geovisual analytics community, because professionals in this domain rely on interactive, visual tools to support their analyses of vehicular and pedestrian movement (Andrienko et al. 2017). Many data types, derivatives, and visual representations have been developed to inform the spatial, temporal, and contextual properties of aircraft, automobiles, pedestrians, ships, trains, and other moving entities. We refer readers to Chen, Guo, and Wang (2015), and Andrienko et al. (2017) for comprehensive surveys of data visualization frameworks and techniques relevant to traffic and transportation data, but we will highlight two particular works that emphasize the diversity of research being conducted in this application area. Zeng et al. (2013), for example, considered both data aggregation and pattern extraction techniques in their exploratory analysis of passenger re-distribution patterns at intersections in traffic networks. The authors further adapted a variant of the circos figure (i.e., a circular plot for exploring relationships among objects and positions; see Krzywinski et al. 2009) to visualize the flow of travelers through interchanges. More recently, Zhou et al. (2019) proposed a visual abstraction approach that leverages a Natural Language Processing word embedding framework, together with adaptive sampling, to make sense of large amounts of OD data. The authors demonstrated how their visualization system reduced visual clutter and highlighted human mobility patterns using bicycle share and mobile phone location datasets.

The work we present in this paper contributes to the growing body of research on the representation and analysis of movement data by introducing and evaluating an integrated network and OD flow map constructed from the aggregation of individual bicycling traces. Network flow maps have received less attention than their radial and distributive counterparts due to limited access to trajectory data, particularly individual trajectory data, as well as challenges surrounding data size and complexity. Through processes of data abstraction and novel techniques for rendering large geospatial data in a web browser, this paper offers an effective framework for making large amounts of individual movement data more usable, useful, and accessible, while also preserving the privacy of the data creators.

URBAN INTERFACES

Beyond the research on mapping and analysis of flow data outlined above, the system presented here also draws upon research on urban data interfaces, often termed *dashboards* (Few 2004). These dashboards provide analysts, decision makers, and the public with access to data about the city, and are increasingly being used for urban planning and real-time city monitoring. For example, Maynooth University, in partnership with Dublin City Council recently undertook an extensive Building City Dashboards (BCD) project. The BCD project focuses on expanding the Dublin Dashboard, one of the most comprehensive urban interfaces to date (Kitchin, Maalsen, and McArdle 2016).

On one hand, urban interfaces provide citizens and planners alike with a multifaceted, data-driven perspective on their city. On the other, this perspective is biased as a result of data cleansing, data that are (un)consciously not included, a lack of information on how the data were sourced and/or derived, and the varying abilities that users have to make sense of the data. Mattern (2014) cautions against the "instrumented" rationalization of the city mediated through an inevitably incomplete interface that lacks in affect and civic collaboration. Mattern provides guidelines for urban interfaces and asks designers to consider composition and framing of screen elements and how they interact over time and space, scale of context (entire city vs. street corner), intended audience, and the types of information about the city that cannot (or should not) be represented by data visualizations. As big social media data are increasingly leveraged to feed urban dashboards and geovisualization tools more broadly, the proper design and use of those tools must reflect the (semi-)volunteered nature of data collection; respect the privacy of the data creators in the collection, storage, analysis and visualization of the data; and consider the uneven density and representativeness of social media data across space and time (Martin and Schuurman 2020).

As humans, our experiences in and understanding of cities are bound in place, space, and time. Urban interfaces undoubtedly benefit from, if not require, a cartographic component. In many cases, the map may be the central element of the interface, thus conceptualizing and creating effective urban interfaces benefits from expertise not only in user interface (UI) and user experience (UX) design, but also map design (Roth 2017). Further, the design process gains from balancing interaction design frameworks relevant to data visualization and cartography (e.g., Shneiderman's [1996] Information Seeking Mantra or Roth's [2013] taxonomy of cartographic interaction primitives) with an iterative, user-centered approach to defining (or refining) interaction flows in response to feedback provided by those who will use the interface. In the following section, we introduce a map-centric urban interface designed to provide city planning professionals, local advocacy groups, and researchers with insights into how bicyclists move across urban networks.

METRO DATAVIEW

Metro DataView is an interactive flow map that depicts volumes of unique bike trips, commute-designated trips, and bicyclists across an urban network. In addition, the cartographic tool provides an option to view a rasterized heatmap of the GPS points that define the activity traces used in the creation of the other views.

DataView differs from many urban bike maps due to its ability to relay objective information on how bicyclists are moving across a street network. Oftentimes, bike map design in urban planning contexts is based on subjective input provided by the "average" bicyclist. Wessel and Widener (2015) surveyed dozens of urban bike maps and found that Departments of Transportation and planning agencies in cities across the United States were publishing maps that assigned bike routes to ill-defined classifications, such as "preferred," "use with caution," or "not recommended." In some cases, subjective context was also used to represent gradient (e.g., "steep hill" vs. "very steep hill") and safety (e.g., "difficult intersection"). This subjective design approach can be attributed to a lack of data on infrastructure and ridership, as well as to the Federal Highway Administration's "bicycle level of service" initiative that aims to evaluate the suitability of roadways for bicycle activity based on "comfortability" ratings provided by a subset of bicyclists for a sample of road segments (Harkey, Reinfurt, and Sorton 1998). Ratings can be correlated with road characteristics (e.g., pavement condition, shoulder width, speed limit, etc.) to extrapolate level-of-comfort designations across the entire network (Landis, Vattikuti, and Brannick 1997).

However, defining the "average" bicyclist is problematic, and as a result, many urban bike maps leave much to be desired with respect to objectively informing a diverse audience of bicyclists on how to successfully navigate the city. There are, though, some noteworthy exceptions to this subjective design approach. Wessel and Widener (2015) designed a printed bike map of Cincinnati, Ohio that intentionally did not include any unquantifiable information on roadway or terrain characteristics, with the intent that bicyclists of all types could make more objective wayfinding decisions. Similarly, but more narrowly focused, Brügger, Fabrikant, and Çöltekin (2017) conducted an empirical study to comparatively evaluate three linear elevation change symbolization methods (variation in color hue, color-coded arrows, and elevation profiles) to gain insight into how to design static maps to better facilitate bicycle route planning. Most similar to the design solution presented in our work is the Madrid Cycle Track initiative, in which Romanillos and Austwick (2016) developed network flow and heat maps from volunteer bicyclists to reveal mobility patterns across Madrid, Spain based on journey purpose (casual vs. messenger) and sociodemographic characteristics (age and gender). Bike maps, such as these examples and *DataView*, which quantify and effectively communicate ridership across the network, as well as other characteristics of the urban environment, can help bicyclists to choose safe and personally appropriate routes and assist city planning professionals in making strategic infrastructure decisions that promote bicycling as a recognized mode of active transportation (Su et al. 2010).

In the following subsections, we formally introduce Strava, the activity tracking platform by which bicycling trips were collected, aggregated, and made available for *Metro DataView*. Next, we provide a high-level summary on how the bicycling trip data are processed to support effective and efficient visualization and interaction. Lastly, system design decisions are described in detail.

CASE STUDY DATA PLATFORM

Strava is a social network for athletes that provides a platform for application users to record, analyze, and share their fitness-related activities. Tens of millions of activities are uploaded to the platform daily from users all over the world, and over two billion activities had been recorded in total between the company's inception in 2009 and December 2019 (Strava 2019).

Activities recorded by platform users provide opportunities that extend beyond just delivering personal value or insight to the individual who engages in quantified-self activities (Lee and Sener 2020). The large volumes of data generated voluntarily by users of these types of applications, when aggregated and anonymized, can be used by city planners, Departments of Transportation, advocacy groups, and researchers to help make cities safer and more efficient for bike and pedestrian activity (DiGioia et al. 2017). This requires transforming large numbers of activity traces into actionable insights for a variety of stakeholders in the urban planning space.

Metro is a small division of Strava that licenses aggregated and anonymized activity data to Departments of Transportation and other city planning organizations. Researchers are leveraging Metro data to better understand spatial patterns in bicycling and pedestrian behavior across many different application (and geographic) areas. For example, Griffin and Jiao (2015) evaluated the relationship between place-based/road network variables and the geography of bicycling-for-fitness in Travis County, Texas. Metro data have been used to facilitate smarter mobility planning in Johannesburg, South Africa (Selala and Musakwa 2016), and to model the relationship between bicycling trip purpose and air pollution exposure in Glasgow, UK (Sun and Mobasheri 2017).

A consideration when using Metro data is that the Strava user group reflects only a subset of the bicyclist population. Many of the users engage primarily in sports and training activities, not necessarily in everyday commuting trips. Recognizing this, prior studies have aimed to evaluate the representativeness of Metro data. For example, the Centers for Disease Control and Prevention reported a strong association ($\rho = 0.60$) between the number of Strava-tracked commuters and the number of active commuters sampled by the US Census Bureau's American Community Survey (ACS) in four major cities (Whitfield 2016). However, *intracity* correlation may vary as result of population density, social (dis)advantage, and overall ridership in the area (Conrow et al. 2018). At the very least, crowdsourced fitness data can complement and extend traditional active transportation surveillance and analysis despite sample and other biases inherent in user-generated data sources (Jestico, Nelson, and Winters 2016; Ferster et al. 2017; Lee and Sener 2020). Moreover, these data exhibit unprecedented spatial and temporal resolution, allowing for new approaches to measuring changes in bicycling behavior across an urban network as a result of infrastructure change and implementation (Boss et al. 2018).

However, the success of such approaches hinges on data accessibility and utility. In the following subsection, we explain the data abstraction process by which streams of individual movement traces recorded on Strava are transformed into summarized data views that a relevant audience can visualize and interact with using *Metro DataView*.

DATA PROCESSING & ABSTRACTION

Bicycling activities (i.e., streams of GPS points) recorded on Strava that are made publicly available by platform users are first queried from a PostGIS database based on a geographic area of interest and specified timeframe. Next, a map-matching process (White, Bernstein, and Kornhauser 2000) is performed to identify street network geometry traversed by bicyclists. More specifically, GPS points are aggregated against a vector street network (e.g., OpenStreetMap extract, TIGER network, etc.), intersection nodes (derived based on where the street network breaks), and arbitrarily defined hexagons with a 350-meter diameter. For street and intersection aggregations, the first and last 500 meters of each activity trace are cropped to preserve user privacy. Activity start and endpoints are only used in the hexagonal aggregation process, because these are created for the purpose of exploring origin-destination patterns in bicycling behavior and the size of the areal unit preserves user privacy. The aggregation processes output counts of unique individuals, activities, and commute-designated trips appended to all three types of spatial geometry. If a trip begins and ends at different locations, it is designated as a commute. Median interchange crossing times are also derived at the intersection level. This results in trajectory-oriented views of movement from both origin-destination and route-based perspectives (Andrienko and Andrienko 2010). The combined approach of map matching and aggregation has been identified as an effective strategy for outputting a useful dataset for transportation planning while also maximizing geoprivacy (Sila-Nowicka and Thakuriah 2016).

The three spatial datasets are output in GeoJSON format and converted into vector map tiles. Rendering GeoJSON directly on the client is not computationally practical because it requires downloading the entire data file on every map load. Vector tiles reduce the amount of data transferred to the client by returning vector representations only of features visible within the current map bounds and zoom level (Eriksson and Rydkvist 2015). In comparison to raster tiles, feature attribution persists through the GeoJSON-to-vector-tile transformation. As a result, features can be dynamically styled, manipulated, and interacted with on the client in real-time.

FEATURES & FUNCTIONALITY

As noted above, *Metro DataView* is an interactive mapping tool that depicts aggregate patterns of bicycling behavior across a road network. The intent of the tool is to provide city planning professionals and stakeholders, particularly those who possess limited or no GIS expertise, with a simple interface for: easily distinguishing commute from recreation bicycle corridors; identifying candidate areas for fixing or creating new bicycle facilities; and quantifying ridership pre- and/or post infrastructure change. Visual representations of counts of unique bike trips are displayed by default. An interactive tutorial is initiated when the application is loaded, to introduce and familiarize users with the interface and functionality. Learnability is one of the fundamental components of system usability, because a user's initial experience with an interface involves making sense of how it works and what it depicts (Nielsen 1993). Interactive tutorials are effective strategies for conveying short, chunked sequences of syntactic knowledge to novice map users (Roth, MacEachren, and McCabe 2009; Mead 2014).

System features can be accessed in the control panel, which is in the upper left corner of the map interface. Area-of-interest, timeframe, and global statistics on the total number of activities and bicyclists being represented in the interface are specified at the top of the control panel. Below this information are buttons that allow users to switch between the following unique data views: *Rides*, *Commutes*, *Cyclists*, or *Heat*. Only one of these views can be selected at a time. Figure 1 provides an overview of the layout of *Metro DataView's* various features. Intersections, origin-destination polygons, and destination-origin polygons can be toggled on or off. When on, these layers are overlaid on top of the street network and correspond to whichever aggregate data view is enabled. For example, if the "Commutes" view is selected, the intersection layer will depict counts of commutes at interchanges across the network (see Figure 2). Similarly, if the "Cyclists" view is selected, the origin-destination layers will depict the number of bike riders starting or ending at each of the

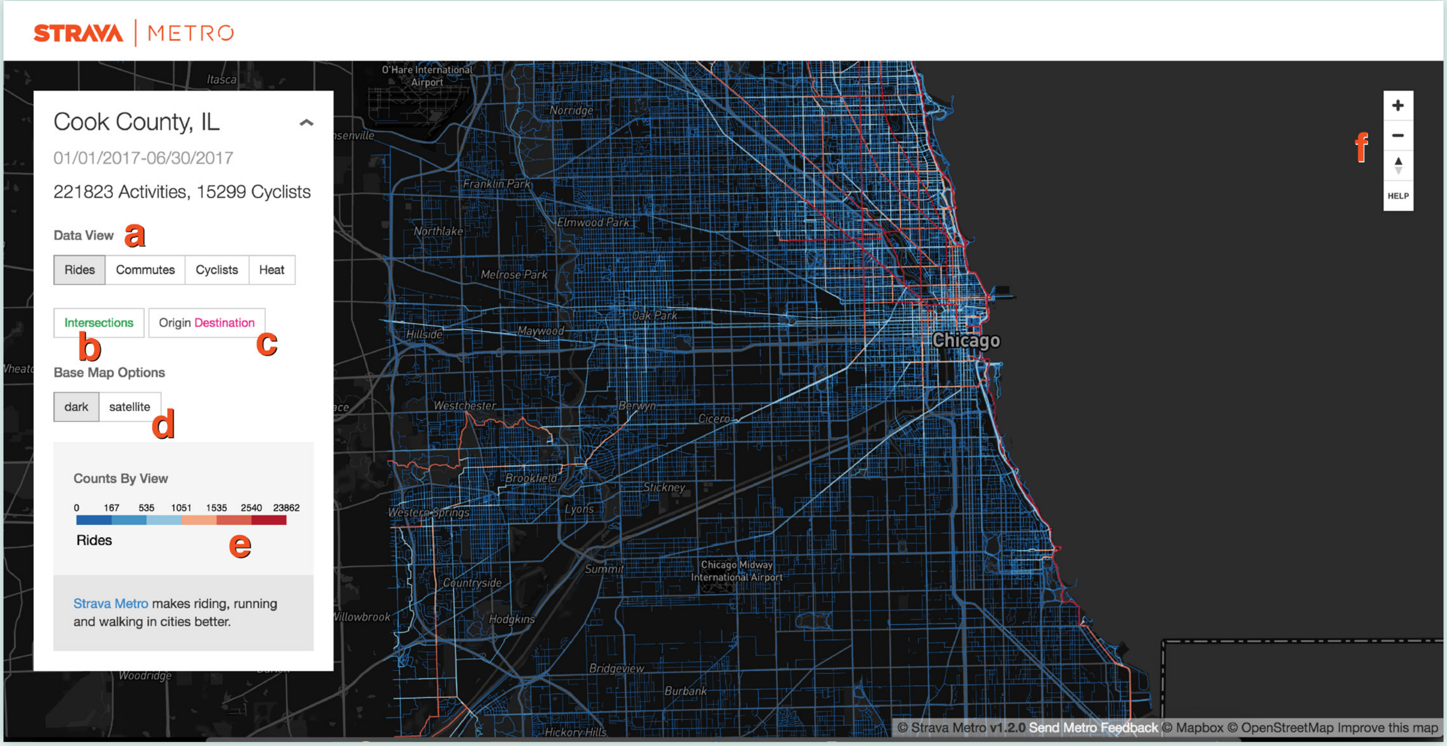


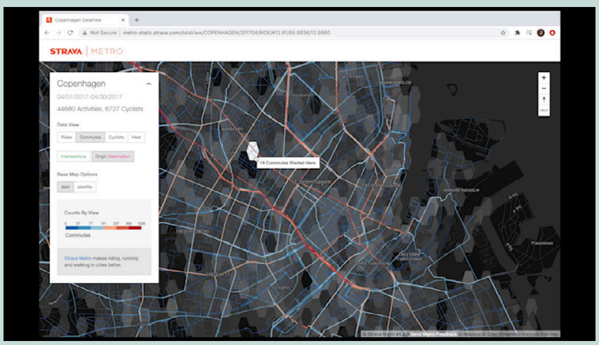
Figure 1. *Metro DataView: (a) network view options; (b) intersection toggle; (c) origin/destination toggle; (d) basemap selection; (e) network legend; (f) navigation and help.*

arbitrarily-defined hexagonal areas across the network (see Figure 3). Additionally, users can view a non-aggregated, rasterized heatmap of GPS points from the activities used to create the other views (see Figure 4). Satellite imagery is also available as an alternative to the default dark base map.

The network flow map is the primary layer within the tool and is symbolized using both variations in line width and a diverging blue-red color scheme to represent the volume of counts across road segments. Counts on streets are binned into six classes based on a variant of the Jenks (1967) natural breaks method, and colors were selected using *ColorBrewer*, an online resource for selecting logical color schemes for thematic data (Harrower and Brewer 2003). Wider lines and darker shades of red signify road segments with higher counts. Narrower lines and darker shades of blue (with dark blue having the lowest visual contrast with the black map background) denote road segments with lower counts. The intent of this symbolization is to show the volume of bicycling behavior, highlight key corridors of activity, as well as identify prominent areas of inactivity.

A complimentary intersection layer can be toggled on and off atop the network flow map to provide additional perspective on whichever network view is selected (Figure 2). The size of intersection point symbols is scaled based on the number of unique bike trips, commute-designated trips, or bicyclists aggregated to the points. Higher counts are represented by larger points. The opacity of intersection point symbols is varied based on median crossing times through the intersections. More opaque point symbols depict longer intersection crossing times, helping to draw attention to potentially problematic interchanges atop a dark base map.

Additionally, a view of origin-destination polygons can also be toggled. These are based on the previously



Click to watch a short video demonstrating DataView mentioned layer of contiguous 350-meter hexagonal bins. *Metro DataView* can support both origin- and destination-first views (i.e., users can select an origin and see all destinations associated with that origin or users can select a destination and find all origins associated with the destination). Polygon color value is varied to reflect the number of unique bike trips, commute-designated trips, or bicyclists that started or ended within the area. Darker shades of grey denote lower counts; lighter shades signify higher counts. Clicking on a polygon returns all destination (or origin) polygons associated with that polygon. The map automatically zooms to the bounds of the associated polygons and highlights them in shades of pink. Figure 3 depicts commute destinations across Fredrikstad, Norway and the associated origins of one selected destination.

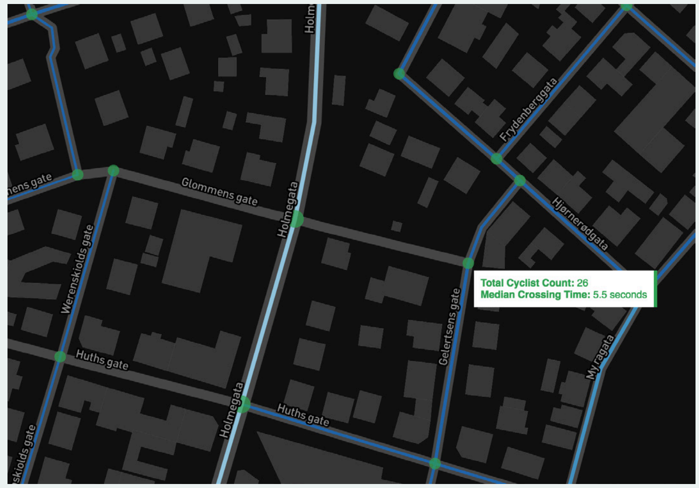


Figure 2. Intersection points representing the aggregate number of bicyclists crossing an interchange; count and median crossing time statistics shown on hover.

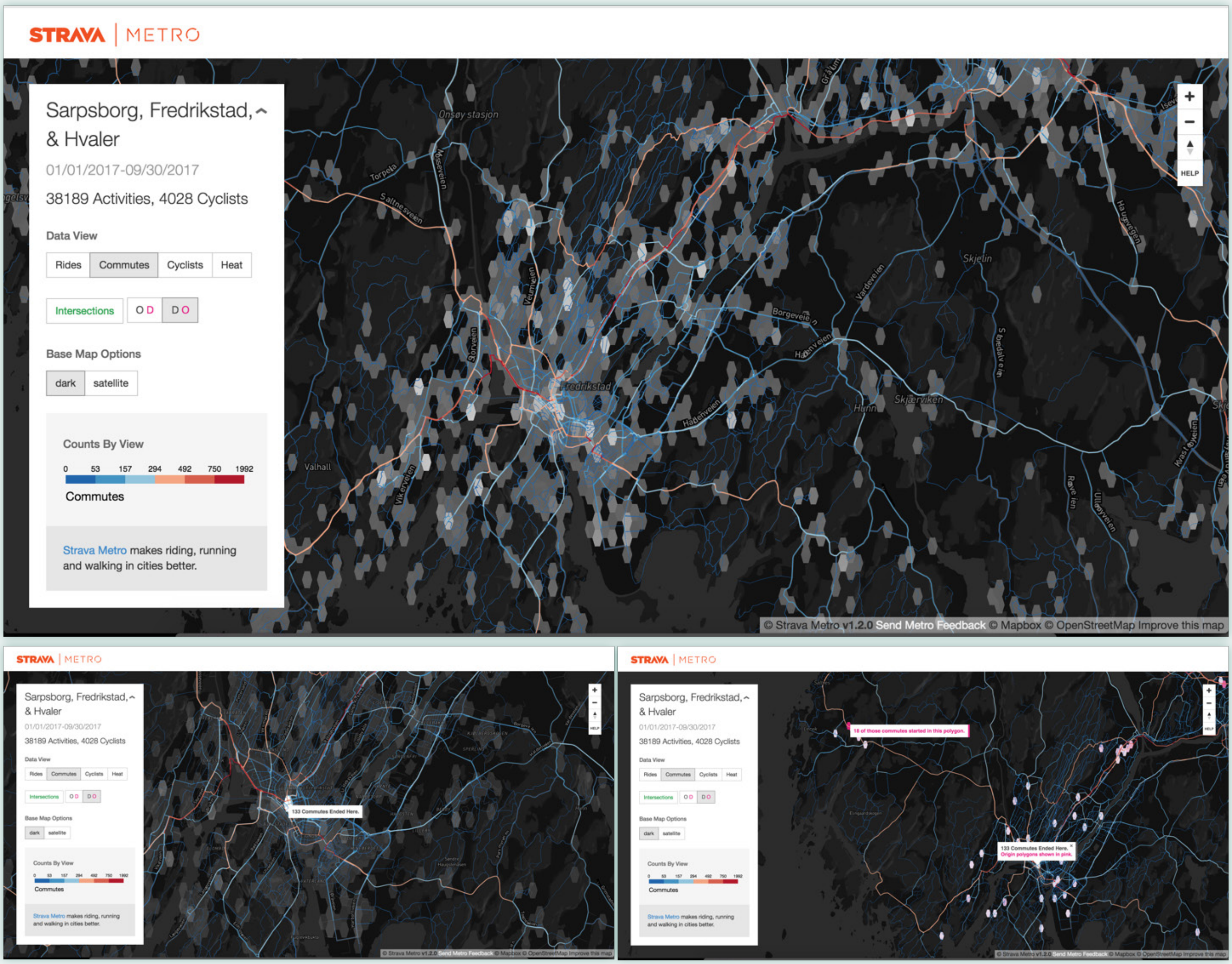


Figure 3. Overall patterns in commute-designated bike trip destinations across Fredrikstad, Norway (top); hover on a destination polygon to obtain a count of commute trips ending in the area (bottom left); click on a destination polygon to reveal all associated origin polygons (bottom right).

Lastly, users can select the *Heat* view, which depicts a rasterized heatmap of the movement traces that were aggregated to create the views described above (Figure 4). Counts are not available in this view. Activity density can only be inferred relatively. This view supports users in discovering missing or inaccurate geometry in the street network that was used for aggregation. The validity of the aggregated counts is contingent on the locational accuracy of the underlying street network. Thus, the heatmap not only depicts a rasterized representation of raw movement traces, but also serves as a guide for correcting or adding to an existing vector road network (i.e., if hotspots are seen that do not follow existing roads or paths, this may suggest that a segment of geometry needs to be created or updated in the base map).

In summary, *Metro DataView* is designed to visualize an aggregated bicycling dataset in ways applicable to an urban planning audience. In the next section, we consider a simplified approach to visualizing individual activity traces that extends the rasterized point heatmap view already incorporated into *DataView*.

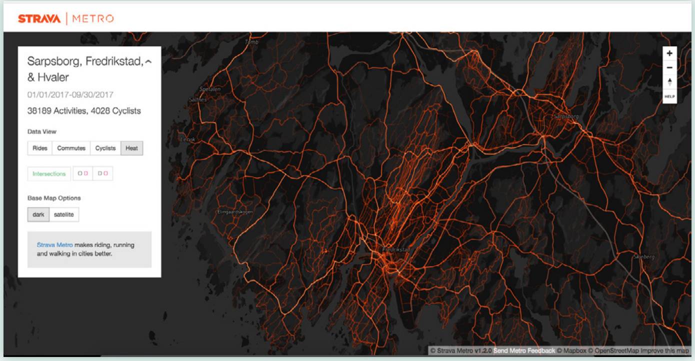


Figure 4. *Rasterized heatmap view of GPS bicycling traces across Fredrikstad, Norway.*

SIMPLIFIED APPROACH TO VISUALIZING ACTIVITY TRACES

To explore directions for future visualization development and further inform the design of *Metro DataView*, we implemented an alternate approach to visualizing patterns in bicycling behavior. The approach consolidated and extended the raster-only heatmap view seen in Figure 4, and did not require a computationally expensive aggregation process. Instead, a hierarchical visualization and interaction design approach was taken to seamlessly transition raster to vector representations of GPS bicycling trace data as a function of map zoom level. As the user zooms in on the interactive web map, static raster tiles representing GPS points transition to vector paths, revealing more subtle intricacies of movement patterns through city centers and along recreational trails. This visual abstraction approach builds upon the foundational work of Peuquet (1981) on translating and integrating raster-vector data representations, as well as the respective works of Brewer and Buttenfield (2007), and Stolte, Tang, and Hanrahan (2003) on multiscale symbol representation for USGS DLG reference map data and multiscale visualization using data cubes. The raster and vector representations are designed to look visually consistent; hence, users should not notice or be distracted by transitions in data representation when interacting with the map. Figure 5 shows small- and large-scale depictions of bicycling traces.

Figure 5. *Small to large (left to right) map scale depictions of raster to vector representations of bicycling traces.*

There were two main objectives for exploring this alternate approach to visualizing bicycling traces. The first objective was to assess if the approach had the potential to further broaden and diversify the *Metro DataView* user group. This raster-vector map integration could be implemented quickly and at a low cost because it did not require data aggregation. The tradeoff, however, was that the visualization of behavior patterns remained relative; functionality to obtain counts on a single street was not provided and was computationally impractical to implement. The second objective for exploring this approach was to further understand the merits of the more comprehensive *Metro DataView* service, and to better outline what a minimally viable product was from the perspective of a non-technical stakeholder in urban planning (i.e., someone unfamiliar with and potentially uninterested in undertaking analysis with Metro data, but who might find value in a simple visualization of bicycling behavior).

In the following section, we discuss the user-centered design and evaluation model used to assess the extent to which features and functionality of both the heatmap and *DataView* support city planning professionals in making informed decisions on bicycle infrastructure implementation.

USER CENTERED DESIGN & EVALUATION

The cartographic interfaces described in this work resulted from a multi-dimensional, in-depth long-term case study patterned after Shneiderman and Plaisant (2006), and consisted of three major stages of user-centered evaluation:

1. Scenario Based Design
2. Insight Discovery
3. Usability & Utility Evaluation

In stage one of the study, we employed scenario-based design techniques (Rosson and Carroll 2002) to formatively assess client (and potential client) feedback that was solicited in various ways (through structured surveys, focus groups, phone calls, in-person discussion, and email correspondence) over a two-year product development cycle.[1] Insights generated through this collaborative effort were integrated into a hypothetical use case scenario and supporting claims analysis to characterize the domain problem, exemplify the design challenges, and synthesize knowledge of map use practice gleaned from the development process.

Stages two and three of the study focused on summative assessment. We recruited seven non-client domain and visualization experts to evaluate the extent to which *DataView*, specifically, supported insight discovery (stage two) and was deemed useable/useful (stage three). Insight discovery was informed through a semi-constrained task and usability/utility were evaluated via survey. We report on the methodology and results for each stage in the following subsections, which are organized at the highest level by assessment type.

FORMATIVE ASSESSMENT

Scenario-Based Design

Scenario-based design (SBD) principles were employed to present a "sketch of use" for both the standalone heatmap and *DataView*. SBD focuses on how people will use a system as opposed to describing a system's features and functionality (Rosson and Carroll 2002). Scenarios of envisioned use are typically defined at early stages of system development to guide the design process (e.g., MacEachren et al. 2011), but can also be effective at informing other stages of system evolution (Rosson and Carroll 2002). In this instance, we are presenting a hypothetical use case scenario and complementing claims analysis to abstract the domain problem into essential tasks (scenario) and the necessary data representations and interactions to support those tasks (claims analysis). This scenario synthesizes insights gleaned from a two-year human-centered business practice carried out by the first author while employed by Strava, working with a range of clients, and is prototypical of one that would be common in a large Department of Transportation organization.

Scenario

Susan is a bike and pedestrian facilities project manager working for a hypothetical State Transportation Agency. Susan is responsible for overseeing all phases of the project lifecycle, from

1. Client feedback collected over the two-year development cycle was part of Strava business activities, thus not considered to be "research" at the time and as a result, is not directly reportable here.

scoping and right-of-way to preliminary engineering and construction. As part of a smart city initiative, the State has appropriated 45 million dollars over a 5-year period to research, design, and implement bicycle infrastructure and recreational facilities in the State's largest urban center.

The initiative is currently in research and scoping phases with some projects already identified and others yet to be defined. Various locations within the urban center have been identified as "hubs" for bicycle activity, and three Eco Counters have been purchased and installed to generate data on how many bicyclists are moving through these specific areas. The challenge, however, is that these counters are relatively far apart in a large urban center and cannot begin to inform key corridors throughout the heart of the network. Installing more counters is not fiscally practical, so Susan searches for cheaper, alternative data sources to complement the counter data. She discovers the report published by the Centers for Disease Control and Prevention (Whitfield 2016) that showed strong correlation between counter data and crowdsourced bicycling data maintained by Strava Metro. Susan reaches out to Metro to inquire more about its data and visualization services. Susan acknowledges that she is not trained in GIS and data analytics, and that she has very limited internal resources to leverage for data mapping and analysis. As a result, she decides to license DataView, and agrees to test out a beta heatmap service that Metro is actively developing.

Susan was informed that the beta heatmap is simpler to use than DataView, so she visits that link first. The webpage renders, and Susan is intrigued by the bright blue and white lines that represent GPS traces from bicycle activities. There's so many of them that on top of the dark basemap, they almost seem to illuminate the entire road network. She zooms in on the map to the locations of each of the three Eco Counters. The heatmap seems to confirm an influx of bicycling activity at those locations. She then zooms in to other areas that have been designated as key recreation and commute corridors, and again finds dense, saturated blue lines on the heatmap. Susan pans outward in various directions. She follows the lines around intersections, into parks, and through the residential and financial districts, attempting to identify popular routes and noteworthy destinations along those routes. Susan tries clicking on the map and the lines, hoping to find activity counts or functionality to toggle between commute and recreational-designated trips, but nothing happens. After fifteen minutes of exploration, Susan realizes that while she has detected known trends, she lacks quantifiable evidence needed to more effectively inform where to construct or modify essential infrastructure. Moreover, Susan isn't a bicyclist herself, which makes parsing the relative distinction between "less" or "more" rides on a given street very difficult.

Next, Susan inputs the URL link to DataView. She steps through the onboarding experience and is optimistic that the functionality will better serve her needs. Upon completing the short tutorial, she first switches between the various data views (rides, commutes, cyclists) in the control panel. Colors and patterns in the network map change, and the street legend updates based on the view. Susan quickly realizes that this map looks much different than the heatmap she had previously viewed; there appears to be fewer lines and less noise. She leaves the "commute" view selected and zooms in to one of the Eco Counter locations on Main Street. Rather than finding many overlaid lines, she discovers that the actual road segments have been colored and widened based on the number of commutes that crossed each one. She hovers on the segment nearest to the Eco Counter, and a dialogue box pops up and relays that 3,577 commute-designated bike trips happened along that segment over the last three months. She then switches between the other two views: "rides" and "cyclists." The color and width of the lines update Agency, and she learns that a total of 5,674 bike trips crossed the segment, accounting for 2,884 unique bicyclists.

Because the street segments are symbolized based on counts, Susan no longer needs to pan around attempting to follow patterns. Rather, she zooms out and quickly detects vibrant shades of red illuminating key corridors throughout the network. Susan has now identified a corridor of interest intersecting the Eco Counter location on Main Street. She toggles between the "origin-destination" and "destination-origin" views. Susan finds many popular origin polygons in the northern suburbs that all relate to a small and spatially-focused number of destination polygons in the southern, financial district. The street network map reveals a handful of popular arteries that all seem to flow into the Main Street corridor. Looking more closely, Susan notices that ten blocks south of the Eco Counter location, the primary commute route abruptly diverges into a residential area for about 13 blocks before returning to Main Street. She zooms back in to the newly discovered area of interest and toggles "intersections" on. The small, brightly colored nodes quickly convey that median crossing times for bike trips through the more direct, yet less traversed part of Main Street are significantly longer than those through the residential area detour. Susan isn't overly familiar with the area, but finds this pattern somewhat surprising because she knows that an unprotected bike lane already exists along the entire stretch of Main Street. She switches the basemap from "dark" to "satellite," and finds *that the number of car lanes on Main Street abruptly changes from two with no roadside parking to one with roadside parking. The bike lane appears to be quite close to the parking spaces, and in some cases, it almost looks like cars are parked partway in the bike lane. Given this insight, Susan initiates a new protected bike lane project in the State's internal prioritization and selection system. She also forwards the DataView link to various local bicycle advocacy groups. Community input and buy-in are essential, and Susan is hoping that these groups can provide additional qualitative insights on the impact of the potential project to bicycle safety and efficiency along that corridor.*

Claims Analysis

SBD claims analysis aims to provide a balanced view on challenges and opportunities surrounding system features that have important consequences for users (Carroll and Rosson 1992). Positive and negative claims are made about features to evaluate system design decisions and help identify focused opportunities for subsequent user testing (MacEachren et al. 2011). Table 1 presents a claims analysis on key features in the standalone heatmap and *DataView*, and was used to guide the design of a post-implementation user study, which we report on in the following subsection.

SUMMATIVE ASSESSMENT

Methodology & Participants

A post-implementation, two-part user study, consisting of task and survey components, was conducted to evaluate the design and utility of *Metro DataView* from the perspectives of non-client domain experts. The standalone raster-to-vector heat map did not move forward to this stage of evaluation because it did not relay activity or bicyclist counts, which was functionality that had been deemed essential by users in stage one. Study design was informed by a synthesis of best practices for evaluation of geovisual analytics systems, which emphasizes *instruction*, *analytical work*, and *feedback collection* as the primary components of an effective study design (Savelyev and MacEachren, 2020). The first part of the study focused on a semi-constrained insight discovery task, in which participants were provided with a web link to the interactive mapping tool for the entire US state of Utah and instructions on how to use it. Participants were asked to explore the interface at their convenience over a period of a week and write a short essay (up to 500 words) based on a self-selected role (e.g., city planner, local advocate, transportation analyst, etc.).

Visualization	Feature, Followed by Claims
heatmap	*Interactive raster to vector representations of GPS bicycling traces*
	+ allows users to explore intricacies in individual movement traces + does not require computationally expensive aggregation process + seamlessly transitions between data representations across map scale + is simple to use and very responsive - does not provide activity counts - does not enable filtering by trip type - is visually noisy
DataView	*Interactive network flow map*
	+ provides aggregated counts mapped to a linear street network + allows users to identify key corridors throughout the network quickly + is visually concise - requires an accurate linear street network basemap for aggregation process - cannot relay individual movement traces
	Option to switch between aggregate data views (rides, commutes, cyclists)
	+ allows users to assess patterns in total vs. commute-designated trips + allows users to relate the number of unique bicyclists to number of trips taken - does not distinguish recreation-designated trips
	Option to overlay intersection data
	+ allows users to identify high (and low) volume movement across intersections + allows users to assess median crossing time - is visually noisy as a result of many overlapping intersection nodes in dense urban areas
	Option to overlay origin-destination and destination-origin polygon data
	+ allows users to identify and quantify prominent patterns in commute behavior + helps users identify candidate locations for new bike facilities - routes between pairs can only be inferred using the network flow map - does not support selecting more than one origin (or destination) at a time

Table 1. *SBD Claims Analysis for Heatmap and DataView.*

The task prompted participants to clearly articulate (1) their selected role, (2) insights gleaned through interacting with the tool, (3) goals or approaches taken when interacting, (4) what visualizations/functionality were employed in arriving at various insights, and (5) to what extent the tool supported insight discovery. The intent of this exploration activity was to provide evidence about *DataView's* ability to support a broad range of insights on the part of participants, while also providing a consistent framework for synthesizing results.

The second part of the study entailed an online follow-up survey, consisting of a mix of multiple choice questions, five-point Likert scale ratings, and open-ended response questions, designed to evaluate the usability and utility of *Metro DataView*. Usability metrics were based on the system usability scale (Brooke 1996). Utility metrics followed a format similar to those designed by Pezanowski et al. (2018) and Robinson et al. (2020) but were adapted to explicitly evaluate the extent to which *DataView* facilitates better understanding of bicycling behavior at various spatial resolutions and could help city planners or Departments of Transportation make informed decisions on bicycle infrastructure design and implementation.

Seven participants engaged in the study; six completed both parts, while one submitted an incomplete and unusable essay alongside a complete survey. Participants were recruited using email lists that targeted experts in the use of interactive maps as an input to decision-making (e.g., geography, urban planning, or place-related policy making domains) and experts in the design of interactive, web-based interfaces to explore data (e.g., data visualization, cartography, or human-computer interaction domains). Figure 6 depicts a visual summary of participants' demographic and professional backgrounds.

Task Activity Results

The task component of the study resulted in six essays, ranging in length from 121–516 words, with a mean word count of 273. Table 2 summarizes essay content, and is organized based on the selected roles, goals, specified interactions, noteworthy insights, and recommendations for tool enhancement provided by the participants.

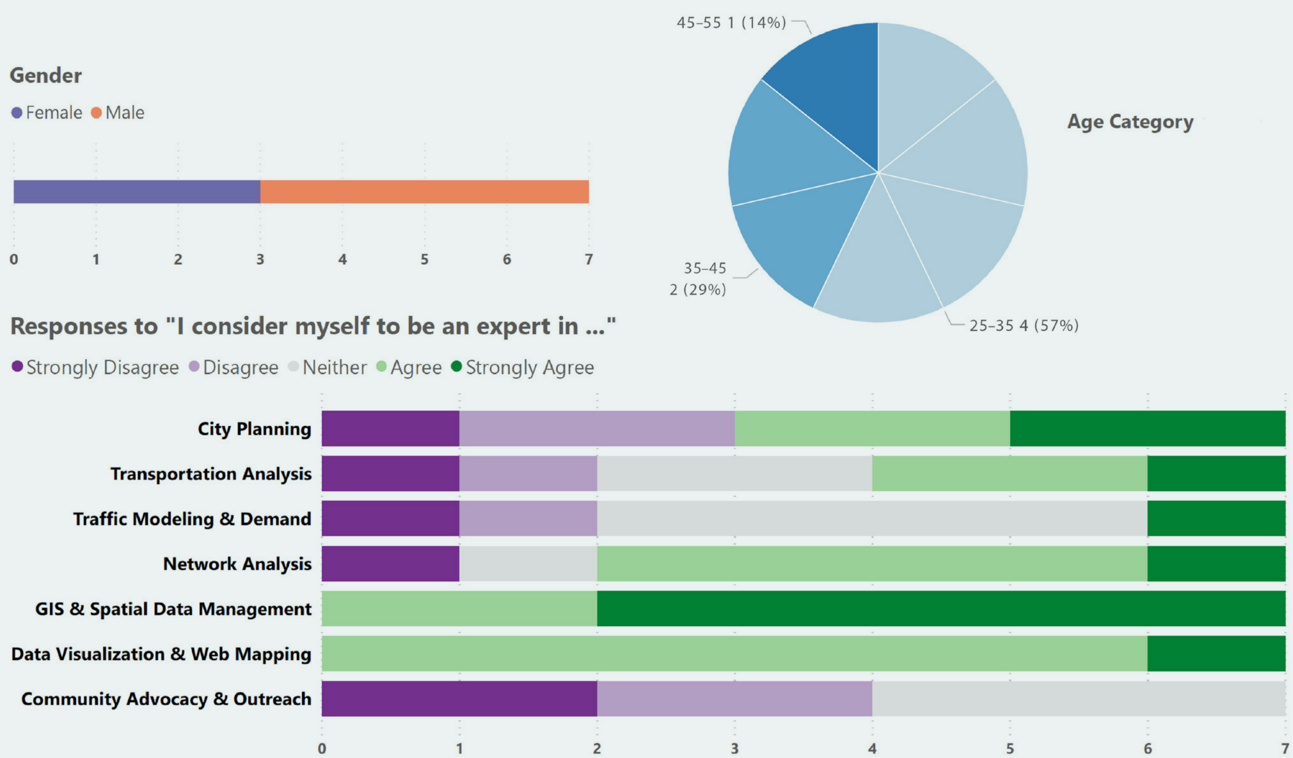


Figure 6. *Visual summary of participants' demographic and professional backgrounds.*

Role		
GIS Mobility Analyst	*Goal/Task*	*Interactions*
	explore patterns in commute behavior (e.g., how long are commutes, do they seem dangerous, do they link the suburbs to the downtown, and how do they differ from recreation rides?); anticipate dangerous intersections	• switched between "ride," "commute," and "cyclist" network views • overlaid intersection points
	Exemplary Insights	*Recommendations for Improvement*
	• people are taking long commutes and using windy roads • most popular intersections were in central Salt Lake City • Heber City looks like it would be conducive to biking but there are not many rides there • commute patterns don't always align with overall patterns	• create ratio between number of unique bicyclists and commute vs. recreation trips • allow users to filter by season
City Planner	*Goal/Task*	*Interactions*
	identify roads that can be converted into bicycle highways (especially for commuters during rush hours)	• switched between "ride," "commute," and "cyclist" network views • overlaid intersection points • overlaid origin-destination polygons
	Exemplary Insights	*Recommendations for Improvement*
	• discovered high-volume routes which were used primarily by commuters	• allow users to select network classification schemes other than Jenks • enhance intersection symbology to more effectively convey wait time
Not Specified	*Goal/Task*	*Interactions*
	exploration	• overlaid origin-destination polygons
	Exemplary Insights	*Recommendations for Improvement*
	• Origin-Destination polygon interaction is most useful for understanding network demand of bicyclists	• disable click to zoom if origin-destination polygons are active to facilitate more effective data retrieval • limit auto zoom to nearest destination polygons when origin is selected
Planner	*Goal/Task*	*Interactions*
	exploration	• switched between "ride," "commute," and "cyclist" network views • overlaid intersection points • overlaid origin-destination polygons
	Exemplary Insights	*Recommendations for Improvement*
	• Constitution Blvd and 3200 West seem to have a lot more waits in daily commute than the distribution of rides, which means the roads are used more often by the local bicyclists than the tourists • Bike trips in Park City are mostly centered in Park City because the OD nodes are in the same area, while only a few trips come from Salt Lake City • Downtown, Park City areas, and the intersection of the highway are popular destinations of bike trips	• Not Specified

***Table 2.** Participants' approaches to insight discovery.* *Continued on next page.*

Role		
Local Advocate	*Goal/Task*	*Interactions*
	increase bike commuting and safety in the Provo/ Orem metro area; identify most popular routes and outliers; determine which routes were on roads and which were on trails	• switched between "ride," "commute," and "cyclist" network views • switched between basemap options • overlaid intersection points • overlaid origin-destination polygons
	Exemplary Insights	*Recommendations for Improvement*
	• mountain biking is popular at the north entrance to Provo Canyon; people also commute around this area, with the other major commuter destinations being downtown Provo and Brigham Young University • routes on the periphery of town near Utah Lake are popular for leisure riding, not commuting • to get between Provo and Orem, routes along the Murdock Canal Trail and University Ave or Canyon Rd are more popular than the more direct, but busier, State St • there is not a real popular way for bikers to go along University Parkway, a major transportation and commercial thoroughfare in these cities • Kuhni Road is very popular with bicyclists, and I wonder if that is a new arterial	• enhance color scheme for linear network when satellite basemap option is selected • enhance intersection symbology to more effectively convey volume vs. wait time
Park / Forest Service Analyst	*Goal/Task*	*Interactions*
	explore overcrowding of outdoor recreation spaces; find park areas that were heavily used and determine what routes were most common	• switched between "ride," "commute," and "cyclist" network views • overlaid intersection points • overlaid origin-destination polygons
	Exemplary Insights	*Recommendations for Improvement*
	• there wasn't as high of a density of rides, commutes or bicyclists in Zion National Park, Arches, and Canyonlands NP as compared to other parts of the state	• ability to filter by user-specified geographic area and season

Table 2. *Participants' approaches to insight discovery. Continued from previous page.*

In summary, the six participants explored the tool from different perspectives with some overlap or similarity in assumed roles. Self-directed tasks or goals ranged from well-defined to broad exploration. Most participants interacted with and commented on insights obtained from using *DataView's* various features; however, one participant chose to focus their assessment solely on the utility of the origin-destination polygons. Four of the six participants provided very specific insights about findings at particular locations, whereas two participants provided shorter, more general insights. Five participants provided recommendations for how to improve the interface. Overall, the types of insights and recommendations for system improvement provided by participants aligned with the claims made about *DataView* based on a synthesis of client collaboration carried out by the first author, Jonathan Nelson, while working for Strava Metro (see Table 1). For example, participants demonstrated success in using the three different network views to identify prominent bike corridors. However, they also expressed the need to distinguish recreation-only from commute corridors. Similarly, participants overlaid intersection and

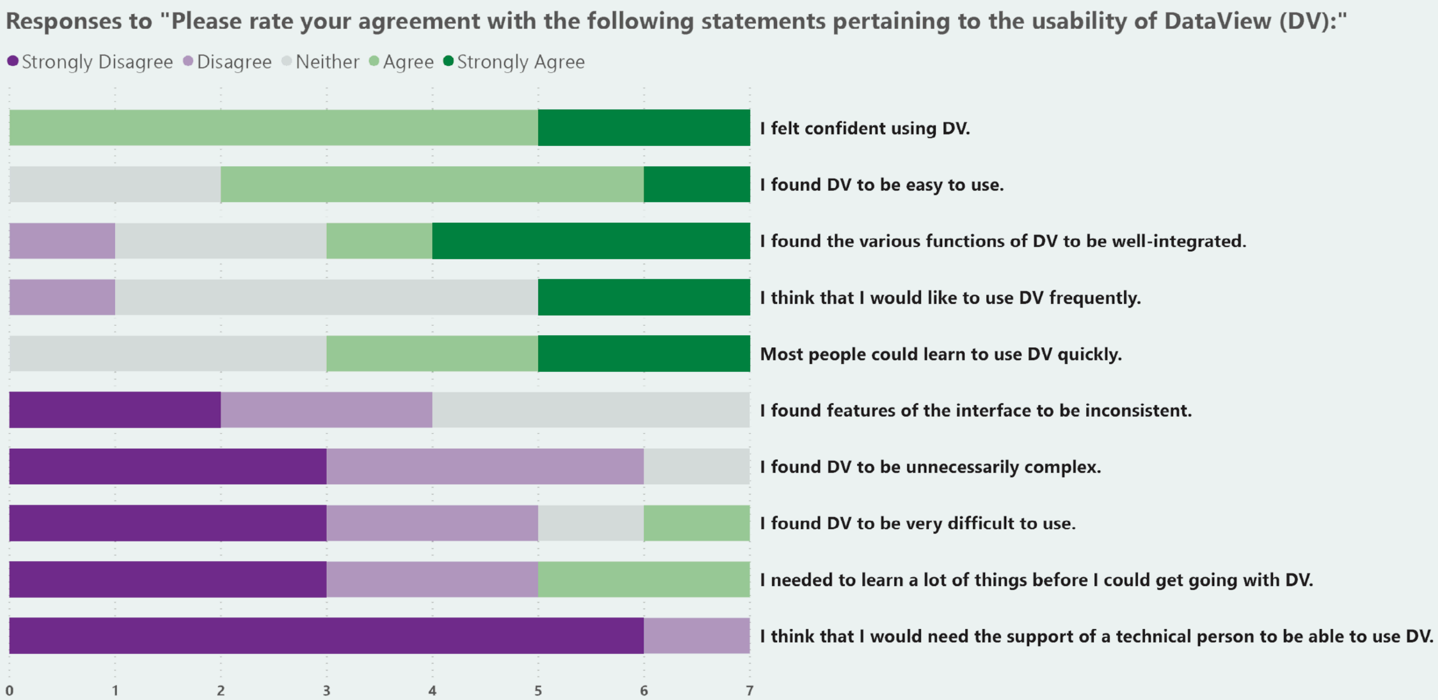


Figure 7. *Visual summary of participants' usability ratings.*

OD polygon data successfully to make inferences about movement volumes, wait times, and prominent origin/destination locations. However, they highlighted additional challenges interpreting symbology. In some instances, participants provided input for system improvement that extended beyond the negative claims identified in the claims analysis. We explore these recommendations in more detail in the following section on usability and utility evaluation.

Usability/Utility Results

Results from the online follow-up survey included seven participants' responses to a mix of Likert scale, multiple choice, and short answer questions designed to collect feedback on the usability and utility of *Metro DataView*. The first four questions focused primarily on time spent using the interface and initial impressions of its design and effectiveness. One participant reported having spent 30–45 minutes using *DataView*, three participants spent 15–30 minutes, and three spent less than 15 minutes. All participants reported stepping through the entire onboarding experience. The majority of respondents characterized their initial experience using *DataView* to be straightforward and found the overall design of the interface to be effective. Figures 7 and 8 provide visual summaries of the strengths and weaknesses of *DataView* in terms of usability and utility.

Overall, the majority of participants found the tool easy to use and its functionality well integrated. Moreover, most participants also agreed that *DataView* facilitated a better understanding of bicycling behavior at various spatial resolutions and that the tool could help city planners or transportation departments make informed decisions on infrastructure design and implementation. However, participants' agreement was more divided on whether or not the tool could prompt new hypotheses about the decisions that bicyclists make when navigating through a city or whether it could be helpful when generating an analytical report to prompt further action.

In addition to rating their agreement with the statements shown in Figures 7 and 8, participants were also asked to provide short answer recommendations for improvements that could be made to enhance *DataView's* usability and utility. Six participants provided input. Some of the feedback echoed what had been distilled in the claims analysis and in participants' essay responses, such as the desire for temporal filtering and spatial selection. Additionally, participants recommended incorporating information on where bicycle infrastructure already exists, to more effectively communicate to decision makers where improvements need to be made, and to better inform bicyclists about more preferred or safe routes. Participants also suggested incorporating other modes of travel and predictive

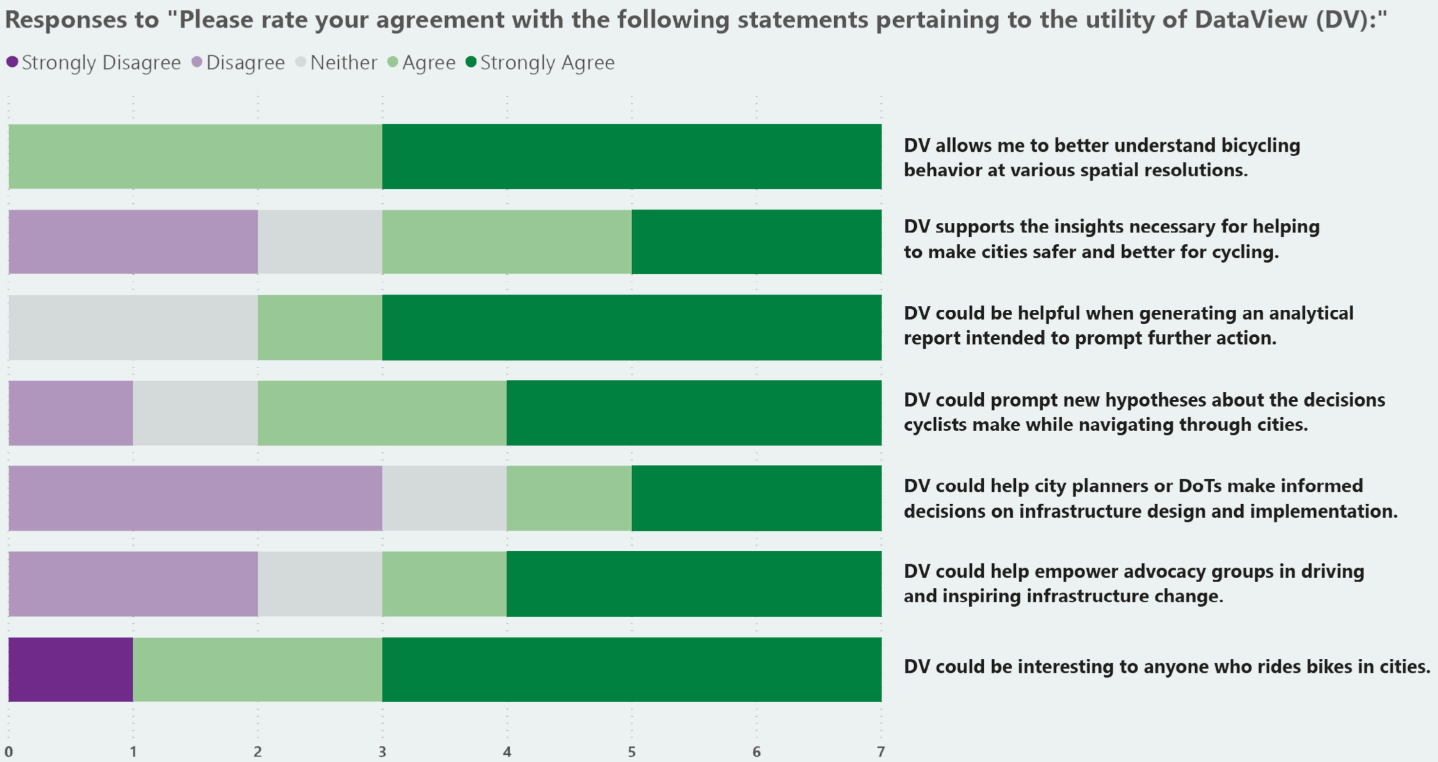


Figure 8. *Visual summary of participants' utility ratings.*

modeling to provide a more complete representation of movement across the network and identify hotspots for accidents. Results from this post-implementation user study will be shared with Strava to help inform ongoing development of Metro's visualization tools and services. In the following section, we highlight the impact of *DataView* in the context of client adoption and propose opportunities for future research and development based on the input from non-client domain experts.

DISCUSSION

Metro DataView has been delivered to city, state, and regional Departments of Transportation, local advocacy groups, and researchers across the globe. From smaller towns (e.g., Conway, Arkansas and Grey County, Ontario) to large government agencies (e.g., Colorado State Department of Transportation and Transport for London), *Metro DataView* is being used to inform the city planning process. For example, Transport for London leverages the interactive mapping tool and the underlying data that support it to generate network demand models and assess the potential for growth in bicycle transport throughout the Capital. In Queensland, Australia, the Department of Transport and Main Roads uses *DataView* to quantify the impact of bicycling infrastructure investment. The Florida Department of Transportation prioritizes street sweeping efforts based on insights extracted from the tool. In October 2017, Texas Public Radio published a piece on how the Texas Department of Transportation and local planning organizations were using the tool to better understand how bicyclists were moving across the state's network to prioritize where to implement new facilities and bicycle infrastructure (Flahive 2017).

This work describes a unique circumstance: a novel and impactful cartographic product was conceptualized and created in an industry setting, while also being grounded in academic methodology and scholarship. On one hand, this situation created an opportunity that enabled the widespread adoption of an effective decision-making tool as summarized above. On the other hand, conducting this research in a commercial environment resulted in not being able to report on specific methods or findings from client-centered design studies that were carried out over a two-year product development cycle. To address this shortcoming, we employed a scenario-based design strategy to distill our collaborative efforts with clients into a hypothetical use case scenario and supporting claims analysis. While some transferable knowledge to other design studies is inevitably lost in the translation, this approach forced us to synthesize both the wealth and diversity of client feedback into a cohesive and guiding design narrative. This narrative served to abstract and characterize a real-world domain problem and helped to focus our follow-up evaluation methods toward assessing system features and functionality that were deemed essential by the target audience. Combining scenario-based design techniques with task assessment, usability, and utility evaluation enabled rich, multi-dimensional insights into how geovisualization tools can be designed to support city planning professionals in making cities safer and more efficient for bicyclists. While this multistage design study required significant time and effort, the depth of insight into the domain problem and effectiveness of the proposed design solution would not have been achievable if only a single method had been employed.

The impact and "success" of this work is a direct result of the multistage user-centered design model that guided its evolution. The value of engaging with intended users and stakeholders of a system during the development process cannot be overstated, echoing recent scholarship in interactive cartography (e.g., Slocum et al. 2003; Robinson et al. 2005; Roth et al. 2010; Delikostidis, van Elzakker, and Kraak 2016). Moreover, this work aligns with at least three opportunities proposed by Roth et al. (2017) for adapting user-centered design methodology to interactive cartographic studies: namely contextualizing and emphasizing the process (not just the result), conducting purposeful rather than convenient study participant sampling, and promoting and illustrating the value in being comprehensive and thorough. While user-centered design aims to ensure system success, defining and evaluating success is challenging. The question of "to what extent does the system meet or exceed the expectations and desires of its users?" can be subjective and inappropriate to quantify. Unlike controlled experiments that are replicable and generalizable, user-centered design studies tend to inform a more specific situation, making its findings transferable and insights contextual only to similar use cases (Sedlmair, Meyer, and Munzner 2012).

For Strava Metro, there was a clear need to develop interactive, visual ways of making activity data more accessible, usable, and useful. Feedback from organizations using the data indicated users' frustration, confusion, and limited ability to generate valuable insight into the spatiotemporal patterns of bicycling behavior. Having identified this need, we conducted a multi-dimensional, in-depth long-term case study consisting of three major stages of evaluation: (1) scenario-based design, (2) insight discovery, and (3) usability and utility assessment. Stage one translated over two years of collaborative efforts—working with Departments of Transportation, local advocacy groups, and other city planning professionals—into a transferable abstraction of a real-world problem, while also illustrating design challenges and identifying focused opportunities for further user testing. Stages two and three of the study explored these focused opportunities through an insight discovery task and usability and utility assessment completed by seven non-client domain experts. This design framework was selected because the goal was to obtain both formative and summative insights, but with a focus on qualitative rather than quantitative results. Moreover, the intent was neither to assess nor quantify how the final system compared to other tools capable of delivering similar insights, but to design and implement a specific system to meet stakeholder and client needs.

Two key findings resulted from stage one of the study. The first is that the visualization solution produced needed to relay counts of bike trips across the road network and distinguish commute from recreation trip types. Second, inferences on relative activity density provided by the raster-to-vector heatmap were deemed insufficient for making informed planning decisions. Results from stages two and three of the study reinforced stage one claims made about *DataView* based on the synthesis of findings from working with clients over the product development cycle. For example, seven non-client domain and visualization experts demonstrated success in using the three different network views to identify prominent bike corridors, and successfully overlaid intersection and OD polygon data to make inferences about movement volumes, wait times, and popular origin/destination locations. These results also revealed important system shortcomings and opportunities for future work. For example, *DataView's* current inability to relay information on the presence and condition of bicycling infrastructure limits users' inferences on the connectedness of the network. Information on volume alone is insufficient for understanding how many people aren't biking but could be if infrastructure was improved. Additionally, functionality to support enhanced spatial and temporal filtering would advance users' abilities to make sense of the more nuanced patterns of commute and recreational behavior.

More broadly, there exist opportunities to extend the technical framework to support the aggregation, tiling, and mapping of multiple data sources to relay a more complete and representative depiction of how individuals and entities move and interact across a network. As noted above, crowdsourced fitness data represent only a subset of the active population, and should serve to complement and extend more traditional approaches to active transportation surveillance and analysis (Jestico, Nelson, and Winters 2016; Ferster et al. 2017; Lee and Sener 2020). User-generated fitness data, for example, can be combined with survey and counter data to more effectively model the flow of bicyclists across a network (Whitfield 2016). Additionally, supplemental data on crash incidents, roadway characteristics, and environmental factors can be integrated with crowdsourced activity data to help prioritize safety initiatives and inform why some routes are more popular than others (Quartuccio et al. 2014; Quercia, Schifanella, and Aiello 2014; Sun and Mobasheri 2017). Multiple data sources, together with civic collaboration and input, foster a more complete and honest urban interface (Mattern 2014).

CONCLUSION

In this work we presented a design strategy to address a problem-driven research question: *how to make large amounts of aggregated and anonymized individual movement data more accessible and actionable to stakeholders in the city planning process*? We employed cartographic principles of representation, geovisual analytics techniques, and best practices in UI/UX design to arrive at an interactive mapping tool that can communicate the complex flow of bicycling traces across urban street networks to experts trained in transportation analytics and modeling, as well as a broader, public audience. A major contribution of this work is our approach to combining scenario-based design methods with a post-implementation user study to characterize the domain problem; map essential user tasks to data representations and interactions; articulate the design rationale; and validate the design solution.

Beyond presenting an adaptable and flexible design approach, we proposed an innovative technical framework for rendering, and enabling interaction with, large geospatial datasets in the browser. Additionally, we explored a hierarchical visualization design approach that seamlessly transitions raster to vector data representations across map scale. The intent of this approach was to leverage scale-specific advantages of each data representation type in the context of web mapping. Rendering activity traces as raster pixels at small map scales and as vector paths at large map scales is an effective strategy for achieving reasonable client performance while enabling more flexibility in map interaction. While the raster-to-vector heatmap did not meet the needs of this study's target audience, there exist opportunities to extend this visualization paradigm through design and evaluation of interaction strategies across scale (i.e., addressing the disconnect between visual consistency and interaction inconsistency across scale). Future research is also needed to address design limitations identified by study participants. While incorporating more advanced spatial and temporal filtering functionality into the interface is a relatively clear need, inclusion of predictive modeling, bicycling infrastructure information, and data on other modes of transportation will require additional user input to capture the context of the need and the breadth of its applicability to the target audience group.

ACKNOWLEDGEMENTS

We wish to thank Strava Metro for its commitment to helping make cities safer and better for bicyclists and pedestrians. This commitment is what fostered the ideation and development of the geovisualization tool, *Metro DataView*, described in this paper. More specifically, we would like to acknowledge Davis Kitchel for his contributions towards solving *DataView's* technical challenges; Kristin Rousseau for her efforts in managing the transition of *DataView* from prototype to product; and Michael Horvath for championing Strava Metro's mission and believing in its potential. We also wish to thank user study participants for their time and feedback and the anonymous reviewers for their helpful input.

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DISCLOSURE STATEMENT

The core of the technology development described in this work was carried out while the first author was employed by Strava Metro as the lead user experience designer for the *Metro DataView* application described in this work.

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