Construction of Interactive and Intelligible Distance Cartograms

by

Ray Hong

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Dissertation Committee:

Dr. Cecilia Aragon, Professor in HCDE at UW, Chair
Dr. Sarah Battersby, Manager, Tableau Research
Dr. Jessica Hullman, Assistant Professor in iSchool at UW
Dr. Jevin West, Assistant Professor in iSchool at UW
Dr. Mark Zachry, Professor in HCDE at UW

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Abstract

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Chair of the Supervisory Committee:
Professor Cecilia Aragon
Department of Human Centered Design and Engineering

Travel time is a critical proxy that people rely on for assessing a cost of travel from one place to another. Although information about travel time is an important part of people's spatial information exploration, decision-making, and information analyses, seeing the *exact travel time* information using the current style of maps, such as equidistant or conformal maps, is not easy. This is because most of the designs use a visual channel of *color* to encode an ordinal level of traffic congestion. *Distance Cartograms* (DCs) apply a visual channel of *position* to encode travel time information from a single location (typically called the origin) on a map. To do so, DCs shift features on a map such that the distances on the map represent a more precise travel time between the origin and any location on the map. This visual encoding choice of DCs enables readers to visually compare travel times to places around the origin with reduced cognitive effort.

Although the concept of DCs was introduced in 1960, the building of interactive DCs has remained a challenge due to the high computational cost for constructing a *time space*, the space that specifies the shortest travel time from an origin to the rest of the locations. In addition,

previous studies indicate that the DCs' information presentation can confuse users when significant discrepancies between the physical distances and the "travel time" distances exist. These technical and perceptual barriers have impeded researchers and practitioners in exploring the potential of DCs as a solution for everyday spatial information exploration and decision-making scenarios.

In this thesis, I propose techniques that enable the implementation of *interactive* and *intelligible* DCs. To enable the building of interactive DCs, I introduce *Scalable Road-network Construction* (SRC) and *Quadtree Time-space Partitioning* (QTP), which improve the computational efficiency for a time space construction. To build intelligible DCs, I suggest *Geo-contextual Anchoring Projection* (GAP) and *Shape-retaining GAP* (S-GAP), which controls the degree of distortion.

Using these techniques, I report on formative studies conducted in order to understand a series of map user interaction types that can potentially present superior spatial information exploration experience. Based on the techniques and the interaction design, I introduce three versions of a system named *Traffigram,* a system built to help users in experiencing Distance Cartograms. This thesis reports on the findings of a series of studies conducted in the lab and in the wild using the three versions of Traffigram. Through the lab studies, the thesis presents findings related to how DCs can improve existing techniques used for seeing travel time information (e.g., color-encoding maps) in specific ways. In the deployment study, I present findings that show initial evidence that people can use DCs in real-world scenarios and that they can identify benefits to using DCs that is sufficient to overcome the adoption barrier. The thesis concludes by discussing the limitations of suggested techniques and study findings, future work, and unexplored problem spaces that remain.

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ACKNOWLEDGEMENTS

Although this thesis describes my journey to gain a better understanding of Distanced Cartograms, I met many friends and collaborators who helped me be persistent and rise again when I encountered failures along my journey. This thesis would never have been possible without their support and collaboration.

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Sam-Pyo Hong and Youngsun Lee

Chapter 1. INTRODUCTION

Exploring places using digital maps is a widespread activity. When finding a place to go, people often ask, “How long will it take?” to weigh their cost of travel [1, 2]. Although information about travel time is a critical proxy for assessing the cost of travel [1, 3], seeing the *exact travel times* using the current styles of map designs, such as equidistant maps or conformal maps, is not easy. This is because the designs merely present an ordinal level of traffic congestion using *colors*. For example, people cannot decode time accurately using color-coded road segments such as those in Fig. 1. (a) [4] or free-form isochrones presented in Fig. 1. (b) [5]. In general, categorical colors can’t be visually summed in a way that allows readers to compare travel times to different places. To find accurate time information, people commonly indicate the addresses of locations to a system that is designed to provide travel (time and path) information between two or more explicitly specified locations. Such input entails multiple user steps and acts as a barrier when

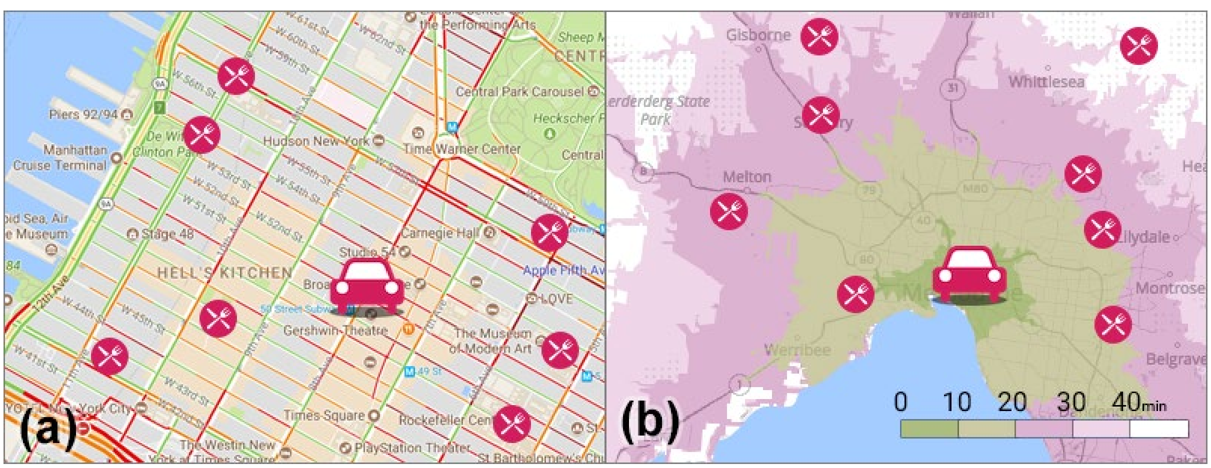

Figure 1.1. Visualization of travel time on maps using colors. (a) **Color-coded road segments**: users cannot see travel time from a car to places nearby. (b) **Free-form isochrones**: users can only decode a range of travel time to a certain location (e.g., 10 min. and 20 min) but not an exact time.

people attempt to assess travel time information while exploring places without having the destinations pre-selected [1].

To help people see travel time information with less effort, this thesis investigates *Distance Cartograms* (DCs). DCs shift the position of features on a map such that the distances between a single location (the origin: typically, a user's current location) and the rest of the locations on the map indicate a precise travel time between them [6]. Such characteristics of DCs enable users to read travel time through the visual channel of a *position*. Studies in human perception show that readers can decode the quantitative information through the position with a higher degree of accuracy than they can with color-based encoding [7]. Using position as a visual channel for encoding travel time also enables users to perceptually decode and compare accurate travel times to multiple places at a glance.

1.1 Thesis Problem

Although DCs' perceptual benefit is notable [1], in the time since their first introduction in the 1960's, it has been seen as unrealistic to deploy them in spatial exploration tasks [8]. This thesis tackles the challenges of ***interactivity*** and ***intelligibility*** to enable live deployment of DCs as a practical solution that can be used in real-world location-based decision-making scenarios.

Interactivity challenge: To date, building an interactive DC was not feasible due to the high computational cost [9]. Building a single DC requires computing the shortest travel time from an origin to the rest of the places on a map. Making a DC interactive means that the system ***should*** finish computing the shortest paths on a given road network (which includes nodes that indicate geographical places and edges that indicate the connections between two nodes) ***per each*** of the user's interaction queries such as zooming or panning ***in real time***. However, the size of the network can easily grow larger than the system can handle within a certain time threshold. Because

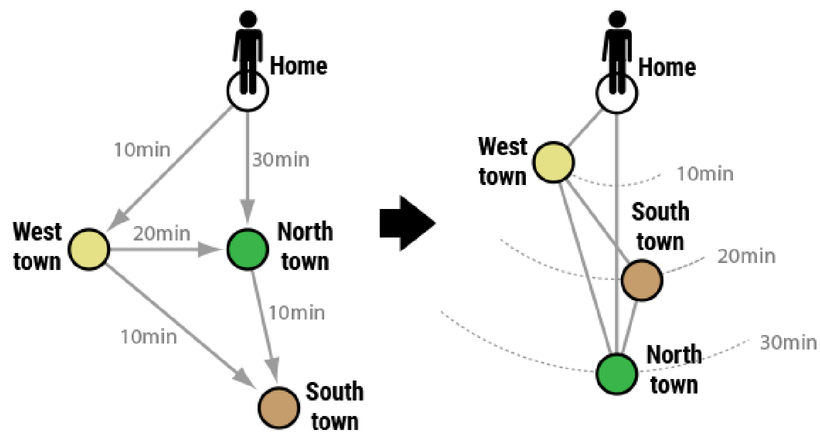

Figure 1.2. Topological violation caused while constructing a DC results in the disruption of relative positions between South town and North town.

of the cost, providing widely used map interaction types such as panning or zooming in DCs becomes a significant challenge [1, 9].

Intelligibility challenge: DCs must not only be technically feasible but also be understood easily [10]. However, distortions in DCs can significantly confuse users in two ways [11]. Fig. 2 shows the first case. In the physical space in the left, "South town" is located south from "North town." However, travel time from the origin to South town is less than the travel time to North town. Consequently, the DC relocates the position of North town to the south of South town. This case is called topological violation, which disrupts the relative position between places and challenges readers' intuition [8, 11]. DCs can also confuse users in the case in which map shapes are distorted to the extent that the users cannot recognize the original shapes (see Fig. 4.2 for example) [12, 11].

Lack of understanding in the effects of using DCs: Solving the challenges associated with intelligibility and interactivity is the first step to designing DCs that can be used in real-world settings. Because the challenges have remained unaddressed, and it was not practical to implement DCs for real-world decision-making, there has been minimal effort made to understand the practical applications of DCs. For instance, there have been no specific studies conducted to understand the following questions: (1) When, how, and why can DCs be more useful than existing solutions? (2) What types of interaction design and visual presentation methods would better support DC users? And most importantly, (3) Can users overcome adoption barriers in using DCs and find DCs to be useful in their everyday spatial exploration and decision-making scenarios?

1.2 Thesis Contributions

The overarching goal of this thesis is to understand the practical implication of DCs as a new way to explore spatial information. To do so, this thesis offers *technical contributions* that enable the overcoming of DCs' interactivity and intelligibility challenges, *system contributions* that come from building the three systems for which the benefits and drawbacks of DCs can be evaluated, and *empirical contributions* from a series of case studies that provide deeper insights regarding DCs' usefulness and adoptability in the lab [2, 4] and in the wild [6].

1.2.1 *Technical Contributions*

This thesis presents novel techniques devised to overcome the interactivity and intelligibility challenges. To overcome interactivity challenges, the thesis introduces two techniques: *Scalable Road-network Construction* (SRC) and *Quadtree Time-space Partitioning* (QTP). SRC adaptively simplifies the size of a network to a different degree depending on a user's zoom level, while QTP improves upon the limitations of SRC using a quadtree structure to enable the construction of scalable systems that can present fully interactive DCs that visualize accurate traffic information in real time. This thesis introduces two other techniques devised to resolve intelligibility challenges: *Geo-contextual Anchoring Projection* (GAP) and *Shape-retaining Geo-contextual Anchoring Projection* (S-GAP). GAP enables the construction of a DC that can maintain topological relationships of an underlying network. S-GAP improves on GAP by both preserving the topological relationship of a network *and* minimizing the distortion of shapes while visualizing accurate travel times.

1.2.2 *System Contributions*

I present detailed design features of the three versions of a system named *Traffigram* which is built to enable users to interact with DCs (some details for each version of Traffigram are shown in Table 1.1). The first version constructs DCs using a small size road network (107 nodes and 435 edges) to represent a simplified structure of the greater Seattle area. The system offers basic map interactions such as map panning. However, map interaction types necessary for full spatial exploration, such as zooming, are missing. The second version uses a much larger and more detailed three-class layered road network that entails 8,530 *pathways*, which are a linked list of nodes representing roads in OpenStreetMaps (includes 66205 nodes) to construct DCs in the same bounding box used in the first version. This version offers map interaction types necessary for

Table 1.1. Major features of Traffigram Ver. 1.0, 2.0, and 3.0.

	Method for a time space construction	**Method for projecting a time space on maps**	**Map interaction types ***
Traffigram Ver 1.0 [6]	Shortest path based on a road network (107 nodes and 435 edges)	Vector shifting methods used in previous works (e.g., [18, 19])	Map panning
Traffigram Ver 2.0 [1]	Shortest path based on Scalable road-network Construction (SRC, contains 8,530 pathways (a linked list of nodes in OSM) and 66,205 nodes)	Geo-contextual Anchoring Projection (GAP) [1]	Map zooming, switching
Traffigram Ver 3.0 [9]	Quadtree Time-space Construction (QTP)	Shape-retaining Geo-contextual Anchoring Projection (S-GAP) [9]	Highlighting, changing mode-of-transportation

* Later versions present map interaction types of the previous versions.

spatial exploration, such as zooming or panning, using SRC. This version also uses GAP and presents DCs that preserve the network used for DC construction. However, the system cannot present live traffic information, which constrains its usefulness. The third version uses QTP which enables presenting accurate, live travel time information. It uses S-GAP and offers a series of map interactions specifically designed for supporting users who use DCs to explore spatial information.

1.2.3 *Empirical Contributions*

Finally, I report on the empirical findings that demonstrate DCs' usefulness and adoptability through a series of studies conducted in the lab [6, 1] and in the wild [9]. In the lab studies, I focused on understanding how DCs can improve existing solutions in a few specific ways. For example, I found using DCs significantly improved the accuracy of decoding travel time in a significantly shorter amount of time than when done using a Web Mercator map (WM) with color-coded road segments [6] or a WM map that shows travel time with text alongside map markers [1]. The studies also found participants preferred the visual *glanceability* and *filterability* of places facilitated by DCs more than traditional maps solutions because they allowed for quicker estimations of travel time [6, 1]. In a four-week deployment study, I evaluated whether people find DCs useful in real spatial decision-making contexts and whether the perceived benefits of DCs can overcome the adoption barrier. The results show that participants quickly became familiar with DCs' distorted presentation. As they had more exposure to DCs, they gradually identified more use case types where using DCs helped them attain better place searching performance. Perhaps the most intriguing finding is that the participants mentioned that using DCs helped people pay more attention to travel times and *changed* their mental representation of distances in the city [9].

1.3 THESIS OUTLINE

Chapter 2 presents a review of related work that attempt to visualize travel times on cartographic layouts. The chapter introduces approaches to visualizing travel time onto maps and analyzing these approaches to compare and contrast them with the unique opportunities that DCs can offer to their users (§ 2.1). The chapter goes deeper into the approaches of DCs and identifies the problem space of this thesis (§ 2.2).

Chapter 3 introduces and describes the Scalable Road-network Construction (SRC) and Quadtree Time-space Partitioning (QTP) methods used to tackle interactivity challenges in DCs. The chapter starts with elucidating SRC (§ 3.1). Then the chapter discusses the limitations of SRC and introduces QTP, which improves upon SRC (§ 3.2). Finally, the chapter concludes with the performance evaluation between SRC and QTP.

Chapter 4 presents the two techniques named Geo-contextual Anchoring Projection (GAP) and Shape-retaining Geo-contextual Anchoring Projection (S-GAP), which improve the intelligibility of DCs. The chapter starts with an introduction to GAP for preserving topological relationships in DC construction (§ 4.1). Next, the chapter presents S-GAP, which improves on GAP by preserving topological relationships as well as shapes to a certain extent (§ 4.2). The chapter also presents performance evaluation results between SRC and GAP (§ 4.3).

Chapter 5 introduces formative studies that I conducted in order to understand the interaction design of DCs. DCs are relatively novel map visualization methods to majority of users. A critical barrier to lowering the bar to DC usage is the general lack of familiarity with the map type. This chapter addresses and presents an evaluation of how we can overcome this barrier. The chapter starts with methodologies that I used in the formative studies (§ 5.1). Next, the chapter documents and describes the interaction types identified to be useful for DCs (§ 5.2).

Chapter 6 presents the three versions of a system named Traffigram. Specifically, the chapter introduces design processes and core features of the Traffigram version 1.0 (§ 6.1), version 2.0 (§ 6.2), and version 3.0 (§ 6.3) in sequence. The chapter focuses on the sequential development of improved versions based on the techniques and interaction improvements introduced in chapters 3, 4, and 5.

Chapter 7 presents findings from a series of empirical studies conducted to understand the impact of using DCs. For example, how can using DCs with the new systems make a difference from using other types of maps? The chapter starts by describing methodological details and results from laboratory-based studies (§ 7.1). Traffigram version 1.0 and 2.0 are used in these studies. Next, the chapter introduces the results of a deployment study that uses version 3.0.

Chapter 8 concludes this thesis with a review of research contributions (§ 8.1) and limitations of the thesis (§ 8.2). Findings in my thesis research suggest that offering adaptive presentation of information depending on the users' spatial information seeking context can result in better support for their spatial exploration tasks. Based on these findings, the chapter also introduces a series of future research directions that can enrich people's spatial exploration experience (§ 8.3). Finally, I finish this thesis with conclusive remarks (§ 8.4).

Chapter 2. RELATED WORK

Maps are an essential resource that people use to find and learn spatial information. Steady progress in spatial data infrastructure, GPS accuracy, and computational power has allowed researchers to introduce a variety of ways to visualize spatial information on maps to support users' diverse information needs [2]. In this review, we start by analyzing different approaches related to visualizing travel times onto maps and by identifying the unique opportunities that DCs can offer to their users. Next, we review approaches in DCs and the problem space of this thesis.

2.1 VISUALIZATION OF TRAVEL TIME ON MAPS

Based on the review of the techniques attempting to visualize travel time on a cartographic layout, I suggest two notable factors that characterize perceptual strengths and weaknesses of the techniques for presenting travel times on cartographic layouts. These are (a) *geographic fidelity*, or whether the technique *distorts* the map so that it has an appearance unlike that of which is expected in a traditional navigational map (e.g., Web Mercator projection in Google Maps) and (b) the *origin* from which users can obtain accurate distance measures. Based on these two factors, existing techniques can be categorized into groups. Table 1 shows the four categories.

Table 2.2. Categorization of travel time visualizations on maps

	Map is not distorted	Map is distorted
Origin is not specified	Group 1: Color-coded roads [13, 14], heat map [15], sinusoid curve roads [17]	Group 2: MDS based approaches [18, 79]
Origin is specified	Group 3: Free-form isochrones [21, 22]	Group 4: Distance Cartograms using circular isochrones [6, 19, 22]

2.1.1 *Group 1. Distortion is not applied, Origin is not specified*

The techniques in Group 1 neither warp common conformal maps (such as a WM) nor require a single specified origin. The general technique in this category is to visualize traffic along specific paths by encoding road segments with distinct hues to represent the ordinal level of travel speed and points with distinct symbols to identify travel impediments [13, 14], which is the most widely used approach in real settings. Alternatively, heat maps that color-code traffic conditions of a given area on maps can be used [15] (e.g., Fig. 2.1 (a) [16]). Replacing each road segment with a sinusoid curve (the curve's amplitude and frequency indicate the amount of travel time) is another approach in this group [17] (e.g., Fig. 2.1. (b)). In this map type, a user can perceive traffic conditions of specific roads or areas [13]. However, users cannot determine an exact travel time with this map type unless additional cues, such as text, are provided. This limitation is closely related to the visual channels being used to encode travel times. People can merely decode an ordinal level of accuracy when the quantitative information is encoded with colors, patterns, or glyphs [7].

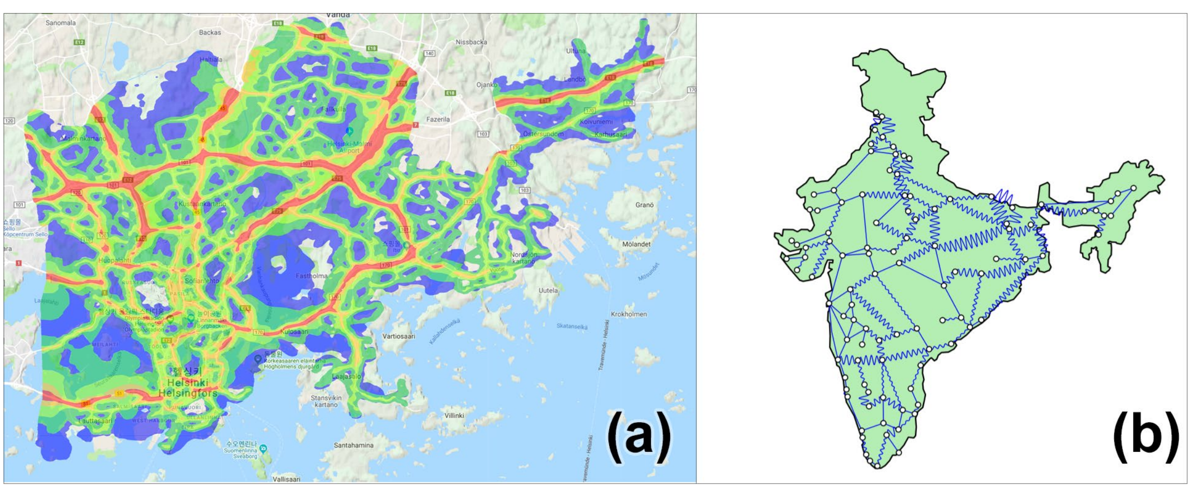

Figure 2.1. Visualization of travel time in Group 1. (a) **Heat map:** Traffic Visualization in Helsinki during day time [16], (b) **Sinusoid railroads** of Indian railroad [17]

2.1.2 *Group 2. Distortion is applied, Origin is not specified*

The techniques in Group 2 distort the map without a single specified origin. The idea behind this type of map is to alter every location's position so that the distances between any origin-destination pair reflect the travel time to the most accurate extent possible. Using distortions, these techniques decode travel times using the visual channel of a *position*, which can deliver the quantitative information with the highest accuracy. Multi-dimensional scaling (MDS) has been widely adopted to shift locations, and a variety of applications have been suggested [18]. With such approaches, a user can see travel times between multiple locations at once using techniques in Group 2. However,

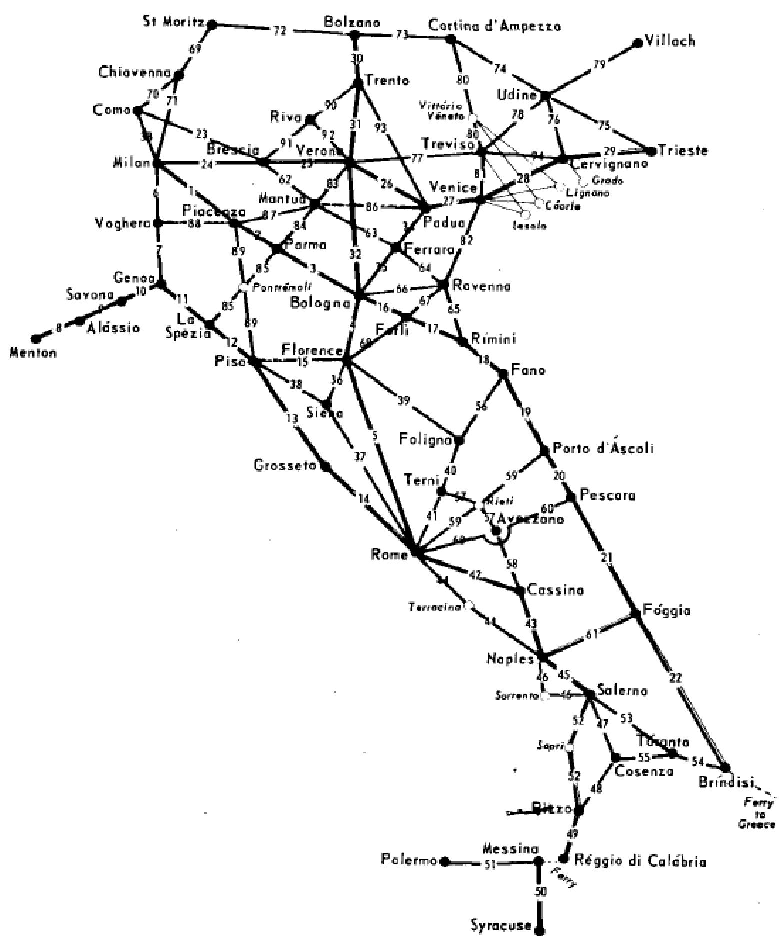

Figure 2.2. "Road cartogram" that visualizes distances between the cities of Italy [42]. The length of the roads does not visualize the actual distances between cities accurately.

projecting accurate travel time in a Cartesian plane is generally not possible. For instance, shifting four geographical points on a map with six pairwise distances based on travel times cannot be embedded in the plane [19]. In general, MDS compromises the accuracy of distances between the locations to present a result in a Cartesian plane [20]. In addition, the travel path from one point to another is not a single straight line, and a user may not be able to immediately decode travel time from one's departure point to the destination.

2.1.3 *Group 3. Distortion is not applied, Origin is specified*

The techniques in Group 3 present travel times from a specified origin without warping the map. The widely used technique deploys free-form isochrones with each isochrone indicating a specific travel time from an origin [21] (e.g., Fig. 1.1. (b)). With this approach, travelers determine the approximate travel time from the origin to each location [22]. Still, travel times are only accurate when the destination-of-interest falls exactly on an isochrone because travel time between two contours is not linearly interpolated. Consequently, a user can only estimate the travel time to any location that is not on isochrones. For example, a travel time to a point located between 10 and 20 mins. isochrones can be 11 or 19 mins., or any time in-between.

2.1.4 *Group 4. Distortion is applied, Origin is specified*

The techniques in Group 4 distort the map around a specified origin. This approach is known as Distance Cartograms [18]. Unlike the approaches in Group 3, DCs use circular isochrones which present travel times with linearly interpolated *time space*[1] around the origin [6]. This characteristic ensures that the distances between the origin and the destinations are *identical* to the actual travel time between them (e.g., Figure 2.3 (b)). DCs encode the quantity of travel time to multiple destinations via a position in an aligned manner from a single origin. DCs can position features on a map without error (unlike Group 2), and a reader can decode travel time information with a higher degree of accuracy than one can with the approaches in Group 1, 2, and 3.

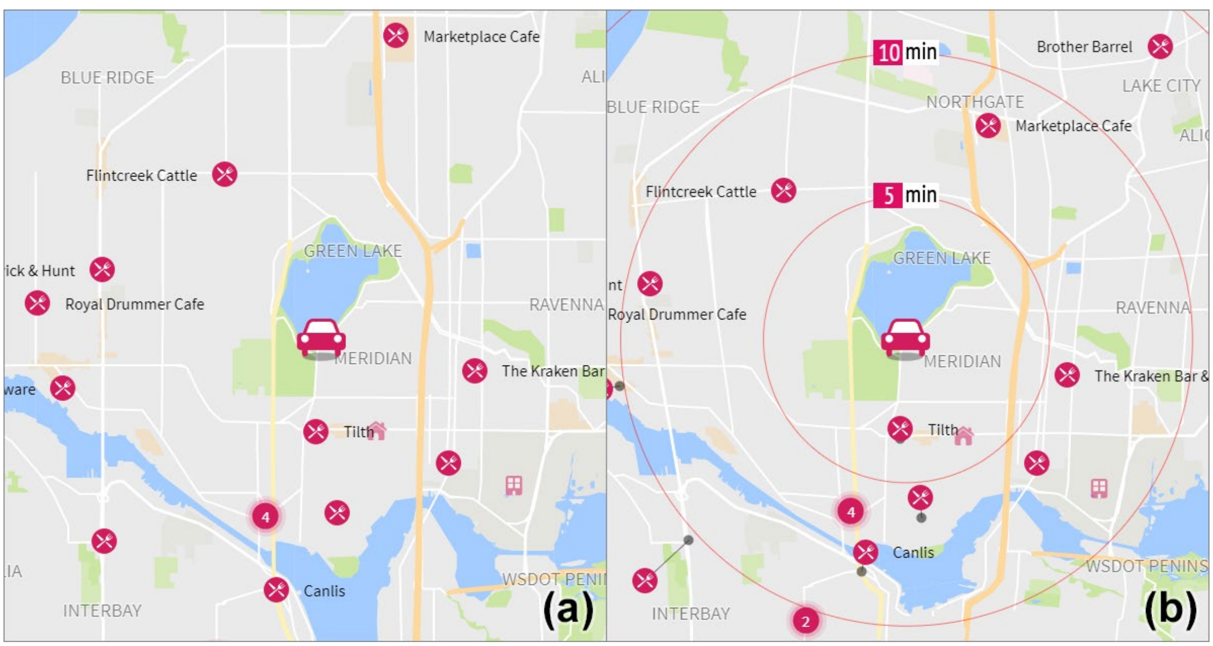

Figure 2.3. Restaurants around Green Lake in Seattle presented with (a) a Web Mercator (WM) and (b) a DC built based on S-GAP. Using the DC, a reader can visually see travel times from an origin (the car icon) to multiple locations.

[1] The space that presents the shortest travel times from an origin to the rest of the nodes.

2.1.5 *Perceptual trade-offs between the four categories*

Through this analysis, I investigated the strengths and the weaknesses of the techniques in the four categories. In presenting travel times on cartographic layouts, the design decision on whether to distort the maps or not is closely related to choosing which types of a visual channel to encode travel times. Maintaining the geographical fidelity means that the visual channel of the position on the screen will be used to precisely encode geocoordinates (i.e., latitude and longitude). Because the position channel is already taken for encoding geocoordinates, using alternative visual channels, such as a color, may be required to represent travel times (e.g., visualizations in Group 1 and Group 3). On the contrary, by distorting maps, one may use the channel of position to encode travel times (Group 2 and Group 4). Approaches that attempt to preserve the physical aspect of the globe would provide a more familiar looking map. But users may not be able to decode precise time information or may need to expend more effort to decode travel time. On the contrary, the other approaches that distort maps would allow readers to more easily and accurately decode travel time. However, the approaches that distort maps would not be suitable for supporting the tasks that need identification of the exact location, such as navigation to a specific place.

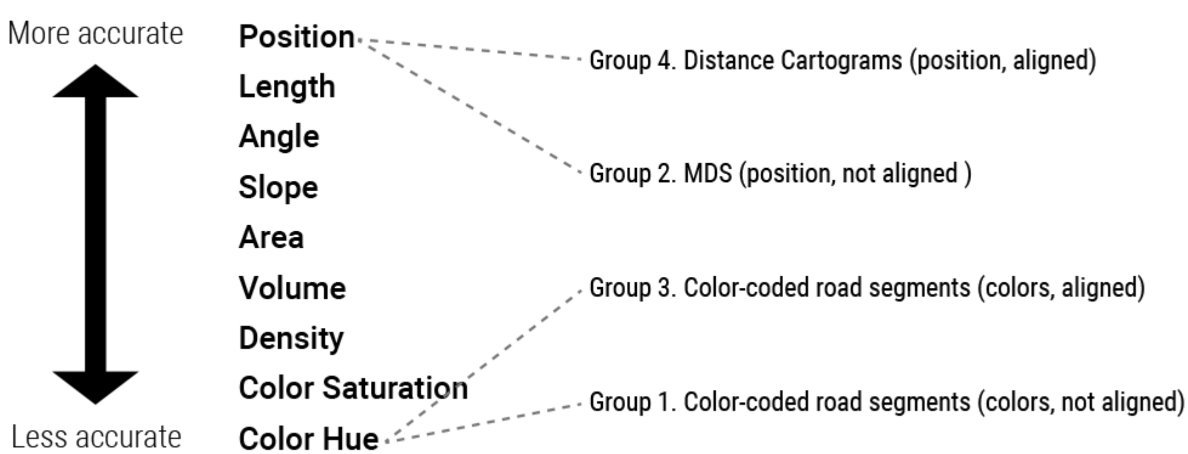

Figure 2.4. Mapping the visual encoding channel's accuracy rankings (for perceptual tasks) [7] and travel time visualization group categories

The second design decision one can consider for presenting travel times on a cartographic layout is the specification of the origin; whether the map would provide travel times from a single point, or attempt to show travel times from any location to any other location on the map. In general, specifying a single origin enables visual alignment of travel time information. For example, users may be able to compare travel times to multiple points using Fig. 1.1 (a) or (b) using colors or positions. The same tasks would not be as easy when using Fig. 2.1 (a) or (b) as readers need to mentally sum the travel time from one point to multiple points. Specifying one origin may allow users to decode and compare travel time from that origin to multiple places *at a glance* (e.g., Group 3 and Group 4). Although readers can still estimate travel time from one place to another using visualizations that do not provide a single origin, it may be more complicated to estimate and compare the travel times using such approaches.

The perceptual trade-offs in terms of presenting travel times between the four categories are aligned with Mackinlay's perceptual accuracy ranking [7]. Approaches in Group 4 encode travel time using position and visually align such information from a single origin, which shows the highest ranking. Approaches in Group 2 also use position, but edge lengths sometimes cannot accurately represent travel time. Approaches in Group 3 encode travel time using colors from a single origin, but colors have limited accuracy in terms of delivering quantitative information than positions do. Finally, Group 1, which has the most widely used approaches in real settings, has the lowest accuracy, as it cannot encode travel time information with position, and cannot align information from a specific point.

Through the analysis, I conclude that such characteristics of DCs can be suitable for supporting users who aim to evaluate and compare the cost of travel time. However, projecting travel time information onto a Cartesian plane using the layout of a DC presents a series of challenges. The following subsection goes over the research and identifies such key challenges.

2.2 A Brief History of Distance Cartogram Research

Thoughts of transforming physical distances into "time distances" first appeared in 1929 in "Theory of the Location of Industries" written by Alfred Weber [23]. As a formal research topic, DCs have been studied in the field of geography since Bunge and Tobler introduced the concept in 1960 [8, 24]. Tobler's early work presents a DC of Seattle with circular isochrones denoting locations that can be reached from the map origin in the same travel time. These DCs assumed that travel times are distributed continuously across space. Angel and Hyman soon discovered, though, that the times are distributed *discontinuously* across space [25]. Even if two given points are physically located in close proximity, travel times from an origin to other points on a map can differ greatly. Two factors are known to contribute to the discontinuity of time space. They are that (a) the Euclidian distance (also known as crow's distance) and the time distance between two locations are generally different [21] and that (b) the uneven traffic will lead to variation in travel time [6].

The notable implication of such a time space's discontinuity is that such characteristics make it impossible to preserve "*geographic neighborliness*" [26] between map features, which can greatly confuse users when reading information as we saw in Fig. 1.2. As a matter of fact, projecting the discontinuous time distances onto continuous Cartesian plane without destroying the planarity of external representation of a DC is not possible, which would make it hard to interpret information. As Dorling noted, "where the travel time space is *inverted*, however, even depiction of a single point may not be possible" [20]. Mainly due to such limitations, DCs have received relatively less attention than other techniques that distort geography to better present of some target information – such as area cartogram – at least until the early 2000. There are only a few studies focusing on DCs, including Muller's "polar isochrone maps" that showed time distances of Edmonton (the capital of Canada's Alberta) in 1978 [26], compared to numerous approaches proposed in area cartogram research [10].

In recent research, DCs have been more actively studied since the early 2000s, in part due to developments in internet capabilities, open data sources, and increase in computational power. As an example, Tom Carden introduced Travel Time Tube Map, a web application based in London that shifts a position of every station based on a travel time from a specific origin in 2005 [27]. In 2009, Shimizu and Inoue represented a network of major Japanese cities (as nodes) and their connections (as edges) using elapsed train travel time in their "time-space map" [18]. In arranging the length of each edge, they combined MDS and network time-space mapping to minimize the discrepancy between the travel time and the actual distance to preserve spatial integrity. Bies and Kreveld suggested techniques called Quasi and Dynamic Delaunay Triangulation to visualize inter-city travel time using the train system in the Netherlands [19] in 2012. Finally, Ullah and Kraak suggested a computational pipeline that represents the Dutch railroad system using DCs (or "time cartogram" in this work) in 2014 [22].

The existing research demonstrated the potential usefulness of DCs. At the same time, the results of the research highlight limitations that have hampered researchers from understanding the possibility of DCs as a solution that people can use to explore spatial information and make decisions in realistic settings. The limitations are:

- **Lack of approaches to construct DCs for "unscheduled" mode of transportation**: Previous studies tend to focus on visualizing travel time for scheduled transportation systems such as trains or subways. Visualization of travel time that is impacted by the unknown or inconsistent traffic patterns from unscheduled transportation systems (e.g., personal vehicles) was left for future work [22]. Building DCs that visualize travel time for unscheduled transportation types (e.g., vehicles) can benefit users in urban areas, where highly variable and ever-changing traffic conditions result in increased travel time uncertainty [6]. However, there has been no specific research for building interactive DCs for unscheduled modes of transportations. Constructing DCs for scheduled modes of transportation means the system can pre-calculate time spaces because the travel times to other places (e.g., subway stations nearby) will not vary over time. However, the visualization of unscheduled mode of transportation entails construction of a time space on-the-fly, which entails high computational expense. Moreover, existing studies indicate that visualization of unscheduled transportation would result in introducing further distortion from a DC for scheduled modes of transportation, which can confuse readers. Therefore, I propose techniques required to overcome such issues in this thesis in § 3 and § 4.

- **Lack of understanding of useful map interaction types for DC users:** The majority of approaches focus on improving algorithmic performance [18] or devising a method for constructing a static DC [6]. Yet, there are few approaches that frame DCs as an interactive feature that a user can use on-the-fly when exploring spatial information. Consequently, little effort has been made on understanding the interaction design of DCs. Having an understanding of this interaction is important in guiding users to efficiently and effectively explore spatial information and is critical to lowering the barrier of adopting DCs. Therefore, I conduct formative studies to understand the interaction designs of DCs and report on the findings and the interaction design outcome in § 5.
- **Lack of empirical investigation to understand the effects of DCs**: Finally, there has been relatively little attention paid to understand (a) the perceptual and cognitive benefit of using

DCs over existing solutions (e.g., how DCs can improve task efficiency, effectiveness, ease of use in controlled situations), as well as (b) DCs' practical implications in the wild (i.e., how DCs can improve people's spatial exploration in real settings). Therefore, the thesis introduces the systems built for study apparatus or tools for spatial exploration in real settings in § 6 and report findings in § 7.

Chapter 3. TOWARD INTERACTIVE DISTANCE CARTOGRAMS

In this chapter, I introduce two techniques named Scalable Road-network Construction (SRC) and Quadtree Time-space Partitioning (QTP) that are devised to enable interactive DCs. To identify the fundamental challenge in building interactive DCs, I briefly review the general process for constructing a DC used in previous works (e.g., [18, 19, 22]) in §3.1. Next, I introduce how SRC improves the existing process in §3.2, (introduced in [1]). In §3.3, I discuss some limitations of SRC and how QTP can improve SRC (introduced in [9]). Finally, I introduce benchmark results between SRC and QTP in §3.4.

3.1 CONSTRUCTION OF DISTANCE CARTOGRAM

Building DCs is the process of distorting the *physical space* (the space that represents geographic reality) in order to present the *time space* (the space that represents travel time from the origin to every location) on 2D space [6]. In general, existing approaches follow the pipeline below:

- **Step 1.** A *network* of a target area is built, which is typically a simplified road network [18]. The network includes *nodes* that present geographical locations of an area, and *edges* that indicate connections between the nodes (see Fig. 3.1 (a)).
- **Step 2.** A *time space*, which presents the shortest travel times from an origin to the rest of the nodes, is computed. To construct the time space, the pipeline sets the cost for traversing each edge based on the travel time between the two nodes that make the edge (Step 2-1, see Fig. 3.1 (b)). Then the pipeline runs the shortest path algorithm from the origin (Step 2-2, see Fig. 3.1 (c). e.g., [6, 18]).

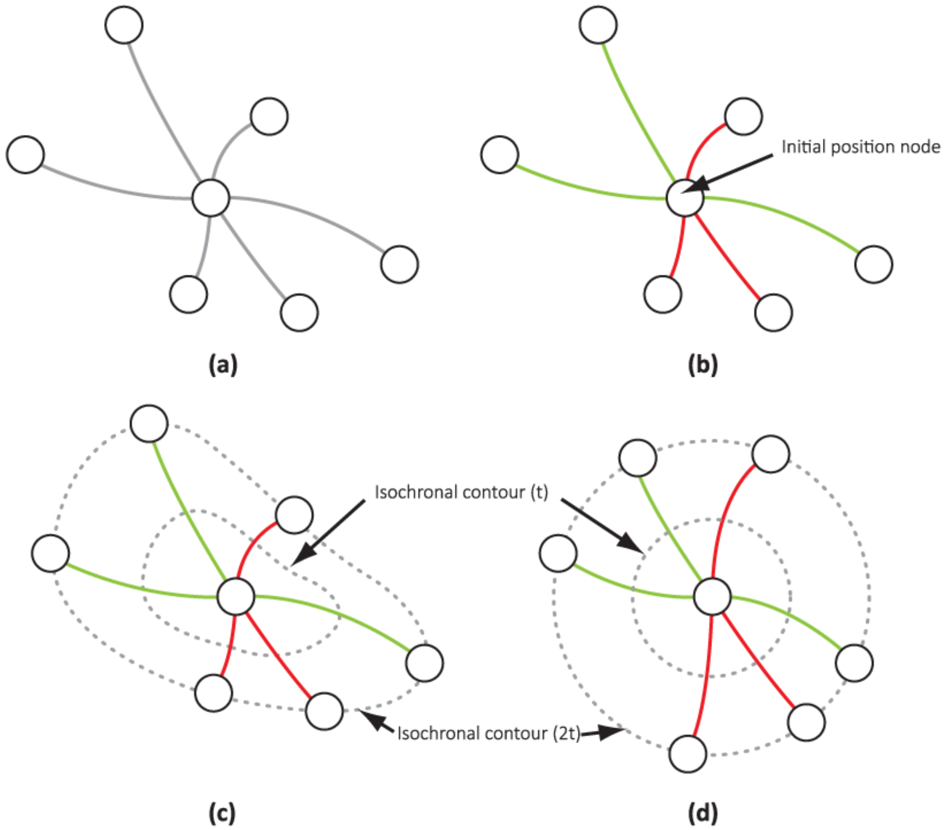

Figure 3.1. A general process for building a DC: (a) Network construction (b) Edge traverse cost updating based on travel time information (c) Yielding a time space based on the shortest travel time from an origin to the rest of the place, and (d) applying distortion

- **Step 3**. Every node on a network is *shifted* based on the time space so that the distances between an origin and locations on a map indicate travel time between them [1]**.** There can be diverse ways for shifting nodes. For instance, warping algorithms such as Delaunay triangulation [28] or Thin Plate Spline [29] can be used.

The fundamental challenge in building an interactive DC is the required computation cost for building a single DC. Implementing an interactive DC means the construction of a time space per each map user interaction, such as map panning or zooming in real time. However, building a time space typically requires finishing the execution of a shortest path algorithm from an origin (e.g., [30]), which is known to be computationally expensive. For instance, Dijkstra's algorithm, the most widely used algorithm in DCs, has $O(n^2)$ complexity[31][2]. Dynamic Delaunay Triangulation requires $O(n^3 \cdot 2^{\alpha(n)})$ in cost ($\alpha(n)$ is the "slowly growing functional inverse of Ackermann's function") [19]. Because of the high computational costs, presenting basic map interaction types such as panning or zooming can become challenging [1]. To date, none of the existing techniques present a DC based on accurate live traffic information in real time.

3.2 Scalable Road-network Construction (SRC)

To build an interactive DC readily used by users, it is required to construct a time space within a certain time threshold. To achieve this, it is necessary to curate the number of nodes and edges to a certain degree so that the system can finish the execution of the shortest path algorithm within the given time. However, the size of a network can quickly grow larger than a system can handle within the given time, especially when considering the complex road networks of urban areas. The goal of SRC is to automatically derive a *key network* that can well represent a given area from a raw road network. The derived key network should (a) capture major features of a raw road network so that a user of a DC can easily interpret the notable spatial features and (b) maintain an adequate number of nodes and edges to ensure a reasonable response time when the construction of a DC is requested from a user. Map generalization researchers studied abstraction and simplification of road networks for decades [32]. It is still an open problem, and such methods should be specifically customized based on the intended purpose of a map [33]. In designing SRC, I see the following two principles as being closely related to achieving the goal. **P1:** when designing a map with distortion, presenting the accurate topological relationship between roads is critical [34]. **P2**: travelers perceive the urban space hierarchically [35].

[2] n refers to the number of nodes in a road network

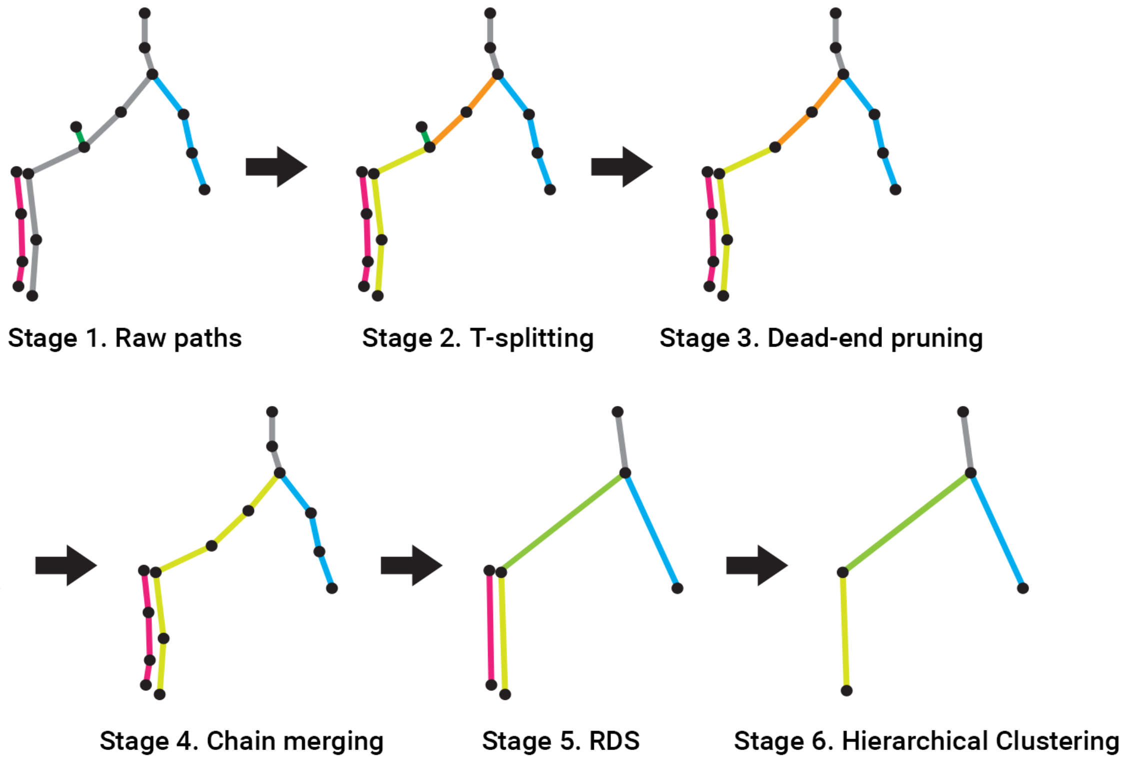

Figure 3.2. The computational pipeline of SRC

The SRC presents a key structure that has a different degree of detail depending on the zoom level a user specifies. The computational pipeline of SRC includes six stages which are: (a) Obtaining raw paths, (b) T-splitting, (c) Dead-end pruning, (d) Chained path merging, (e) RDS, and (f) Hierarchical clustering. The pipeline for SRC is illustrated in Fig. 3.2.

In **Stage 1**, SRC obtains a raw road network from OpenStreetMap (OSM). OSM provides one of the richest and most extensive open map data to the public, and the map features in OSM have been identified as reasonably accurate for general map users [36]. OSM includes diverse types of *pathways* (i.e., an ordered list of *nodes* used in OSM where each node is defined by longitude and latitude), such as highways, arterial roads, and bicycle roads. Among these, we collect the pathways related to vehicle traffic. They are: (a) *highways* (i.e., motor way and trunk – we call this **H class**), (b) *arterial roads* (primary, secondary, and tertiary roads, **R class**), and (c) *links* (links that connect different types of roads, **L class**). For testing the computational performance of SRC, I collected pathways in the greater Seattle area, between -122.440 and -122.075° longitude, and between 47.396 and 47.859°N latitude, which includes Seattle and 24 other cities. This resulted in a dataset of 8,530 pathways and 66,205 nodes.

In **Stage 2**, SRC *splits* the pathways obtained from OSM to enforce the rule that every pathway starts from or ends at the node where the *degree* (i.e., the # of connected edges in a node) is more than 3. This way, SRC can ensure preserving of the topological relationships during the simplification process in Stage 5. To do this, we split one pathway into two if one intermediate node between two terminal nodes appears in any other pathway (T-splitting). In **Stage 3**, SRC prunes short pathways that include a dead-end node for simpler presentation (we used 100 meters for the threshold). In **Stage 4**, we concatenate two pathways if one of the terminal nodes in each pathway is the same (i.e., has the same longitude and latitude), and none other than the two pathways in a network share a node.

In Stage 5 and 6, SRC starts modifying a key structure (i.e., adding or removing nodes in a pathway or shifting a node's coordinates). In **Stage 5**, SRC executes Ramer-Douglas-Peucker (RDP) line simplification [37] for each pathway. The purpose of RDP is to remove the intermediate nodes that are aligned in a straight line and prefers not losing much of geographical accuracy. We used 5 meters for the threshold. Finally, in **Stage 6**, we simplify the overall complexity of a key structure by merging a group of pathways that are either (a) highway ramps (i.e., pathways in L class start from or end at H class), (b) multi-lane roads, or (c) roundabouts. For each group, we use hierarchical clustering [38]. In this process, the two nearest nodes in the same group of pathways are merged into one. This process continues until distances between every two nodes are above the threshold. The result is shown in Fig. 5.3. Fig. 5.3. (a) shows the raw road network whereas Fig. 5.3. (b) shows the key network of a given area.

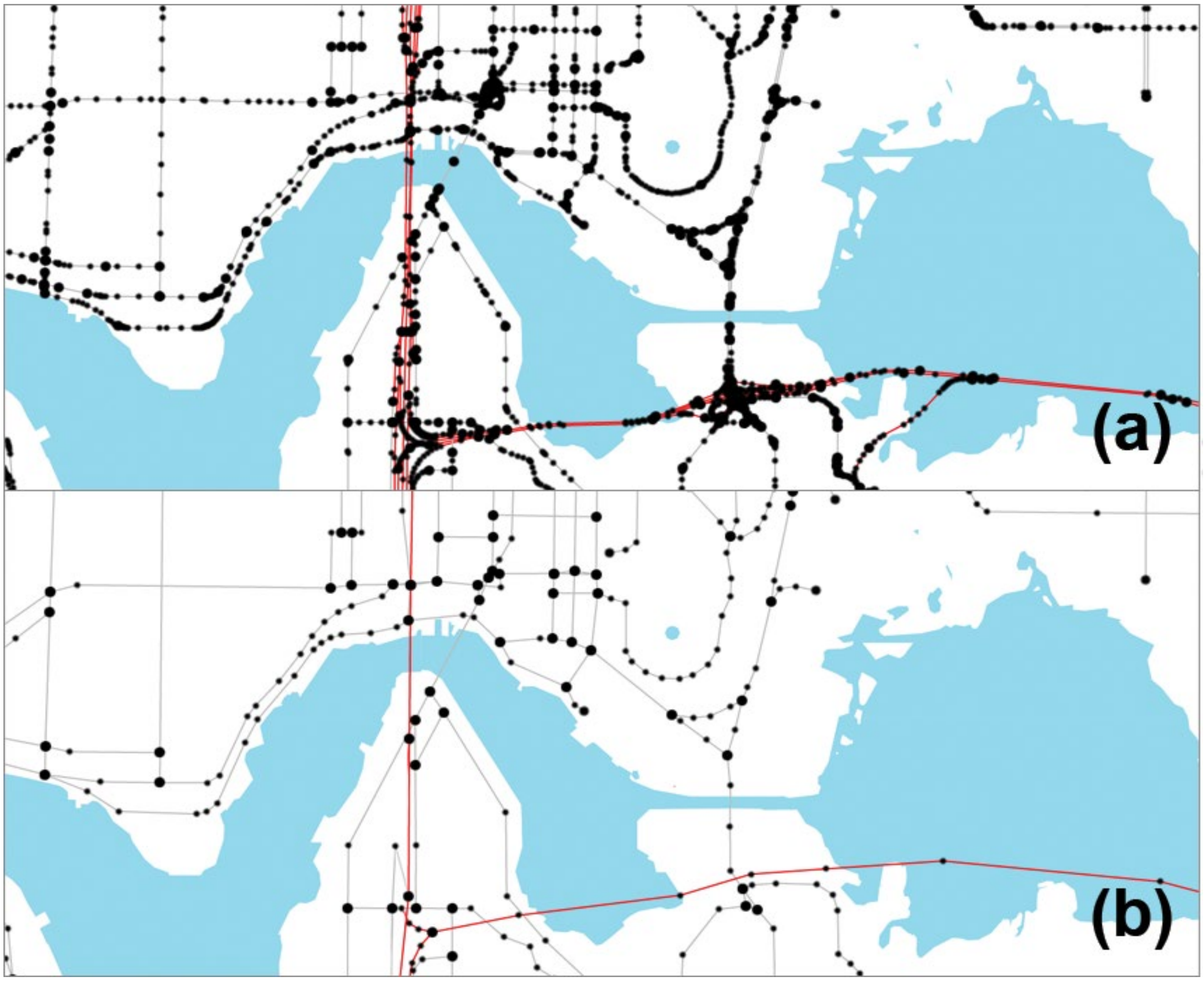

Figure 3.3. (a) A raw road network obtained from OSM, and (b) the derived key network using SRC. Red paths indicate the highways. Bigger nodes are the nodes that have a degree of 1 or over 3, and smaller nodes are the nodes with the degree of 2.

In developing an interactive system, SRC glues several types of pathways in different classes derived from SRC depending on the zoom level. With this class-based method, the key structure can present perceptually salient roads in a given area. It can also reduce the number of order (i.e., number of nodes in a graph) and size (i.e., number of edges in a graph) of a key network. Using SRC, it is possible to develop map interaction types such as zooming or panning. In this implementation, however, I note that SRC still needs pre-processing for (a) preparing a key structure and (b) calculating all pairs' shortest travel time of the given key network to smoothly present DCs in real time.

3.3 QUADTREE TIME-SPACE PARTITIONING (QTP)

SRC adaptively simplifies a raw road network to a different degree depending on a user's zoom level [1]. However, SRC has a couple of limitations as follows. First, applying SRC can over-simplify a network structure, which would cause inaccurate shortest path results (**Limitation 1**). Also, SRC executes all pairs of shortest paths for a network periodically to pre-calculate a time space [6] which results in presenting "frozen" travel time rather than capturing live traffic (**Limitation 2**). Finally, using SRC requires preparation of the network of a target area, which can impose an additional burden when developing a system that can present DC without the restriction of where an origin is located at (**Limitation 3**).

To resolve the limitations, I introduce *Quadtree Time-space Partitioning* (QTP), which enables time space construction that captures live traffic information without the restriction of where the location is at. The most notable feature of QTP is that it constructs a time space without relying on a road network and shortest path algorithms. Instead, QTP constructs a time space with a *quadtree grid* [39]. Pseudocode presented in Fig. 3.4 explains how QTP works. The first step in our pipeline is to construct a Cartesian grid G_{init} that spans the area presented on a screen (the grid made with the thickest strokes in Fig. 3 is an example of G_{init}). Then, for each rectangular *cell* in the G_{init}, QTP calls travel time API such as Google Distance Matrix API four times to get travel time from an origin *o* to the four corners of the cell. Based on the four travel times, QTP yields six travel time differentials between every pair (line #27 in Fig. 2). If any of the differentials exceeds a threshold θ_{time} (e.g., 4 minutes), this means that the traffic condition in the cell is uneven and

```
/* Step 1. Apply QTP to subdivide a Cartesian grid */
  G_init = constructCartesianGrid()
  G_QTP = new Array()
  o = getOrigin()
  for each cell in G_init
    QTP(cell, θ_time)
/* Step 2. Check how much of a shift to control points is
within a distortion threshold */
  CP_init = getInitialQTPGridControlPoint(G_QTP)
  CP_target = getTargetQTPGridControlPoint(CP_init)
  CP_S-GAP = new Array(length(CP_init))
  for w = 0 to 1
    for each (cp_init, cp_target) in (CP_init, CP_target)
      cp_S-GAP = cp_init * (1-w) + cp_target * w
     S_distort = distortCellwithCP(CP_S-GAP)
    if (S-GAP(S_init, S_distort) > θ_shape)
      break
/* Step 3. Apply distortion to map vector layers*/
  W_S-GAP = TPS(CP_S-GAP)
  W_target = TPS(CP_target)
  L_shape = getVectorLayersfromOSM()
  for each L in L_shape
    W_S-GAP(L)
  L_places = getPlacesLayerfromClientBoundingBox()
  AddAnchor(L_places, W_S-GAP, W_target)
/* Functions*/
  function QTP(cell, θ_time)
    for each pair of two points p_a and p_b in cell
      if (|time(o, p_a) - time(o, p_b)| > θ_time)
        S = subdivideCell(cell)
        for each subcell in S
          QTP (subcell, θ_time)
        break
    G_QTP.add (cell)
  function S-GAP(S_init, S_distort)
    [a, b] = getFFTCoefficients(S_init)
    [a', b'] = getFFTCoefficients(S_distort)
    return getDistance(a, a', b, b')
```

Figure 3.4. Pseudocode of QTP

finer granularity should be applied to yield an accurate time space. In such case, QTP *subdivides* the cell into four *subcell*s (see line #29 in Fig. 3.4) and recursively runs the travel time differential check routine on each *subcell*. In examining a subdivision, Ray-casting [40] can be applied to identify whether four corners in a given cell are located above the land. Point(s) located over the water can be excluded in yielding paired travel time differentials. Running QTP will result in building the Quadtree grid G_{QTP}.

Applying QTP can overcome the three limitations that SRC has. First, QTP applies a different degree of cell subdivision depending on the degree of traffic congestion of the areas shown on a map. Some areas with traffic congestion would be subdivided into several sub cells, which enables capturing travel times in a fine-grained manner (e.g., three depths of recursion are applied in "Downtown Seattle" in Fig. 3.5). On the other hand, areas with less traffic would be subdivided

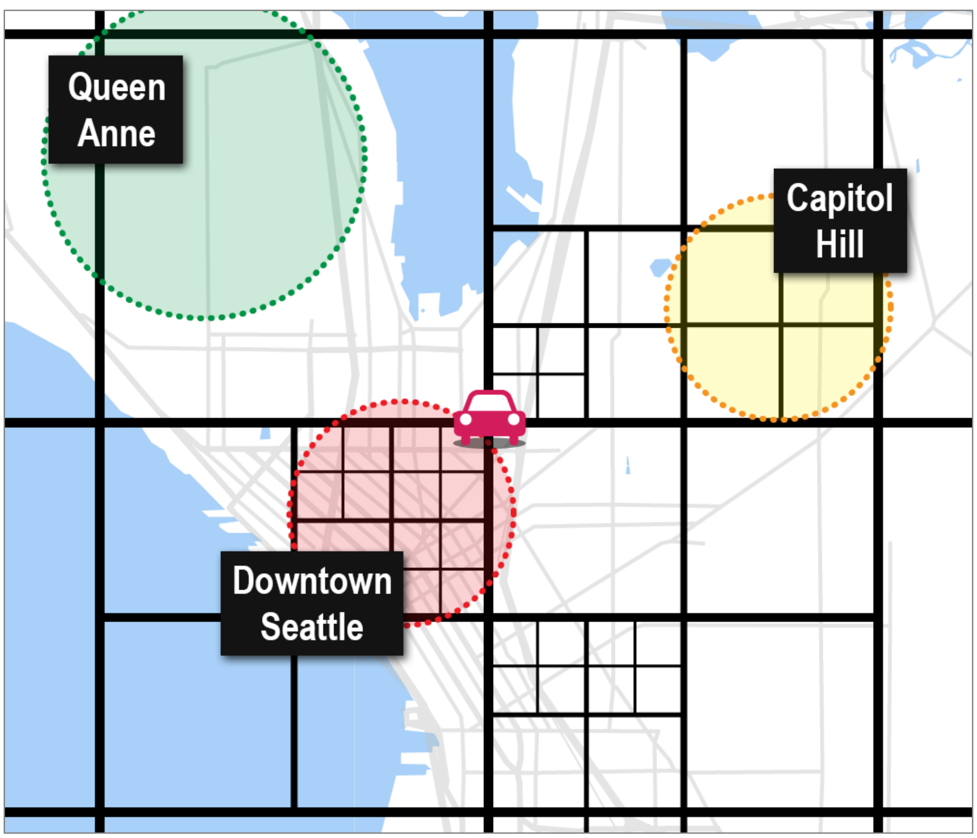

Figure 3.5. (a) A Cartesian grid (the grid with the thickest lines) and subdivided cells ($\boldsymbol{\theta_{time}}$ = 4 minutes).

with fewer cells (e.g., no recursion is applied at "Queen Anne" in Fig. 3.5). Such recursive subdivision can reflect traffic of a given area in an accurate manner (overcomes **Limitation 1**). I note that there is a trade-off between the accuracy of a time space and the amount of time it takes to yield a time space; tighter θ_{time} for a cell subdivision will create a more accurate time space while resulting in increased response time with more recursions. Second, QTP can construct a time space within a few rounds of API calls, which enable on-the-fly time space construction with live traffic information (overcomes **Limitation 2**). Finally, QTP does not rely on a pre-defined road network structure (resolves **Limitation 3**).

3.4 PERFORMANCE EVALUATION

3.4.1 *Methodology*

Among the three limitations that QTP can address, two (Limitation 2: constructing DCs in real time based on live traffic, Limitation 3: without being limited by the origin location) are enabling features that have not been feasible in SRC. Thus, I compared the accuracy of time spaces constructed with QTP against those constructed with Scalable Road-network Construction (SRC).

In the performance evaluation, I compared the accuracy of time spaces built with QTP and SRC in 48 scenes, which reflect 3 different zoom levels (OSM zoom levels 11, 13, and 15) and 16 randomly chosen origins within a bounding box from 47.396°S, -122.440°E to 47.859°N, -122.075°W. For each of these scenes, we constructed a time space with SRC and QTP (allowing one depth of recursion). To generate a time space with SRC, we constructed a network that had three levels of hierarchy as suggested in [1]. Each of these hierarchy levels was used for constructing a time space of zoom levels 11, 13, and 15. Finally, we constructed 48 pairs (16 origins for each DC x 3 zoom levels) of time spaces for a single time (5pm on a Friday: 7/28/2017).

We chose a rush hour time as the traffic conditions make it more challenging to create accurate time spaces and incur more distortion than less congested times of the day (e.g., midnight) [6].

To measure the degree of accuracy of a time space, for each of the 48 scenes, we selected 30 random locations. While we were constructing the time space with QTP and SRC, we simultaneously collected ground truth travel time (i.e., the actual travel time) from the origin to each of the 30 locations in each scene using Google Maps [4]. For each pair of time spaces, we measured the mean absolute error (MAE) appearing between the 30 locations and the ground truth travel time for both the QTP and SRC generated time spaces.

3.4.2 *Results*

To see whether QTP constructed a more accurate time space than SRC, we ran a paired-samples t-test with 48 pairs of time spaces constructed with QTP and SRC. As a result, we found that the MAE in QTP (M=95.2sec., SD=105.59) was significantly lower than the MAE in SRC (M=431.5 sec., SD=439.52, t=5.154, p<.0001). A graph on the left in Fig. 3.6 shows MAE between SRC and QTP for each zoom level. Through the evaluation, we found QTP-generated time spaces to be more accurate than the SRC-generated ones. QTP time spaces had an average time error (to each destination) under 30 seconds in zoom level 15 (where a user can see every detail of each street), (M=27.7 sec., SD=4.83). In level 13 (a user can see multiple neighborhoods), the time accuracy error was still below one minute (M=58.1 sec., SD=24.84). However, the time error was greater than 3 minutes at level 11 (a user can see multiple cities, M=199.7 sec., SD=127.7).

3.5 Conclusion

The overarching goal of both techniques was to enable building interactive by improving the computational cost for building the time space. I first tackled this challenge with SRC, which was used as the basis technique to develop Traffigram 2.0 (I will introduce this in greater detail in § 6.2). Then I devised the second technique named QTP to overcome the three limitations that need to be solved for live deployment (QTP is used to develop Traffigram 3.0, which I will present the details for in § 6.3). We will discuss the limitations of the QTP in greater detail in the conclusion section.

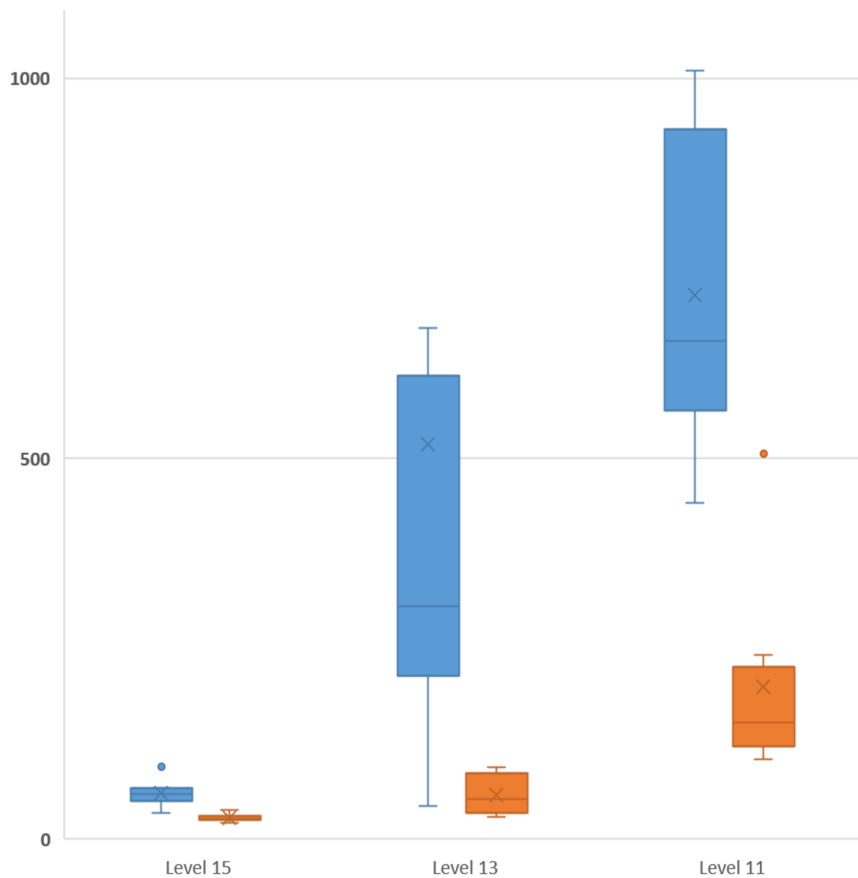

Figure 3.6. Performance evaluation

MAE (second) for SRC (blue bars) and QTP (orange bars)

Chapter 4. TOWARD INTELLIGIBLE DISTANCE CARTOGRAMS

In this chapter, I will briefly discuss how applying distortion on maps that attempt to retain physical distances, such as Web Mercator projection (WM), can confuse users and see how such *intelligibility* issues can also incur in DCs in §4.1. Next, I introduce the two techniques named Geo-contextual Anchoring Projection (GAP) and Shape-retaining Geo-contextual Anchoring Projection (S-GAP) devised to improve intelligibility of DCs in §4.2. Next, I explain S-GAP, an improved version of GAP in §4.3. Finally, I describe benchmark results between GAP and S-GAP in §4.4 and conclude the section in §4.5.

4.1 APPLYING DISTORTIONS ON MAPS

For anyone who has explored the many different projections of the Earth, it is easy to understand the difficulty of the cartographer's task of reducing three dimensions to two [41]. While there are challenges associated with people realizing that the landscape is not "accurate" as represented on a traditional map, it is important to realize that cartographers have been wrangling with this issue perhaps since the age of Anaximander, the ancient Greek cartographer, who first scribed such representations over 2500 years ago. With these efforts, many researchers have attempted to use unique geo-visualization methodologies to convey more insightful context to people and to enhance human perception and cognition [2]. In some cases, designers intentionally distort the maps that preserve spatial relationships such as distances or angles (e.g., Web Mercator maps) to improve the presentation of the *information-of-interest* [11, 42]. For example, Beck invented a map named schematic network map, which distorted the map of London to stress the underground connections between stations in his London tube map [43], which has been named *schematic* *network map*. Newman distorted state boundaries to be proportional to the amount of voting power each state had in the US presidential election maps [44]. Such a technique is called *area cartogram*.

While the approaches in area cartograms and schematic network maps use different strategies from those used in distance cartograms, all of these mapping types share a common goal. That is, to improve *information communication* via distorting reality while maintaining a user's geographical context [45]. Applying distortion on equidistant maps or conformal maps can be an effective way to visualize quantitative metrics tied in geography. But at the same time, researchers noticed that distortion can also negatively impact geographical integrity, perception, and usability. Kadmon [42], Guseyn-Zade and Tikunov [46], Kocmoud and House [12], Tobler [10], Li [34], and many other researchers have discussed desirable characteristics that can make usable, intuitive, and intelligible outcome. I analyzed their work and list the two notable characteristics that are directly related to map intelligibility in table 4.3: these are, preserving (a) topological relations between map features and (b) boundaries and shapes of the original maps.

In cartography, the term "topology" can be understood as spatial objects (i.e., the features in a map such as *points*, *lines*, and *polygons*) and the relationships between the objects (e.g., two *points* can be *connected*, or two *lines* can be *intersected*) [47]. Such topological relationships serve

Table 4.3. Categorization of travel time visualizations on maps

Principles	Quotes that Describes Desirable Properties
Preserve geographical topology	"Preservation of topology can help readers to understand the geographical context" [42] "Topological test is required prior to the modification of a vertex" [12] Appeared in **Invalid source specified.**
Preserve geographical shapes	"The most common are the outer boundary of the area be preserved, so creating a cartogram, the shape of which looks familiar" [20] "Preservation of the original geographical shapes to the extent possible" [12] Appeared in [20, 10, 12, 49, 51]

as a fundamental cognitive anchor that people rely on to establish the relationship between reality and the scaled map model [48]. However, if one uses a road network as a key structure to construct DCs, preserving the topological relationships of a key structure becomes a conundrum [22]. While shifting the nodes of the road network, however, a node can easily intrude on the adjacent nodes and edges and violate the topology of the key structure [20]. If these shifts intrude upon the adjacent nodes or edges in a key network and create a new intersection between edges, the topology of the key network is said to be violated, which can severely impair the map recognizability [20]. Fig. 4.1 demonstrates such possibility: Fig. 4.1. (a) shows the physical space, with a topology of a simplified key road network used in [6]. Fig. 4.1. (b) shows a node-shifted time space. In this figure, white nodes preserve the topological relationships and readers may easily infer the corresponding nodes between Fig. 4.1. (a) and Fig. 4.1. (b). However, the same task becomes

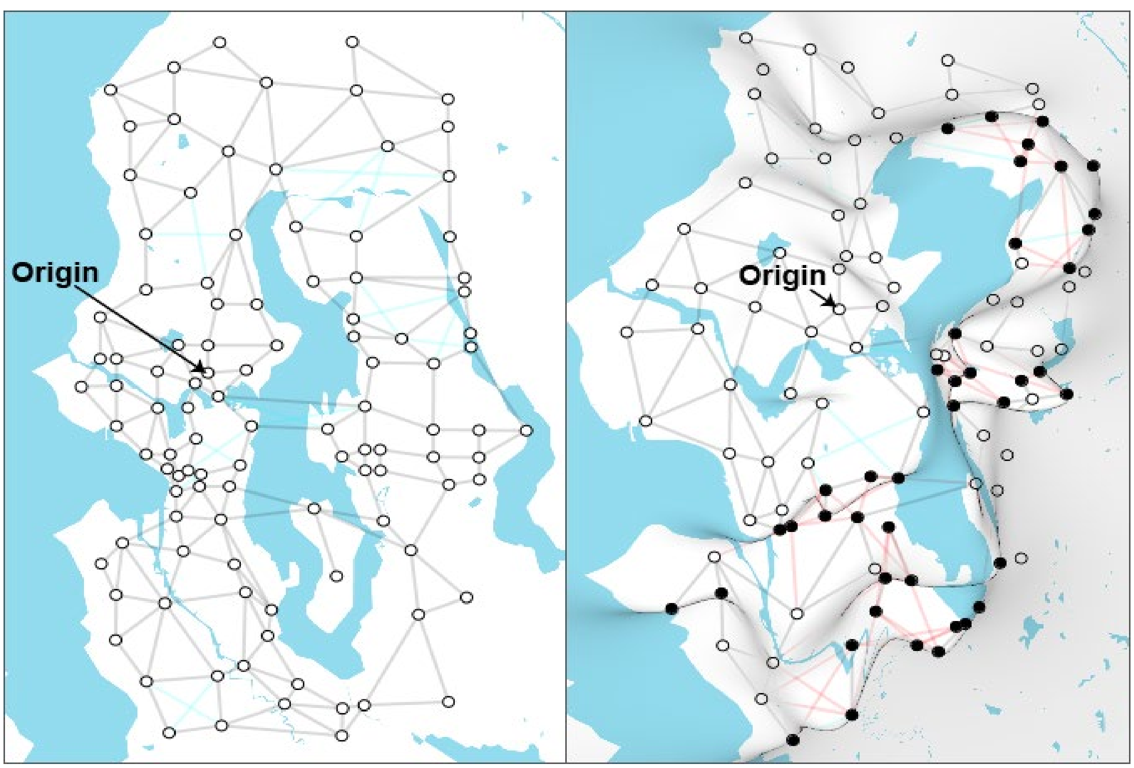

Figure 4.1. (a) A map projected using a Web Mercator. The key network in [6] was used (b) a DC and a rearranged key network: black nodes violate the topology of the structure.

nontrivial for the black nodes, which contribute to topological violations. Such violations mean that the node's position in a physical space is *inverted* in a time space; the *closer location* from the origin does not always mean *less travel time* to reach the location from the origin. Such violations make it impossible to project the time space without overlapping the map features. As Dorling stressed, "where the travel time space is inverted, however, even depiction of a single point may not be possible" [20].

Beside the topological violations, findings in previous works imply that distortion application in maps can result in introducing excessive deformation of shapes and make readers not be able to recognize the geographical shapes and locations they were once familiar with [34, 49, 50]. Fig. 4.2 shows such a possibility. The figure shows the result of area cartogram presented in WorldMapper that visualizes the death toll of each country for Malaria in 2016 [51]. While this impressive depiction dramatically stresses many people dying by Malaria in Africa, it is not easy to identify the boundaries of the countries located in North America, Europe, or Asia. Applying such amounts of distortion in DCs can confuse users who search for spatial information.

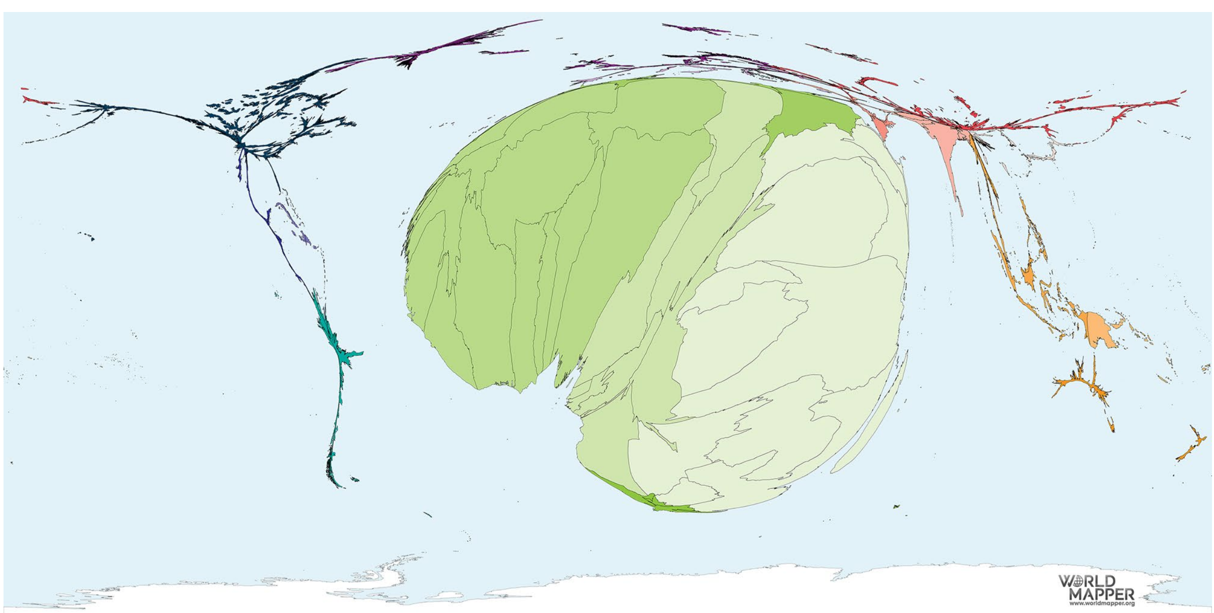

Figure 4.2. Death toll by Malaria in 2016, captured from WorldMapper

4.2 Geo-contextual Anchoring Projection (GAP)

Geo-contextual Anchoring Projection (GAP) is a method that impedes the occurrence of topological violations while shifting locations to build a DC. GAP shifts every node's position in a key network structure to its destination position without violating the topology of the key structure. The key idea is that the GAP iteratively moves each node from its initial position to the target position while preserving the topology of the network. If moving a node further would violate the topology, the algorithm stops moving the node and adds an *anchor* to visually mark the disparity between the stopped position and the target position. Fig. 4.3 presents the visual distinction between the result without GAP (Fig. 4. 3 (a)) and with GAP (Fig. 4.3 (b)). In Fig. 4.3 (a), the makers of "Space Needle" and "Bellevue Square" are presented with less transparency because uneven travel times cause topological violations, which lead some nearby areas to overlap

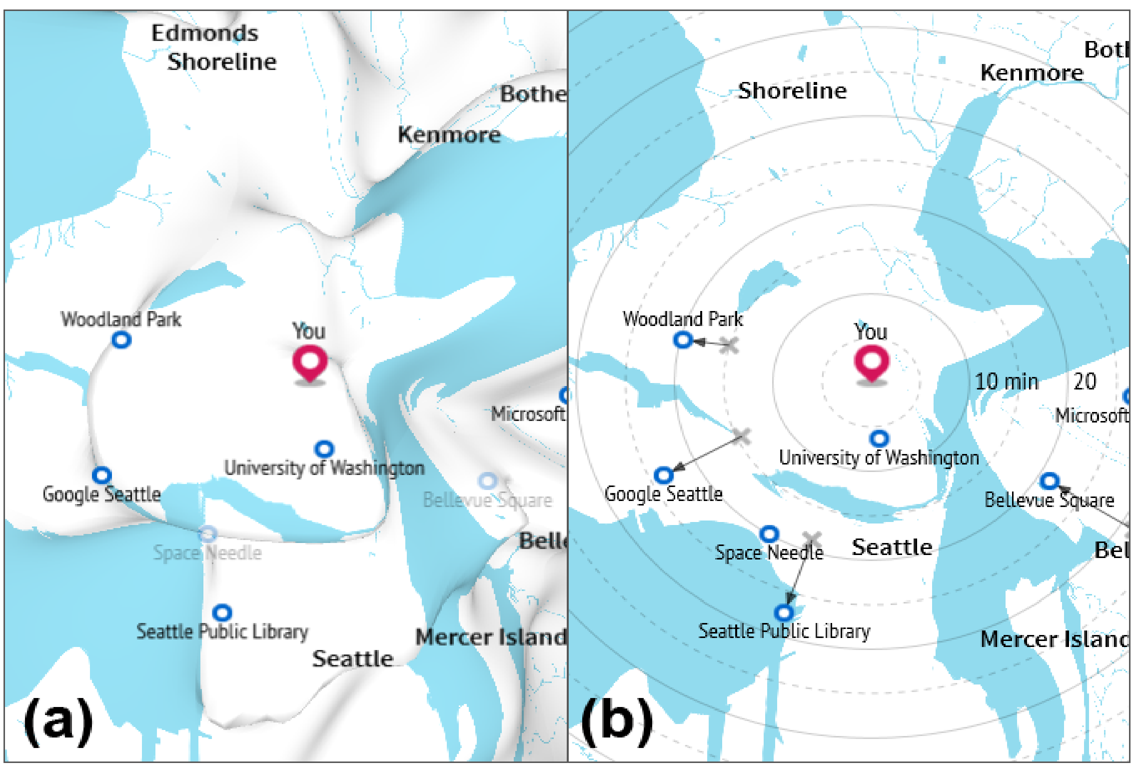

Figure 4.3. (a) a DC constructed without using GAP: the overlaps appear
(b) a DC constructed with GAP: overlaps are removed and replaced with anchors.

the areas that include the Space Needle and Bellevue Square. Fig. 4.3. (b) shows GAP replacing the overlaps with anchors.

Fig. 4.4 presents the pseudocode of GAP. O_i denotes the original position of node n_i in a key structure G and T_i denotes the target position of n_i. We derive n_i's target position via Dijkstra's algorithm with $getTargetPosition(Origin, n_i)$. δ denotes the displacement of a node for iteratively checking a topology violation. With modifying δ, GAP can control the granularity of the topological violation detection. N_i denotes the newly updated position of node n_i. Finally, A_i denotes the anchoring line of node n_i. Topological violations can be detected with $detectViolation(t)$ in GAP. This subroutine is designed based on the fact that every topological violation in planar graphs embedded in a Euclidean plane entails a change in the edge intersections in the graph [52]. To check for topological violations, we find all edges that are connected to a node. Then for each incremental shift in the node location, the intersections between the connected edges and other adjacent edges in the graph are calculated. When detecting the change in an intersection between edges, we see if the determinant of the two edges has changed from the previous step. (i.e., two lines are parallel or coincident if the determinant between the two is zero).

```
for all nodes n_i in a key structure G
  T_i = getTargetPosition(Origin, n_i)
  N_i = T_i
  for t = O_i; t ≤ T_i ; t = t + δ
    if detectViolation(t) is true
      if t is identical to O_i
        N_i = t
      else
        N_i = t − δ
      end
      A_i = getAnchor(T_i, N_i)
      break
    end
end
```

Figure 4.4. Pseudocode of GAP

4.3 SHAPE-RETAINING GEO-CONTEXTUAL ANCHORING PROJECTION (S-GAP)

Geo-contextual Anchoring Projection (GAP) ensures the construction of DCs that preserve topological relationships of a road network [1]. However, GAP (or other DC construction techniques such as [18]) does not factor in both the preservation of topological relationships *and* shapes. GAP adds an *anchor* that connects the stopped position and the target position. In doing so, users can visually decode accurate travel time without seeing a topological violation among map features [1]. However, GAPs only provide minimal constraints on the degree of shape distortion [1], which can result in presentation of severely distorted shapes and/or collapsed shapes while constructing a DC. Such a limitation could result in unfamiliar and unintuitive presentation of the DC, which can make the DC hard to read and recognize.

S-GAP is a projection method built upon the technique called GAP [1]. GAP gradually shifts each node on a road network from an initial position to a target position and stops the shift when the shift creates a new intersection on the network. S-GAP, on the other hand, provides an explicit *metric* that one can use to prevent such extreme distortion. S-GAP uses every intersection and corner point in G_{QTP} (in Fig. 3.4) as a control point for applying distortion. In this step, S-GAP first yields CP_{init}, which specifies initial coordinates of every control point. Then, CP_{target}, an array that stores the target coordinates of every control points, is specified. To yield target coordinates of control points, a technique explained in Fig. 7 in [1] is used. Each control point is then shifted gradually from cp_{init} to cp_{target} (see line #13 in Fig. 3.4). Upon each shift, map grid shapes S_{init} are converted to $S_{distort}$. Then S-GAP measures the distortion applied to $S_{distort}$ based on a shape-preservation metric suggested in CartoDraw [49]. The metric compares the similarity of shapes between S_{init} and $S_{distort}$ by factoring in the differences of *edge length ratios* and *angles* between the two shapes. This metric is invariant with respect to scaling and rigid-body motion, and hence is known to be robust for measuring shape differences between an original shape and the shape after distortion [53]. This metric also allows for the detection of a violation of topological relationships [54]. In effect, using this metric not only allows S-GAP to judiciously preserve the shapes, but also allows it to flag topological violations. The detail of the function *S-GAP* (described in line #34 in Fig. 3.4) can be found in [49]. To detect the shape preservation, S-GAP uses the heuristically driven threshold θ_{shape}, based on the suggestion in [49]. The pipeline stops the shift of a control point if S-GAP detects that the amount of distortion in $S_{distort}$ exceeds the threshold amount. The coordinates of every control point's *allowed* shifts are stored in CP_{S-GAP}.

In the final stage, S-GAP applies distortion to multiple vector map layers to construct a DC. Specifically, the pipeline builds L_{shape} (in Fig. 3.4), a set of vector map layers that includes layers of coastlines, land-use, and roads from Mapzen Vector Tiles. In applying distortion to each layer in L_{shape}, the pipeline uses CP_{S-GAP} as an input for constructing Thin-Plate Spline (TPS) warping function W_{S-GAP} [55], which is an efficient method for warping grids [6]. Fig. 4.5 contrasts the different depictions of the distortion of L_{place} constructed with S-GAP and with GAP. Fig. 4.5,

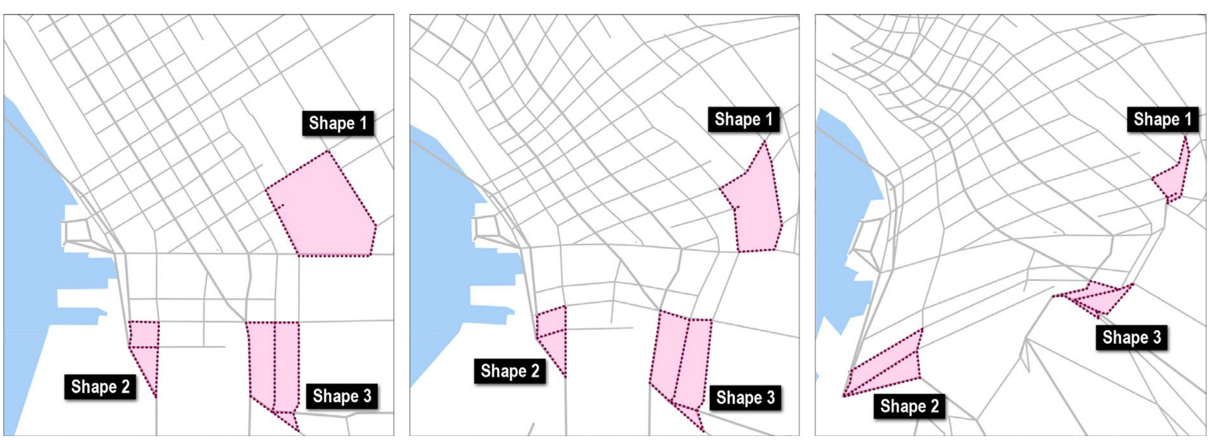

Figure 4.5. Three shapes in Mercator projection (left), and distorted shapes in the DC with S-GAP (middle) and with GAP (right).

left shows three shapes in a Mercator Map. Fig. 4.5, middle shows how the three shapes are distorted with S-GAP while Fig. 4.5, right shows the three in GAP based distortion. Finally, the pipeline presents a map layer L_{place} that contains place information. To present L_{place}, two TPS warping functions W_{S-GAP} (which shows a *stopped* position of the places) and W_{target} (which shows a *target* position of the places) are constructed. With the two warping functions, line #24 in Fig. 3.4 connects a line between the two positions.

4.4 PERFORMANCE EVALUATION

4.4.1 *Methodology*

To evaluate the performance of GAP and S-GAP, I conducted a performance evaluation aimed to compared the two techniques in terms of their capability in preserving edge length ratios and angles. More specifically, I measured the average *edge length ratios error* (which shows the difference in edge length ratio between every corresponding shape and path pair in Mercator map and the DC) and average *angular error* (which shows the difference in angles between every corresponding shape and path pair in Mercator and the DC). The two measures are the measures that Keim et al's metric aimed to minimize for preserving shapes (see Def. 3 in [49]). To compare between S-GAP and GAP, I used 48 new pairs (16 origins for each DC x 3 zoom levels) of S-GAP and GAP used in §3.4. Then we measured two distortion error types in the DCs constructed by both S-GAP and GAP.

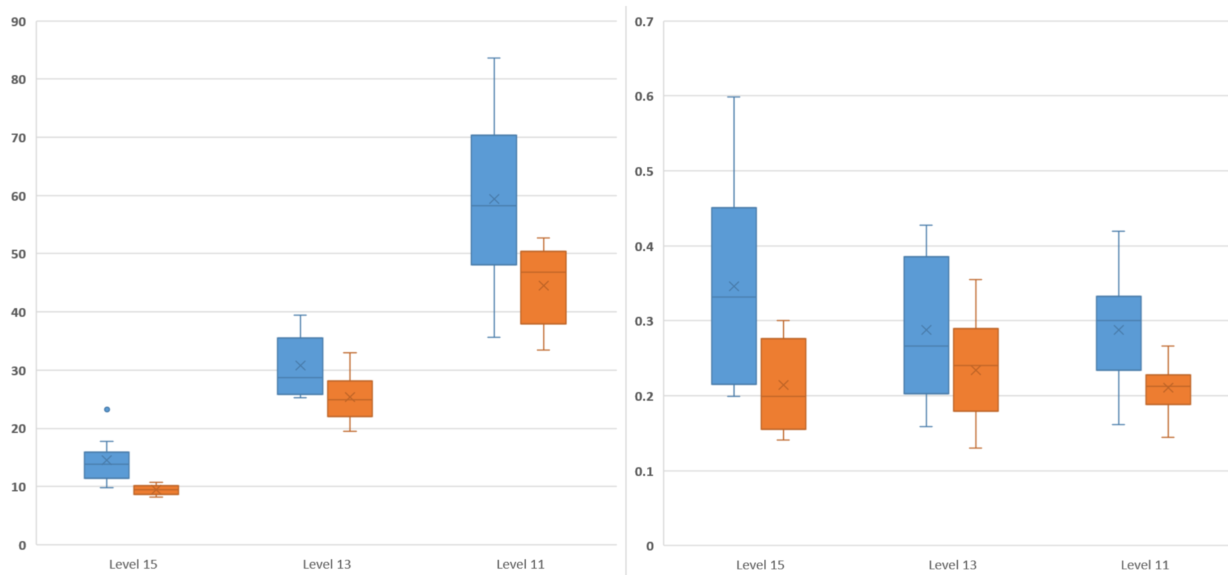

Figure 4.6. Performance evaluation: edge length (left, meters)
and angular ratio error (right, rad) for GAP (blue bars) and S-GAP (orange bars)

4.4.2 *Results*

A graph on the left in Fig. 5 shows the MAE between SRC and QTP for each zoom level. In terms of average edge length ratios error, a paired-samples t-test showed that the average edge length ratios error in S-GAP (M=26.4 meters, SD=15.23) was significantly lower than those in GAP (M=34.9 meters, SD=20.6, t=-2.285, p<.05). A graph in the middle in Fig. 5 shows the error between GAP and S-GAP. Finally, a paired sample t-test showed S-GAP has significantly less average angles error (M=0.21 rad, SD=0.05) than GAP does (M=0.30 rad, SD=0.10, t=-5.056, p<.0001). A graph on the right in Fig. 5 shows the error between GAP and S-GAP. We found S-GAP was better than GAP at preserving edge length ratios and angles of shapes. While the results show superiority of S-GAP, we see that a further evaluation with human subjects is required to assess the perceived visual quality of S-GAP.

4.5 CONCLUSION

The goal of both techniques was to enable the improvement of intelligibility of a DC based on the characteristics I derived in §4.1. I first devised GAP to enable constructing a DC that doesn't cause topological violation of a key network. The technique is used for building Traffigram ver. 2.0 (I will introduce this in greater detail in § 6.2). Building upon GAP, I devised S-GAP to preserve topological relationships of a key network as well as shapes to a certain degree. The technique is used to build Traffigram 3.0, which I will describe in § 6.3. Finally, we will discuss the limitations of GAP and S-GAP in greater detail in the conclusion section.

Chapter 5. INTERACTION DESIGN OF DISTANCE CARTOGRAMS

The interaction design takes a critical role in defining users' dialogue with the system as the users explore the data set to uncover insights [56, 57]. One of the overarching goals of this thesis is to build an interactive system that can support real-world users who explore locations using DCs. DCs would be unfamiliar to most people, and therefore it is not well understood in terms of how people would perceive benefits and drawbacks of DCs in their real-world scenarios. Studying the interaction design of DCs is critical to lower the barrier of unfamiliarity of DC and increase the chance of adoption. However, there is a lack of studies conducted to understand the interaction design of DCs. In this section, I introduce formative studies I conducted to see people's *perceived importance* of travel time in spatial exploration in general to understand the potential usefulness of a DC. Then I introduce *interaction types* that a system can use to present DCs.

5.1 Formative Studies

5.1.1 *Methodology*

Due to the limited prior work focused on user interaction design for DCs and specifically for the interactive map system we aim to design, I conducted two formative studies to better understand the need for using DCs and direction for interaction design. In the first study, I conducted an online survey using Amazon Mechanical Turk (I refer to the workers recruited from Amazon Mechanical Turk as Turkers hereinafter) to understand the general importance of travel time and the challenges that map users currently face in accessing it when exploring travel time information. I collected data from 40 Turkers (58% female) with a mean age of 31.4 years (range: 18-55). The session took on average 15 minutes and Turkers were rewarded $1.50 for their participation. To elicit the viewpoints of Turkers, I chose to focus on mobile platforms in this formative study. Finding local places as well as traveling and commuting short distances are the two most popular mobile phone use cases [58] that together cover almost 45% of all user interactions with mobiles. In addition, due to the novel nature of DCs to audiences, I presented concrete scenarios in which understanding travel time can be an important part of the decision-making process. The scenarios are as follows:

- spontaneously finding the next travel destination while on the move
- deciding on a place to go to while considering multiple factors (e.g., ratings, travel time)
- changing the travel destination while already heading somewhere
- familiarizing oneself with new surroundings
- comparing multiple destinations in terms of travel time while driving.

Turkers were asked to rate the severity of experiencing each of the 5 common mobile use problems [58] in each of the scenarios, modified to focus specifically on travel time. They were also able to enter their own problems. To make sure each scenario is considered realistic and practical, I asked Turkers to indicate the frequency of experiencing such a scenario as well as the degree of importance of the scenario. Finally, I also asked Turkers to report on the important factors for them in making short-distance travel decisions.

In the second study, I used a focus group session to identify *the necessary interaction design requirements* for DCs. To conduct the study, 3 UI design experts (i.e. doing active research on UI design) and 2 map experts (i.e. doing active research on map interfaces) were recruited (collectively referred to as Experts). To begin with, I introduced a concept of a DC to Experts. Next, the Experts conducted a brainstorming session to derive scenarios where DCs can be useful and identified the key scenarios where using DCs can be potentially helpful for users who explore locations nearby. Finally, the Experts derived key recommendations for interaction design for DCs.

5.1.2 *Findings*

Finding 1. Knowing precise travel time information is important yet cumbersome. Turkers considered travel time to be the most important aspect when making short-distance travel decisions (42%), followed by physical distance (32%) and convenience (24%) when using cars or public transportations. Based on the 5 common mobile phone use problems provided, they indicated the following as the most severe: the need for multiple interactions with the map to obtain travel time (46%), comparing multiple travel destinations with respect to travel time (41%), and familiarizing oneself with the surroundings with respect to travel time (41%). Finally, the Experts' comments from the focus group session pointed to some potential advantages of DCs as follows: helping travelers make quick travel-time based decisions in mobile situations (4 Experts), and visually presenting the precise travel time information without the need for additional interaction (3 Experts). These results indicate that accessing precise travel time information with the least interaction steps is needed yet is problematic in existing map interfaces.

Finding 2. Understanding the geographical reality is crucial. The discussion in the focus group session revealed that a Web Mercator map (WM) would be preferred in situations where a precise understanding of the physical reality is important (e.g., navigation). All Experts expected that users might lose physical context when using a DC exclusively. Furthermore, three experts expressed concern that the users may experience adoption barriers in using a DC, as the layout will likely be novel to them. This chain of thought led the Experts to suggest that devising a visual representation of a DC that allows users to infer the physical context of destinations would improve the decision-making quality and user adoptability. They also suggested that the temporarily precise but unfamiliar DC should provide a quick and easy way of switching to geographically precise and familiar EM to avoid potential confusion and increase adoptability.

Finding 3. Common interactions supported by existing map services should be provided. The focus group session also suggested that DCs can be useful as an extension or additional layer on top of a WM (4 Experts). Consequently, when interacting with a DC, the users will likely have similar expectations related to interacting with a WM. Therefore, the interface should allow users to interact with a DC through widely used interactions such as zooming, panning, and setting the origin. Two Experts mentioned that devising these familiar interactions in DCs would increase the chance of easy adoption.

5.2 MAP INTERACTION TYPES

Based on the findings, I ran a series of additional design ideations with a group of designers and engineers and identified four types of map interaction design: those are switching [1], zooming and panning [1], and highlighting [9]. In this sub-section, I will briefly introduce a brief concept of each interaction and describe details of implementation when necessary.

Switching interaction: Switching interaction is a map interaction type that allows users to transform the map layout between a WM and a DC using a smooth animated transition. The Experts expect that enabling the switching would allow users to quickly access both geographical and temporal information using a WM and a DC depending on the two expected user benefits and help them to familiarize with a DC. There are interaction techniques suggested by the previous studies that enable presenting multiple map layouts (in most cases, two) in a single screen, such as a juxtaposed view, lens view, overlay, or swipe interaction [59]. However, such techniques are designed based on the assumption that the different layouts presented in a single screen are built based on the same projection method (e.g., a WM). Presenting a WM and a DC using the overlay or swipe can confuse users because a map in DC may be highly distorted from WM. Or, juxtaposed view that shows multiple layouts in a single screen can be not suitable in the case where users use limited sizes of screens for mobiles. On the contrary, the animated transition can help users easily track the changes between two stages [60] and facilitate comprehension of information [61].

To implement the transition, I used linear interpolation between a WM and a DC. In my implementation, the duration has been set to one second to help users to maintain their *focus* [62] while interacting, but can vary. Fig. 5.1 briefly shows this process. From the technical perspective, the switching interaction can be divided into the following stages: (a) for each node N in a road network of EM, N 's Cartesian coordinates $N_{start}(x, y)$ is converted into polar coordinates $N_{start}(r, \varphi)$ from the origin O. (b) Then the system derives the destination of N_{start}, $N_{end}(r', \varphi)$, where the distance from O indicates travel time in DC. r' in N_{end} can be defined by multiplying t_n (travel time from O to n) and c (a constant that minimizes the displacement between all N_{start} and N_{end}; For details, see Section 3.2 in [6]). Finally, (c) the polar coordinate $N_{end}(r', \varphi)$ is converted into Cartesian coordinates $N_{end}(x', y')$. Finally, (d) once the target location $N_{end}(x', y')$ is defined, the system continuously shifts N's location from $N_{start}(x, y)$ to $N_{end}(x', y')$ by linearly interpolating layers to provide a smooth animated transition between a WM and a DC. The result of implementation provides at least 10 fps of performance on the iPhone 6. Fig. 5.2 shows the four snapshots that shows how switching interaction works.

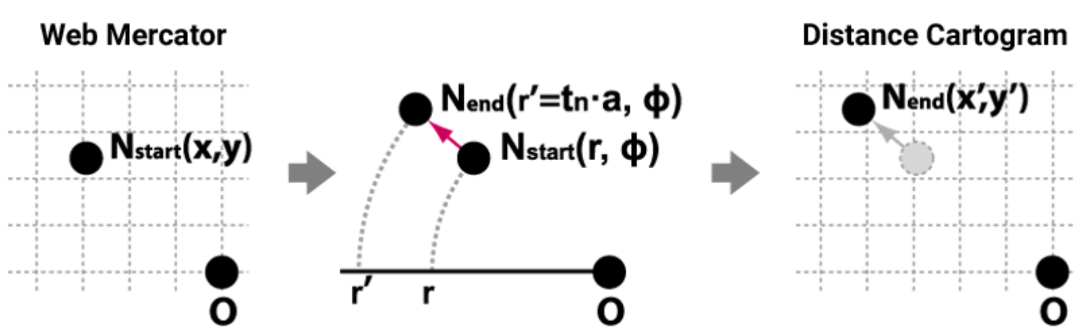

Figure 5.1. Yielding $\mathbf{N}_{end}(\boldsymbol{x'}, \boldsymbol{y'})$ by converting coordinate system

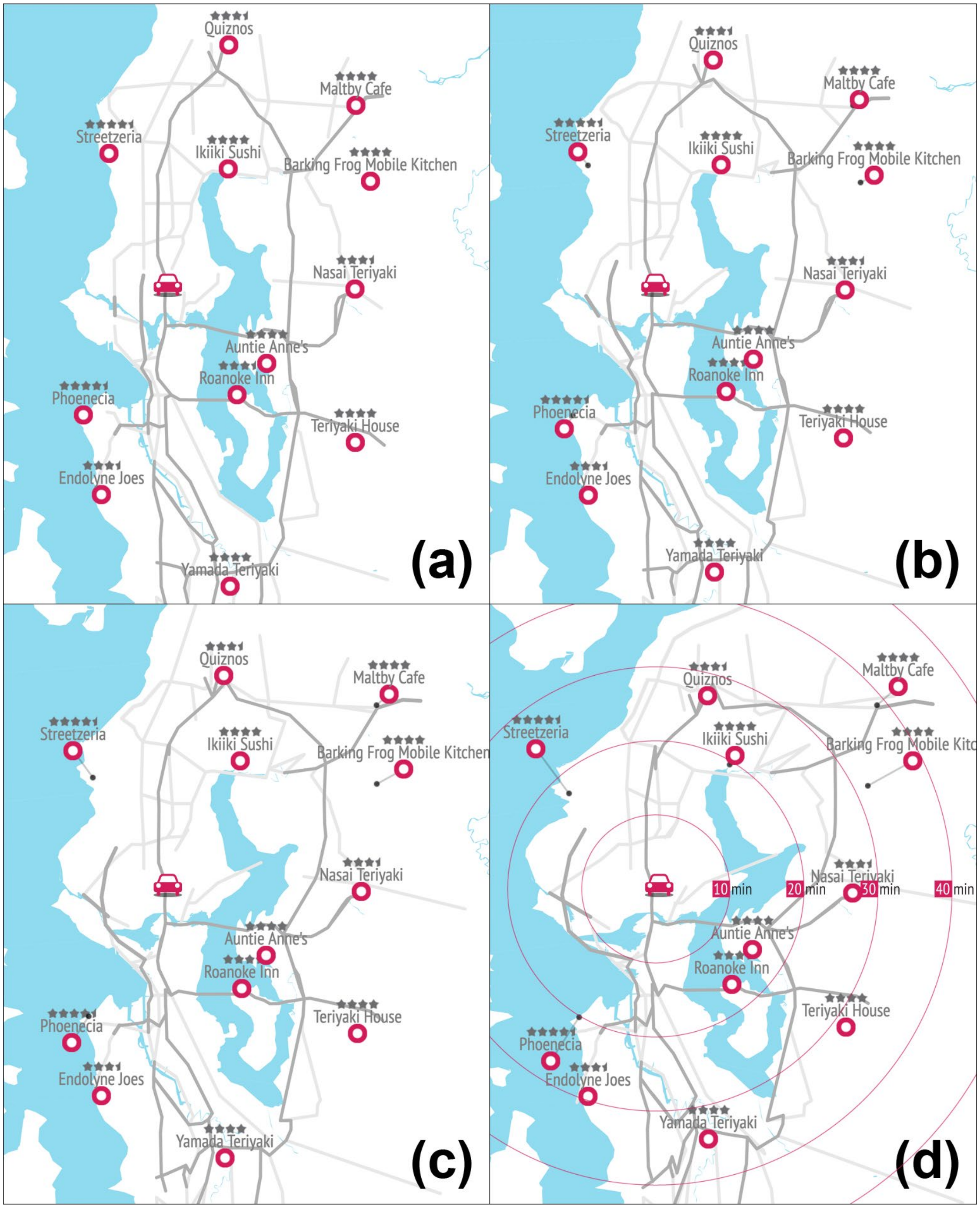

Figure 5.2. Linear interpolation from a WM to a DC:
(a) t=0 (i.e., a WM), (b) t=0.3, (c) t=0.6, (d) t=1 (i.e., a DC)

Zooming and panning interaction: zooming and panning are perhaps one of the most common map interaction types that are support in map user interfaces. The idea of zooming or panning interaction is not novel, but the actual implementation entails some computational challenges, as we discussed in § 3. Zooming and panning interaction can be implemented by using SRC or QTP. SRC uses a road network to construct a time space then shifts each node in a network to make a final outcome. Once a user triggers zoom in or zoom out, the technique constructs another time space using different road network built based on different class (see § 3.2 for details). In general, it is required to complete running all-paired shortest path routine to implement a seamless user experience, as the size of the road network can entail more nodes and edges than the system can handle to run its algorithm. On the contrary, QTP does not rely on the road network structure to construct a time space. Rather, it uses recursive quad tree structure to spatially approximate the travel time from one origin to the rest of the points. QTP enable capturing real time traffic (see § 3.3 for details).

Highlighting interaction: As DCs position locations based on a radial layout, users may face difficulty in precisely comparing travel time between multiple locations as the angle between the locations and the origin gets wider. To overcome this limitation, I devised a highlighting interaction, an interaction that uses *isochrones* – a circular visual indicators that present a set travel time from the origin [18] – as a visual filtering indicator. Specifically, the highlighting interaction allows users to create one's *own* isochrones and *resize* them by dragging inward or outward to

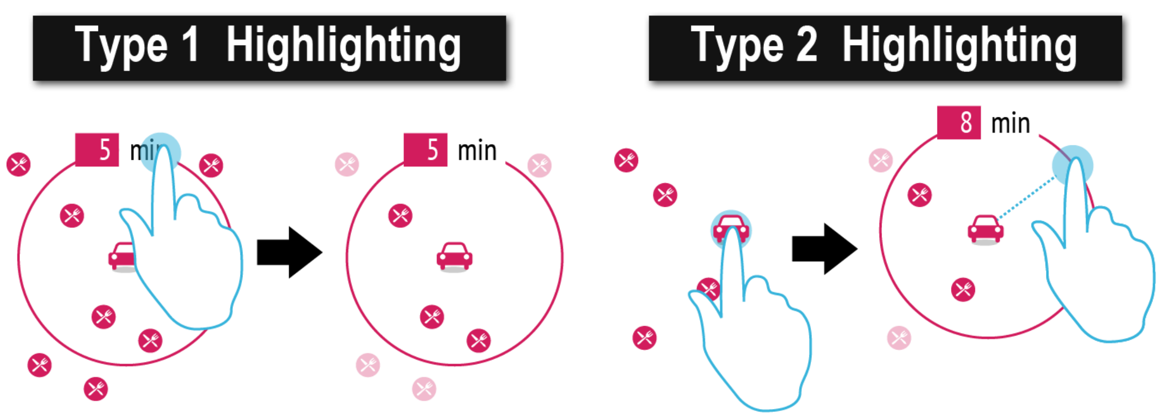

Figure 5.3. Highlighting interactions: Type 1 (left) & Type 2 (right)

compare any location on a map in terms of travel time to reach the locations. Highlighting visually emphasizes locations within a circle by making locations outside the isochrones semi-transparent. Highlighting can be triggered in two ways. *Type 1*: tap on an existing isochrone (see Fig. 5.3, left), or *Type 2*: tap on the origin or existing isochrones and drag inwards or outwards (see Fig. 5.3, right).

5.3 Conclusions

In this section, I explained the design process for defining a series of interaction types related to DCs in order to guide people to easily use DCs and overcome the barrier of adoption. As the outcomes of the studies, I introduced a series of interaction types, which were applied in three different systems which will be introduced in § 6. In developing the systems, additional interaction types, such as changing the mode of transportation (the time space of a DC can expand or shrink depending on different modes of transportation, such as on-foot, bicycles, or vehicles) were applied. Detailed additional interaction types of each system are described in § 6. In addition, the effect of presenting different interaction type discussed in this section will be introduced in § 7 quantitatively and/or qualitatively. It is worth noting that the studies I introduced in this section are based on the assumption that a DC can be used as a tool for exploration of nearby locations for applications like destination recommender systems. Design outcome of the interaction types can be highly different depending on use context. For instance, DCs could be applied for supporting different use context, such as visual analytics or story-telling.

Chapter 6. SYSTEMS

Researchers and practitioners have shown long-standing interest in understanding how people cognitively perceive distance when exploring spatial information [3]. Among many factors that influence such a *cognitive distance*, travel time has been considered a dominant factor that people rely on to weigh the relative costs of travel [63, 64]. In one way or another, almost everyone uses travel time in everyday spatial decision making, for instance to select a route to work, a restaurant for lunch, or accommodations to book for their upcoming vacation [65].

Traffigram is a system that helps users assess travel time using DCs when exploring locations. The chapter describes how I applied different techniques introduced in § 3, § 4 and interaction design introduced in § 5 to evolve the Traffigram. As we have briefly discussed in previous sections, previous research generally saw DCs as a way to show travel times of a scheduled type of mode of transportation in a static view, and there have been few efforts for adopting DCs for building an interactive user interfaces for supporting people who explore locations. Although Traffigram is still in progress, I introduce three versions, each which was introduced in 2014 (Ver. 1.0 [6]), 2017 (Ver. 2.0 [1]), and 2018 (Ver. 3.0 [9]) respectively. While there are different details and interaction types supported in only a particular version, the later versions are built based upon the former versions and shows progress in computational performances, visual design, and interaction features.

Table 6.4 shows the major differences between the three versions of Traffigram. Ver. 1.0 is the earliest version and arguably the first interactive system that presents DCs to users. It uses a road network of hundreds of nodes and edges and present only limited interaction types such as map panning. This version also does not visually handle intelligibility issues of a DC such as topological violations and shape distortions. Ver. 2.0 scales up the road network to multiple tens

Table 6.4. Specification of Traffigram: Ver. 1.0, 2.0, and 3.0.

	Traffigram Ver. 1.0	**Traffigram Ver. 2.0**	**Traffigram Ver. 3.0**
Time space construction method	Existing techniques	SRC	QTP
Size of the key network	435 nodes and 107 edges	8,530 pathways (a linked list of nodes in OSM) and 66,205 nodes	Not relying on a network based method
Supported Interaction types*	Panning, time expectation	Panning, Zooming, Switching	Panning, Zooming, Switching, Highlighting, Changing the mode of transportation
Showing estimated travel time or capturing traffic on-the-fly	Estimated travel time	Estimated travel time	Real travel time
DC projection method	Conventional	GAP	S-GAP
Device platform	Desktop	Mobile	Desktop and mobile
Presentation	Water layer (i.e., contour of lands) and road layer	Water layer and road layer	Water layer, road layer, land use layer

* a bounding box from 47.396°S, -122.440°E to 47.859°N, -122.075°W is used in the three systems.

of thousands of nodes and edges and apply SRC to selectively choose a subset of nodes and edges to construct a key network for a DC construction, which enables implementation of zoomable DCs. This system is the first system that adopts the switching interaction. But this system cannot reflect the real traffic information on-the-fly. It applies GAP to handle cases of topological violation. The Ver. 3.0 is the latest version that presents every interaction types introduced in § 5 in real time using QTP. It uses full raw road network of Open Street Map (OSM), but doesn't rely on a road-network based shortest path for time space construction. This version applies S-GAP to project a time space onto 2D screen, which puts more severe constraints on applying distortion on maps in order to preserve topological relationships among map features as well as shapes to a certain

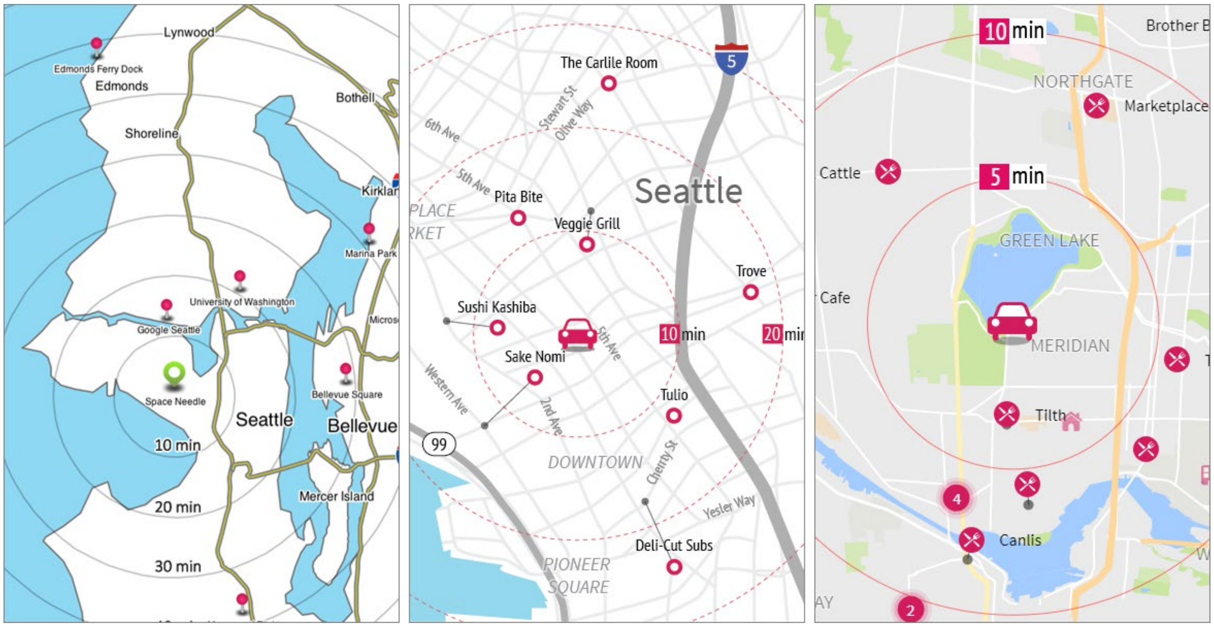

Figure 6.1. Presentation of DCs in three systems:
Ver. 1.0 (left), Ver. 2.0 (middle) and Ver. 3.0 (right)

degree. Figure 6.1 shows how the presentation of a DC has evolved through three versions. The left shows a DC in Ver. 1.0. It presents the result of water layer and major roads (highways). Road information in Ver. 2.0 presents roads more adaptively based on a user's zooming level. It covers every level of roads, from highway level to arterial roads. Finally, Ver. 3.0 presents a series of multiple layers, such as the water layer, road layer, and land use layer (e.g., park, residential area) in DC construction. For the rest of the subsection, I will introduce the three versions in detail. Although "I" is used as a subject in describing the detailed features of the three systems, I acknowledge that the systems are the outcomes of collaboration with my colleagues.

6.1 TRAFFIGRAM VERSION 1.0 (2014)

This version of Traffigram follows the four steps in Figure 3.1. I introduce a process for constructing a DC, then shows the general features of the system.

6.1.1 *Pipeline for building a Distance Cartogram in Ver 1.0*

Step 1. Road Network Construction: The first step in the construction of Traffigram Ver. 1.0 was developing a directional key network structure (i.e. directionally-weighted graph) that reflects an existing road infrastructure in the Greater Seattle area. This task is accomplished by overlaying a network structure onto a traditional spatial-based map. The key network functions as a skeleton when warping; this structure must accurately represent the real road infrastructure and general traffic information. In this system, every node in the key network represents a geographical point. In practice, we have two types of nodes: one, a crossroad with geographic significance and above a certain threshold of traffic; the other, a point on a highway related to an entrance, exit, or fork. Every edge represents a road that connects two nodes; the presence of an edge means two nodes are geographically adjacent and physically connected. Our system contains crossroad/crossroad edges, highway/ crossroad edges (highway exit), crossroad/highway edges (highway entrance), and highway/highway edges. Fig. 6.2 (a) depicts the traffic network structure of Traffigram applied to the Greater Seattle area. The challenge of structuring this network lies in applying the following factors: occasional one-way traffic, numerous highway entrances/exits, and complex connections related to inter-highway junctions. As a result, I simplified the road infrastructure by representing it with 107 nodes and 435 edges. I considered the following aspects when sampling for traffic network construction. First, we evenly distributed every node and edge in our coverage area considering population and traffic issues. Second, I represented existing routes to preserve geospatial realism. Third, we focused on building an interactive warping and construction system to provide a faster, more responsive user interface.

Step 2. Traffic data acquisition: The second phase involves the gathering of information on traffic conditions. In the key network structure I implemented for this system, I weighted every edge with real travel time. Different types of temporal traffic information are available; data might be aggregated from individuals (i.e. observed on a highway) or collected from a public data center. For this implementation, I chose to use the Bing map API and data since publicly-available sources in the Seattle area currently only address primary arterial routes. Traffigram gathered travel time data every 30 minutes. Upon user request with a specific time and origin, Traffigram fetches weekly periodic data and presents the weighted mean value to the user. Utilizing periodic traffic data to estimate traffic flow is a classic and broadly-adopted technique and with this approach, the database delivers a meaningful and concrete estimation model to the user. I then calculated a congestion factor for every edge by dividing the actual travel time (with traffic) by the baseline time (without traffic). Fig. 6.2. (b) illustrates one snapshot of our data. The roads depicted in red

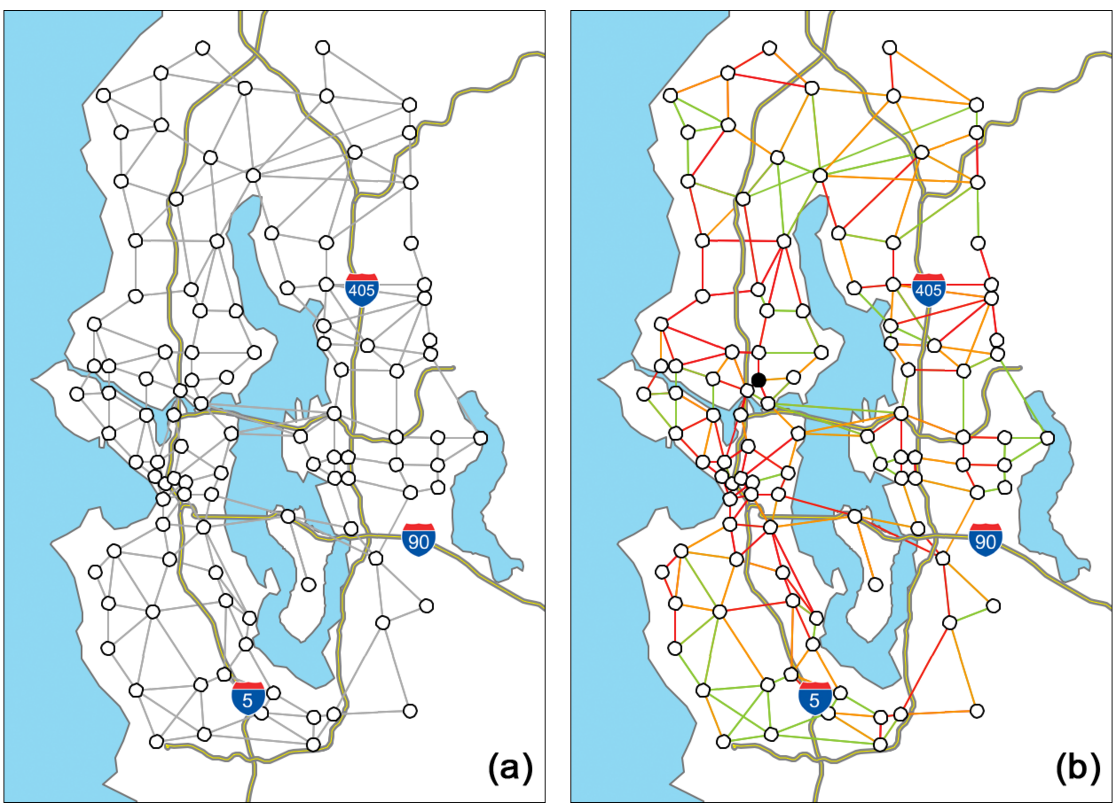

Figure 6.2. Network construction and data acquisition.
(a) Traffic network structure, (b) Congestion factor from black nodes:
green $C_{ij}=1$, yellow $1< C_{ij} <2$ and red $2\leq C_{ij}$

show congestion while those in green are clear or uncongested. Fig. 6.2 (b) depicts a visualization of the congestion factor of the network. The congestion factor $\boldsymbol{C_{ij}}$ from node *i* to *j* is encoded as edge color in this figure. A value of 1 is green, $1 < C_{ij} < 2$ yellow and $2 \leq C_{ij}$ red.

Step 3. Isochrone generation: Traffigram then calculates every node's shortest route from the origin via Dijkstra's shortest path algorithm [31]. In our network, the system generates one virtual edge if the user's chosen origin is not the same as the representative, predefined node; the virtual edge links the user-selected origin and the "adjacent node" that has a minimum geospatial Euclidean distance from the origin. Based on the shortest path analysis, Traffigram creates isochrones by connecting all points that are equitemporally distant from the origin; i.e. all points on a given contour are an equal amount of time away from the origin. Fig. 6.3 depicts this process.

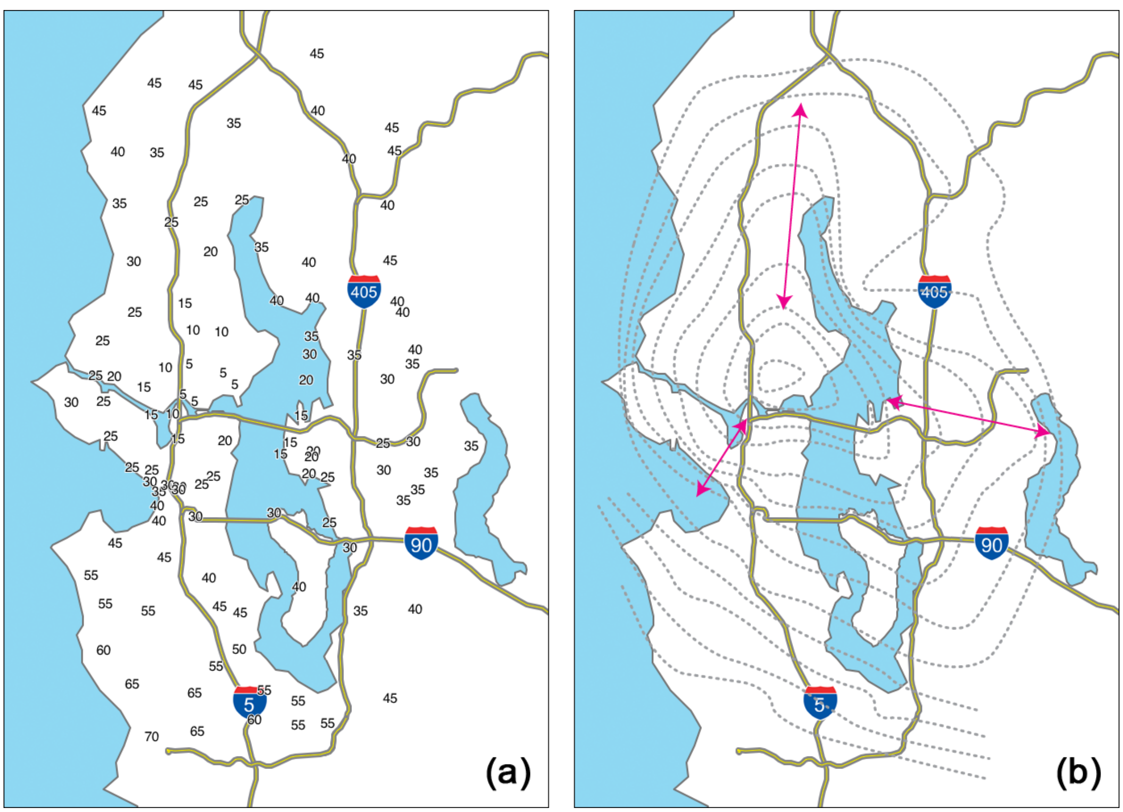

Figure 6.3. Isochrone generation:

(a) Shortest path analysis; (b) Isochrone construction;

the length of the double headed arrows represents congestion

With the shortest path analysis, Traffigram gathers travel time information (see Fig. 6.3 (a)). In Fig. 6.3 (b), we can see the disparity of several contour intervals by comparing the three double-headed arrows. For each arrow, a traveler spends the same amount of time traversing the varying distances. Thus, the lengths of these arrows are inversely proportional to the degree of congestion. The route through downtown Seattle is highly congested (the shortest arrow), Bellevue (to the right of the bay) is less congested, and Northgate (north of the center contour) is the least congested.

Step 4. TPS Warping: For the final step, Traffigram warped the equidistant map to generate a DC using thin-plate spline warping (TPS). TPS is a well-known algorithm that has been widely used as a non-rigid transformation model in image alignment and shape matching [29]. TPS was chosen since it has two important merits. First, the algorithm provides closed-form solutions for

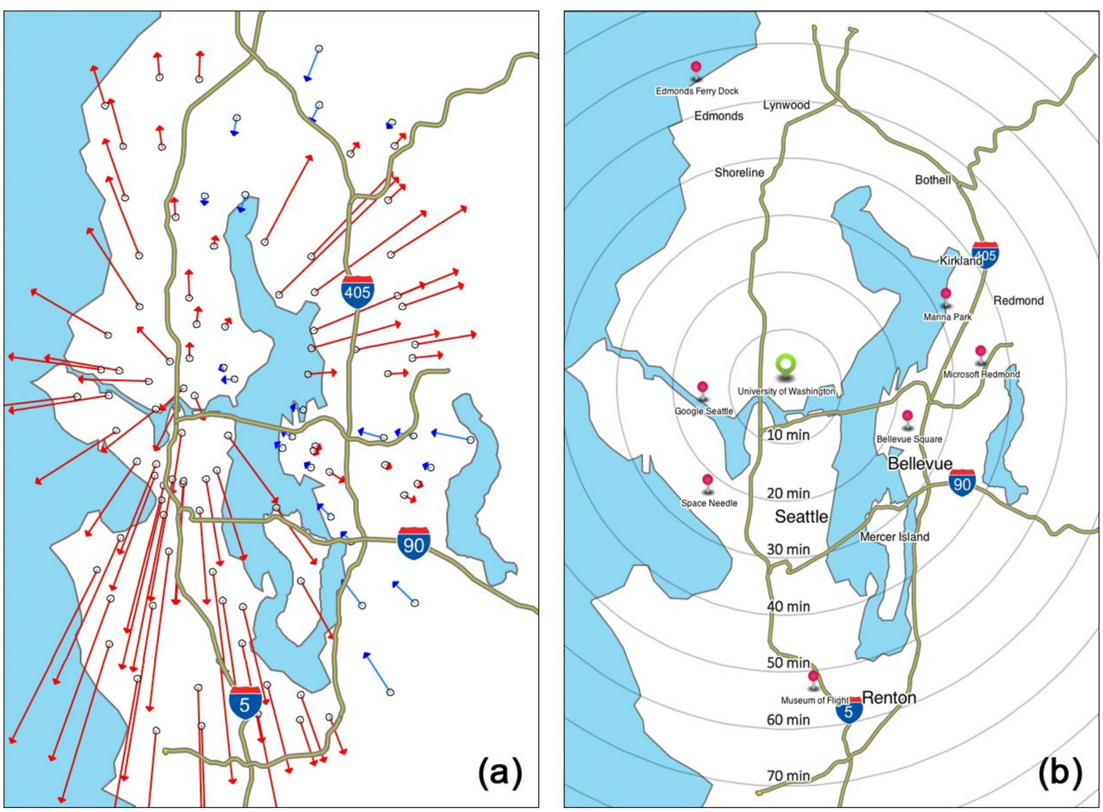

Figure 6.4. Isochrone generation: (a) Shortest path analysis; (b) Isochrone construction; the length of the double headed arrows represents congestion

interactive warping and thus enables fast computation. This feature of TPS fits well with the goal of Traffigram since the system should generate an isochronal map within a short amount of time threshold to provide a seamless map usage experience to the user. Furthermore, TPS can generate smooth map results while preserving the source among several smoothing techniques; TPS is known as one of the most robust-toward-outlier solutions [29]. We begin by generating a sparse vector map (See Fig. 6.4 (a)) that illustrates the displacements necessary to align isochronous nodes into circular shapes. The red and blue vectors visualize the gap between geospatial accessibility and actual geography. With this sparse vector map, we interpolate a TPS surface and apply it to create a final result. Fig. 6.4 (b) shows a warped map; note that the landmass located west of the bay (downtown Seattle and the University District) is largely expanded while the landmass located east of the bay (Bellevue/Newcastle) is condensed compared with Fig. 6.4 (a).

6.1.2 *System Design*

Using the pipeline, I built Traffigram Ver. 1.0. Fig. 6.5 presents a user interface of the Traffigram screenshot in 2014. Users can input their origin as text (i.e. address) or can drag and drop the cursor in the map display area. In this version, WMs and DCs are presented simultaneously and are synchronized as the user pans. Zoom in/out feature is not available in this version. At the bottom, a user can select time. Drop box input allows the user to select from Monday to Sunday or “now”. If users select one day of the week, the time setting is enabled, and users may choose a specific time. In that case, the average travel time for that specific timeframe is retrieved from the database and the isochronal map is updated. If user selects the “now” option, the system fetches the most recent travel time information. As we described, the database periodically gathers the travel time of every edge every 30 minutes. Users can also show or hide three visual components in a DC, which are roads, landmarks, or traffic information. Finally, users can select five design variations of a DC via a radio button.

Version 1.0 was the earliest system and I designed five design variations that show the same information differently to understand people's preferences. During our ideation phase, I considered the following questions: What are the cognitive processes involved with "consuming" the information presented on a map? What roles do maps play in embodied experience? How do cartographers convey physical constructs to a map user and how might a distorted map advance this conveyance? After the development of multiple low-fidelity prototypes, I produced a set of design variations that I believed were functionally useful, cognitively efficient, and aesthetically appealing. The result of evaluation will be described in more detail in § 7. Fig. 6.6 (a) shows the basic warping result without additional visual cues. Fig. 6.6 (b) was designed to maximize the power of "position" in Mackinlay's theory by placing 10-minute band circular isochrones. We combined color information in an interlaced manner in 6.6 (c) to enhance the recognizability of each band, as used in Carden's visualization [20]. In figure 6.6 (d) and 6.6 (e), we offered a grid

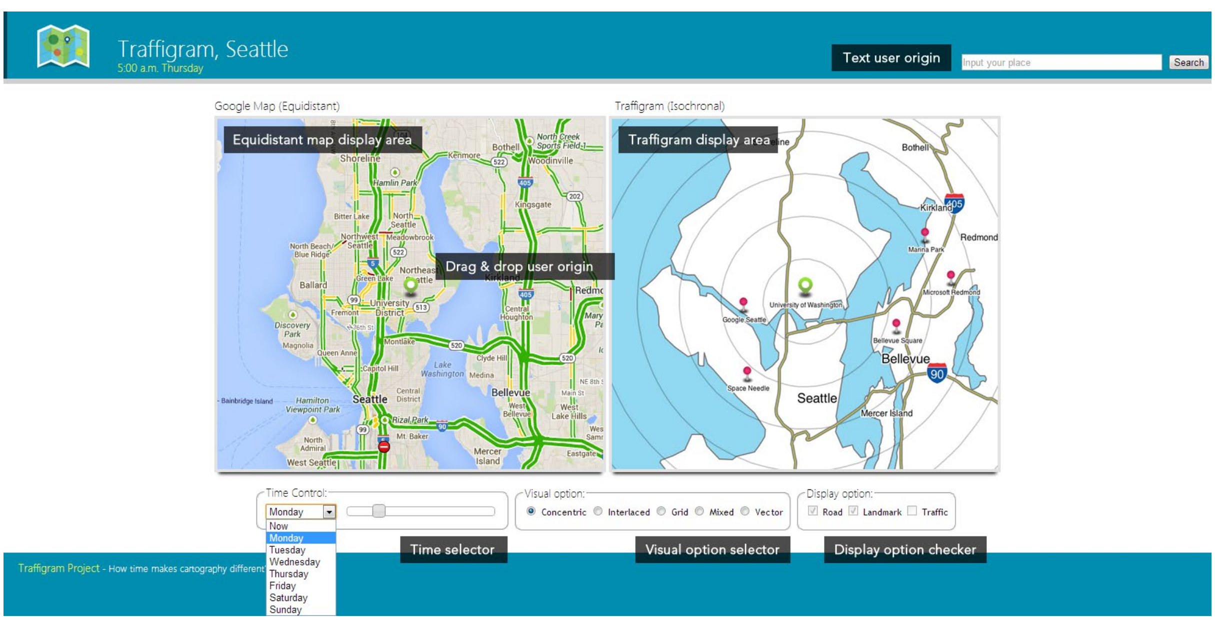

Figure 6.5. User interface of the Traffigram Ver. 1.0

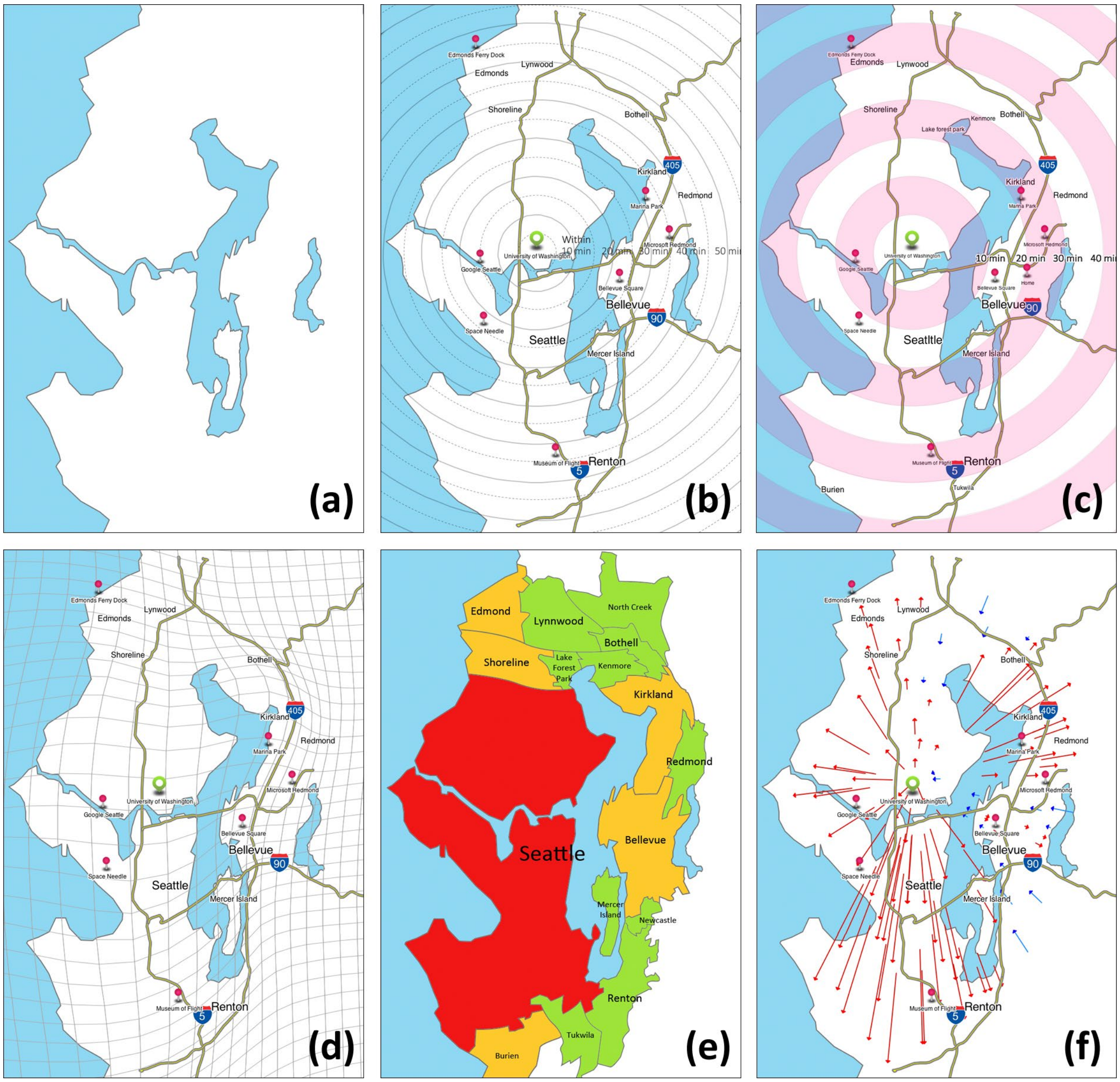

Figure 6.6. DC Design Variations: (a) Warped map; (b) Concentric circular view; (c) Color-interlaced concentric circular view; (d) Grid view; (e) City view; (f) Vector view

and city boundary respectively in order to present users with a sense of geographical spatiality by utilizing "area". The grid gives users a visual cue for physical distance; each grid has 1.5-mile length and height. 6.6 (e) gives users geographical information via city boundaries, often used in area cartograms. We also added a color scheme in this visual variation for each city we covered. Seattle shows the most congestion. Cities adjacent to Seattle, such as Shoreline, Bellevue, Kirkland, Burien, and Edmond have a congestion factor between 1.00 and 2.00. Other cities have minimal traffic issues. In Fig. 6.6 (f), we added vectors whose lengths represent expansion or shrinking based on the current traffic situation.

6.2 TRAFFIGRAM VERSION 2.0 (2017)

6.2.1 *Pipeline for building a Distance Cartogram in Ver. 2.0*

The second version of Traffigram uses SRC for constructing a key structure unlike the first version. The pipeline of SRC has been explained in detail in § 3.2. In this section, I will briefly describe how SRC glues different types (or class) of roads to build a single key network. As we briefly discussed, the raw network collected by OSM is divided into the three classes: (a) the *highway class* (hereinafter **H class**), which includes motorway and trunk, (b) the *road class* (**R class**), which contains arterial roads, such as primary, secondary, and tertiary roads, and (c) the *link class* (**L class**), which links the roads in the H and R classes.

The OSM pathway data I itself is a series of points, and there is no information about how each pathway crosses or connects each other. Thus, it is necessary to *link* between the different pathways (after pruning nodes using the pipeline in Fig. 3.2). To establish the links between different OSM pathways from raw data, I introduce two types of operation, namely (a) *Intra-class*

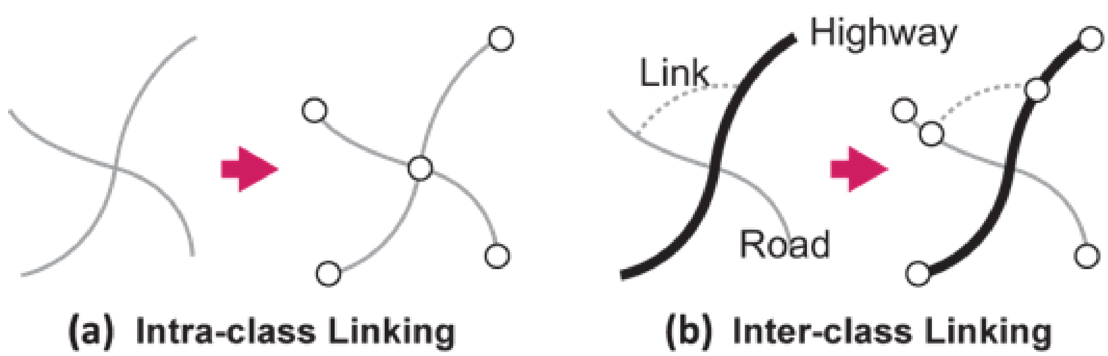

Figure 6.7. Linking different OSM pathways:
(a) Intra-class Linking, (b) Inter-class Linking

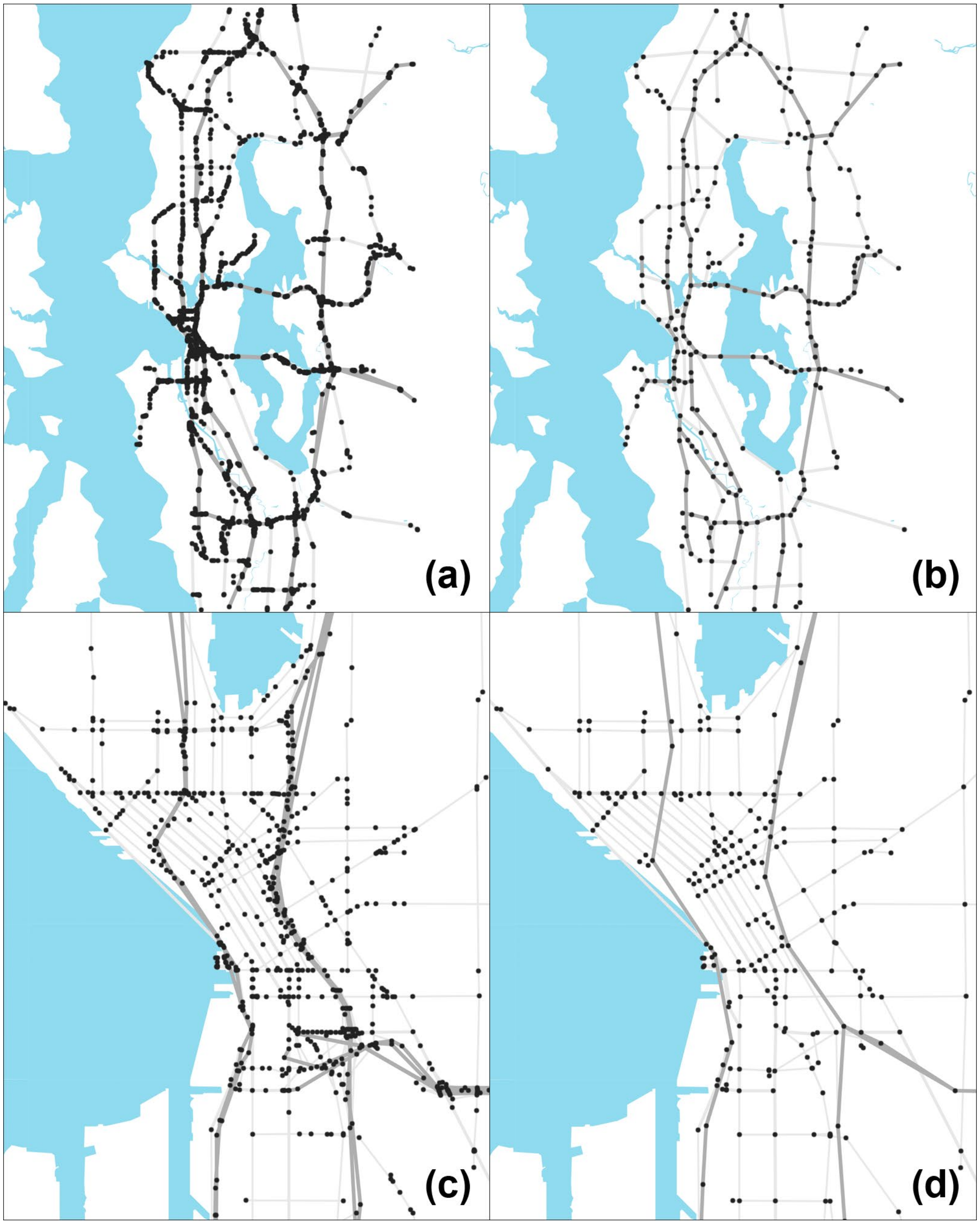

Figure 6.8. The key network of the Greater Seattle area: (a) before and (b) after SRC. The key network of Downtown Seattle: (c) before and (d) after SRC.

linking (**L1**) and (b) *Inter-class linking* (**L2**). If multiple pathways in the same class cross each other, L1 builds the links that connects both pathways (Fig. 6.7 (a)). This operation inserts a node in the road network at the crossing and splits the crossed road into two edges. L2 performs a similar operation, but it only considers linking between H class and L class, or R class and L class (Fig. 6.7 (b)). This operation connects heterogeneous classes in a road network. Fig. 6.8 demonstrates the results of SRC. Fig. 6.8 (a) and (b) shows the Greater Seattle area. The raw pathways are comprised of 2,515 nodes and 3,267 edges (Fig. 6.8 (a)). Fig. 6 (b) shows the result of SRC, which has 265 nodes (90% were pruned.) and 324 edges (91% were pruned). Fig. 6.8 (c) and Fig. 6.8 (d) shows road networks of Downtown: Fig. 6.8 (c) has 952 nodes and 1,094 edges, whereas Fig. 6.8 (d) has 349 (63% were pruned) nodes and 471 edges (56% were pruned).

There are notable features that the second version of Traffigram newly presents. First, using SRC, Traffigram Ver. 2.0 presents the first zoomable DCs. Second, the system is built on mobile. Third, the system presents a switching interaction, which allows users to use both WM and DC depending on their use context. These new features were minimal requirements for building a system that enable users to use DCs to explore locations. Although implementation entails some technical challenges, presenting zooming is indispensable in supporting users' spatial exploration in maps. In addition, finding local services as well as traveling and commuting short distances are the two most popular mobile phone use cases [58] that together cover almost 45% of all user interactions with mobiles. Finally, users will need to use a WM to see the accurate physical distances in order to start using a DC.

6.2.2 *System Design*

I designed and built an interactive mobile map system in which users can explore spatial information and discover various types of local businesses in the Greater Seattle area. The GAP and SRC have been embedded in the system to improve the DC's visual quality and the system's interactivity. The types of locations available to users are: restaurants, bars, movie theaters,

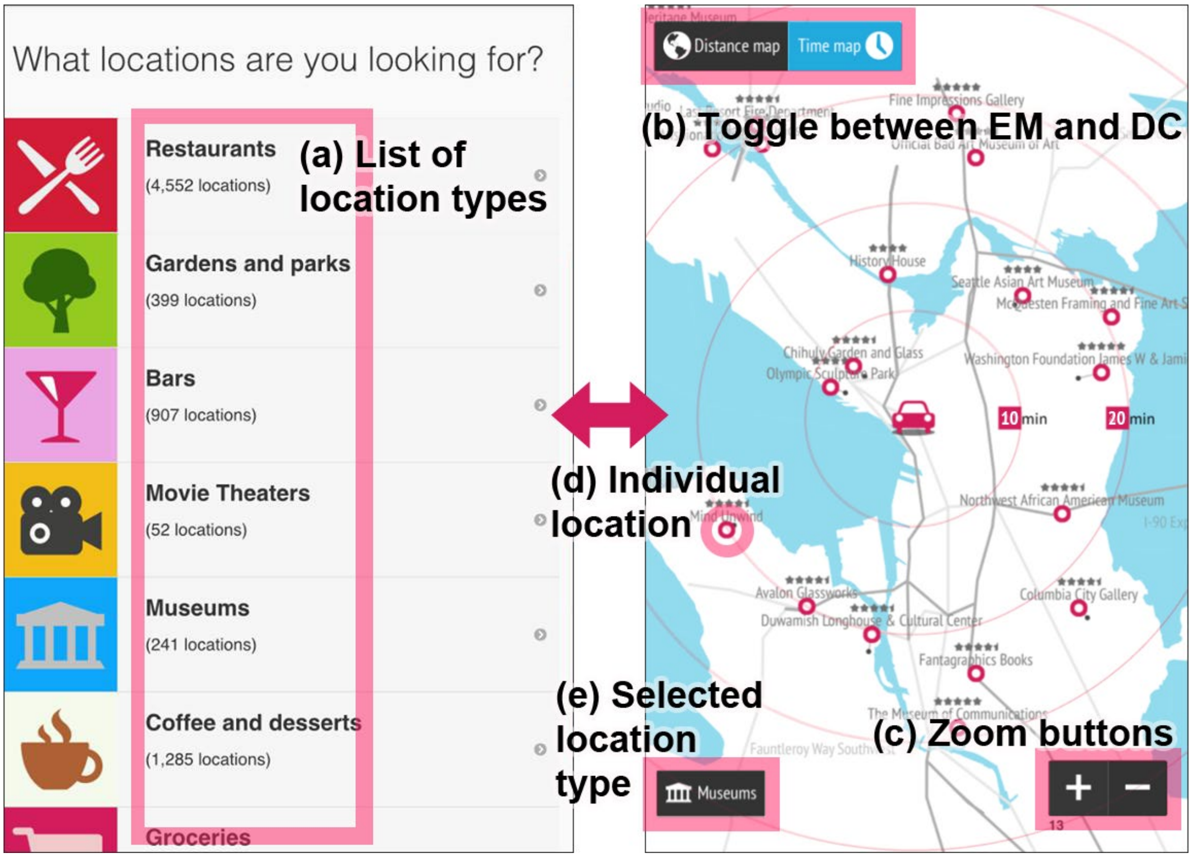

Figure 6.9. Mobile UI design of Traffigram Ver 2.0:
A user can select a type of location (left), and explore areas in the greater Seattle area (right)

museums, coffee and desserts, groceries, and places for sports activity. To present real local businesses around the target area, we used Yelp API 2.0 to gather 8,572 local businesses.

To support effective location discovery with the system, I designed a mobile UI where a user can choose one of the location categories on the list (Fig. 6.9 (a)). Once a user selects a category, a screen presents a map. Five features are available in the map screen. First, a user can switch the cartographic layout between a WM and a DC with a toggle, as shown in Fig. 6.9 (b). Second, a user can use zooming interaction with buttons (Fig. 6.9 (c)). Third, a user can learn more about each location by tapping it on the map. Upon a user request, information, such as a business category of the location, thumbnail image, address phone number, rating, rating count, review, and travel time to get to the location, is presented. Fourth, the location type in a map is displayed (e.g., “Museums” in Fig 6.9. (e)). When the user taps this button, the screen returns to the initial list. Finally, map panning is available.

6.3 TRAFFIGRAM VERSION 3.0 (2018)

6.3.1 *Pipeline for building a Distance Cartogram in Ver 1.0*

Ver. 1.0 was built mainly to understand effect of using DCs in static settings (in the evaluation, still images constructed with Ver. 1.0 were used). Building Ver. 2.0 enabled evaluating DCs in interactive settings. More specifically, I focused on understanding the effect of DCs as an explorative tool for location discovery and examined the effects of some of the interaction types introduced in § 5. The overarching goal of Ver. 3.0 is to develop a system that allows users to use DCs in their real-life settings. I aimed to understand how real-world users, who are not familiar with DCs, would use DCs to explore spatial information and how they perceive benefits and drawbacks of DCs. To elicit the system requirements, I first explored research in HCI focusing on designing a transferrable system (e.g., [66]). Methodologies for design, such as innovation pipelines [67], adoption-centered design [68], or implications for adoption [69] have been proposed to bridge the gap between research in the lab and adoption in the wild. These approaches agree that a system’s transferability to the real world is closely related to its adoptability by users [70, 71]. To weigh opportunities and barriers for adoptability of DC by real world users, I briefly review DC research on perceived usefulness, perceived ease of use, and technical feasibility. Such factors are critical in explaining why users would accept or reject new technologies [70].

Perceived Usefulness of DCs: One of the fundamental reasons that users adopt a new system comes from the *belief* that using the system can help them can attain better performance on tasks they encounter [68, 71]. The previous study results identified that DCs are more useful than other existing map techniques when users explore locations and decide a location to travel with travel time in mind. As we've briefly covered in § 2, map readers cannot interpret accurate travel time using color-coded road segments (e.g., Google Maps) [6]. Also, it is possible to indicate travel time without applying distortion to a map by adding free-form isochrones. However, such presentation can become overly complex, and users' decoding of time is less accurate than DCs (ranges vs. absolute travel times). Although I didn't cover the studies I conducted using Ver. 1.0 and Ver. 2.0, findings in the studies have shown that using DCs enabled users to decode travel times with significantly higher accuracy and/or within significantly shorter times compared to using color coded road segments [6] and a map interface showing travel time as text [1]. Travel time is a primary proxy that people rely on when gauging their cost of travel [63, 3]. While DC's benefits of assessing travel time to multiple destinations "at a glance" [1, 72] have not been tested in the wild, such perceptual benefits may trigger users' belief that adopting DCs can make their spatial information seeking tasks more efficient.

Perceived Ease of Use of DCs: Another critical aspect for adoption is the perceived *ease of use* [73, 71]. To adopt a new system, users should be able to understand the meanings of UIs and discover possible features that they can use [73]. As we've discussed in § 4, distortion applied in DCs can potentially confuse users who only have experience with more traditional map UIs [74] in two ways: by violating topological relationships of features on a key network and by introducing excessive amount of distortions to shapes. GAP ensure constructing DC while preserving topological relationships. But GAP (or other DC techniques such as [18]) does not factor in both preservation of topological relationships and shapes (**L1** in table 1). To improve the intelligibility of DCs (which is closely related to ease of use), I use S-GAP in Ver. 3.0.

Technical Feasibility of DCs: To facilitate adoption, building a robust system that can work in the wild should be *technically feasible* [68, 73]. DCs would be perceived as useful when it can interactively show live travel time to destinations accurately. However, there are a couple of limitations that act as constraints in developing such a system. First, it is not feasible to present accurate live travel time with existing techniques (e.g., [1, 22]), due to the high computational costs for constructing a time space. Although Ver. 2.0 attempt to handle this computational complexity using SRC, the technique can over-simplify a network structure, which would cause inaccurate shortest path results. In addition, SRC executing all pairs of shortest paths for a network periodically to pre-calculate a time space, which cannot capture live traffic. Finally, road network-based approaches typically require preparation of the network of a target area, which can impose an additional burden for developing a system that can present DCs without the restriction of where an origin is located at. For example, the state-of-the-art DC systems can cover an area that spans multiple cities [1]. To overcome such barriers and build feasible systems, I use QTP in Ver. 3.0.

To sum up, Ver. 3.0 applies QTP rather than SRC (used in Ver. 2.0) for constructing a time space in the pipeline for DC construction. Then it applies S-GAP than GAP (used in Ver. 2.0) for distorting a WM, which puts further constraint on distorting shapes than GAP. Interaction types introduced in Ver. 2.0 were zooming, panning, and switching. On top of the interaction types presented in Ver. 2.0, Ver. 3.0 provides highlighting interaction, mode of transportation interaction (a user can set on-foot, bicycles, or vehicle), and the ability to change the origin.

6.3.2 *System Design*

Based on the basic requirements and map interaction types, I worked with a group of collaborators and designed two high-fidelity UI prototypes for desktop and mobile to examine usability issues. The prototypes were used in heuristic evaluations with 6 UI designers (every designer reported that one had more than 3 years of professional UI design experience). The experts were divided into 2 groups of 3. Each group examined the desktop and the mobile UI prototype respectively.

We followed the guidelines suggested by Nielson and Molich to identify major and minor usability issues [75]. Based on the suggestions and findings from heuristic evaluation, I iterated two high fidelity prototypes. The design outcome of this informal usability examination is shown at Fig.

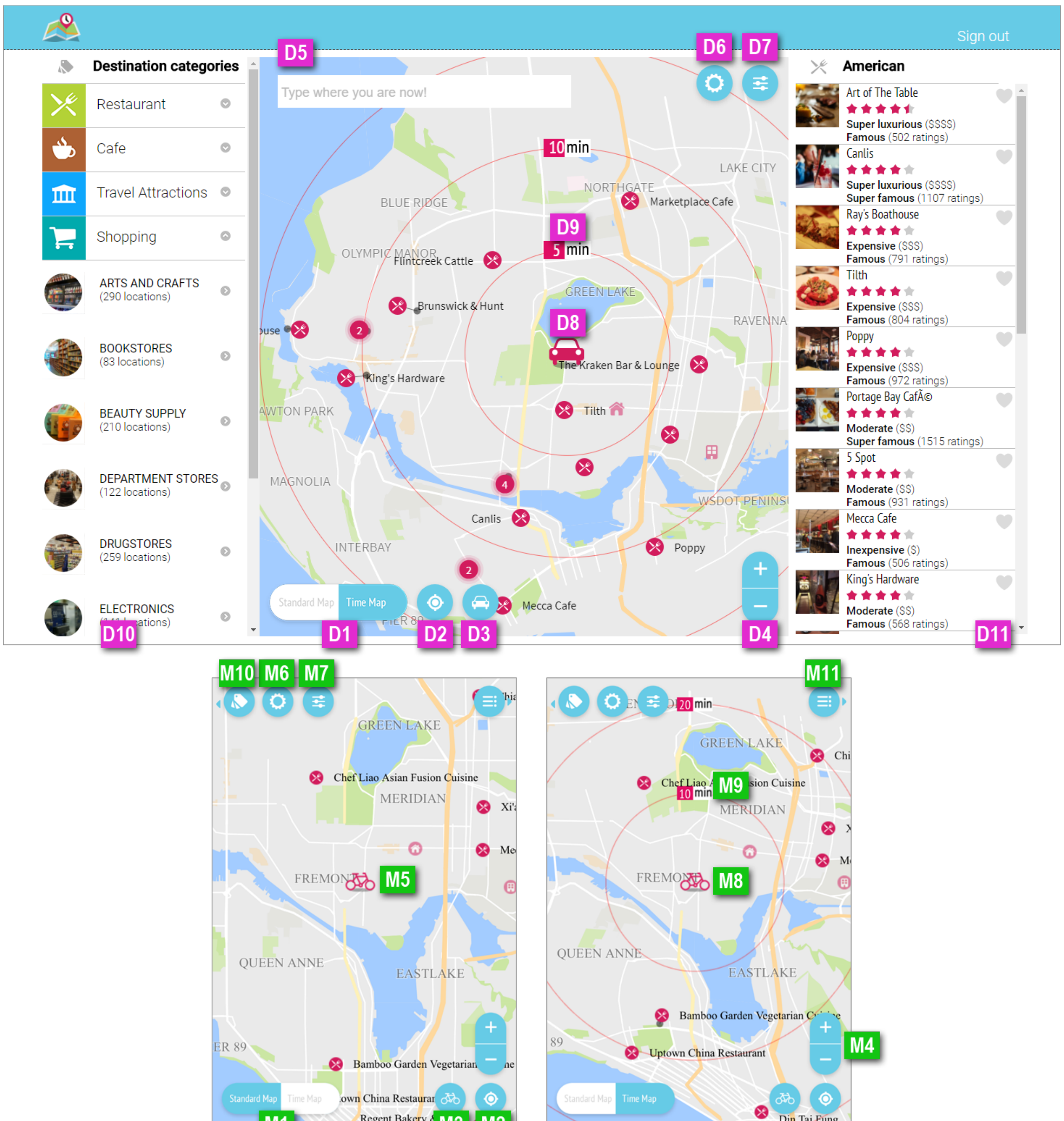

Figure 6.10. Traffigram Ver. 3.0 user interface design for a Desktop platform (top) and a mobile platform (bottom) and major features. Boxes start with D indicate the feature is for desktop whereas M indicate the feature is for mobile.

6.10. A UI screen at the top shows Traffigram works in a desktop platform, while two mobile screens at the bottom shows Traffigram works in a mobile platform. The figure overlaps UI components with boxes started from D (which denotes “Desktop”) or M (“Mobile”). Specific features of each UI component are presented as follows:

- **Switching toggle (D1, M1)** triggers switching interaction.
- **Resetting origin button (D2, M2)** resets the origin based on GPS information.
- **Mode of transportation button (D3, M3)** presents a pop up that helps users to select one of the mode of transportation among vehicle, bicycle, or on foot.
- **Zoom buttons (D4, M4)** trigger map zoom interaction.
- **Modification of the origin (D5, M5)** is designed in two different ways. In the desktop UI, a user can type in an address. In the mobile UI, a user can long press the origin and drag it in WM mode. Changing the origin is disabled in DC mode in both Desktop and Mobile.
- **Setting button (D6, M6)** opens a pop up in which a user can set the addresses of their home and office.
- **Filter button (D7, M7)** opens a screen that presents filters.
- **Highlighting type 1 (D8, M8)** is triggered with tap an existing isochrone (Type 1) in DC mode.
- **Highlighting type 2 (D9, M9)** is triggered when a user taps an origin or existing isochrones and drag inward or outward (Type 2) in DC mode.
- **List of location types (D10, M10)** is available.
- **List of locations nearby (D11, M11)** presents locations within geographic bounds in a screen.

6.4 Conclusions

In this section, I introduced three versions of Traffigram whose later versions were built upon the earlier versions. The overarching direction that I aimed to achieve through building the systems was enabling users to use DCs in real situation. Therefore, the main direction of this evolution of Traffigram was toward making DCs a more interactive and intelligible system, which were the core challenges we reviewed in § 2. The techniques and interaction types introduced in § 3 and § 4 were gradually adopted to develop the systems. In the next section, I introduce the process and results of a series of studies conducted to understand potential of DCs in the lab and in the wild.

Chapter 7. EMPIRICAL EVALUATIONS

Cartograms, which apply distortion on maps to visualize statistical figures tied in geography such as population, GDP, or travel times, have been mainly seen as a useful tool to effectively deliver insights in educational context or dramatically present stories of specific themes [11, 76]. Yet, there has been a relative lack of research that aims to examine the potential of DCs as a decision-making support tool in people's every day spatial exploration. Progress on digital maps has improved the capability of understanding information using a variety of digital devices. Such progress has led people to achieve a broader line of tasks related to spatial information-seeking. One notable aspect of knowledge often sought by digital map users is temporal information. For instance, users may wish to select a place to live based on travel times from their workplace, evaluate the traffic situation downtown at a particular time, or select a branch bank in an unfamiliar area. Presenting a travel time from a point to another point can be relatively easy. However, presenting travel times to multiple points on cartographic layout can be difficult. In such case, it is crucial that limitations in human working memory must be addressed to support cognitive offloading [21]. DCs apply the encoding of position to visualize travel times to multiple destinations from an origin, which can enable users to assess to their destinations with relatively less cognitive effort compared to other solutions such as colored-coded road segments or free-form isochrones.

However, despite of the long history of research in DCs for multiple decades [24], such potential strengths of DCs for spatial information-seeking and exploration have not been thoroughly examined, and DC's usefulness in spatial exploration and adoptability remains elusive. To have a deeper understanding of DCs' effect in spatial information exploration, I conducted a series of studies in the lab and in the wild. This chapter introduces the methodologies and the results of the studies. In evaluation, the three versions of Traffigram were used. Using Traffigram ver. 1.0, I explored the cases where DCs can be more useful than the existing map solutions in static settings in the early stage of DC research. In the next round of the studies, I used Traffigram ver. 2.0 and aimed to understand the benefits and drawbacks of using DCs in interactive settings. Finally, I report on the results of a recent study where I used Traffigram ver. 3.0 and examined adoptability of DCs through a deployment study. § 7.1 introduces the study results based on Traffigram ver. 1.0 and 2.0 that I conducted in lab settings. § 7.2 introduces the study with Traffigram ver. 3.0 that was conducted in the wild. Although "I" is used as the subject throughout this section, I acknowledge that the outcomes in this section are the results of collaboration with my colleagues.

7.1 IN THE LAB

7.1.1 *Evaluation (Traffigram Ver.1.0)*

7.1.1.1 Methodology

In this stage of the evaluation, I conducted a usability test to evaluate how DCs might be perceived and used. With my collaborators, I recruited 25 participants (19 male), 12 in the USA and 13 in South Korea, via sending e-mails to student mailing lists. All participants were university students. Prior to each session, I verbally explained the concept of a DC to participants. After participants felt comfortable with the main purpose of DCs, we conducted the session. Participants completed four tasks and one design preference survey. After the survey, we inquired about their perceptions of the Traffigram user interface. Participants were tested with several visualizations generated by Traffigram via a think-aloud protocol. All images used in the study were displayed on a computer monitor. Twelve subjects lived in the Seattle area were familiar with the area that Traffigram covers. In contrast, the 13 participants from South Korea had never been in Seattle and had little knowledge of the area. None of the subjects dropped out through the tasks and analysis was performed on all responses (n=25). The orders of every comparative analysis (i.e. task 2 and task 4) were generated using a Latin square to counterbalance carryover effect.

Task 1. Landmark Matching: The first task was designed to understand the effect of distortion on map recognizability. We presented two images to participants on the same screen. One of the images showed a non-distorted map containing area, district, and freeway information with seven different landmarks (See Fig. 7.1 (a)). The other image showed a distorted Traffigram visualization with the same seven landmarks. Participants were asked to move seven pin icons in the distorted map to where they thought each landmark belonged. There is a possibility that geo-

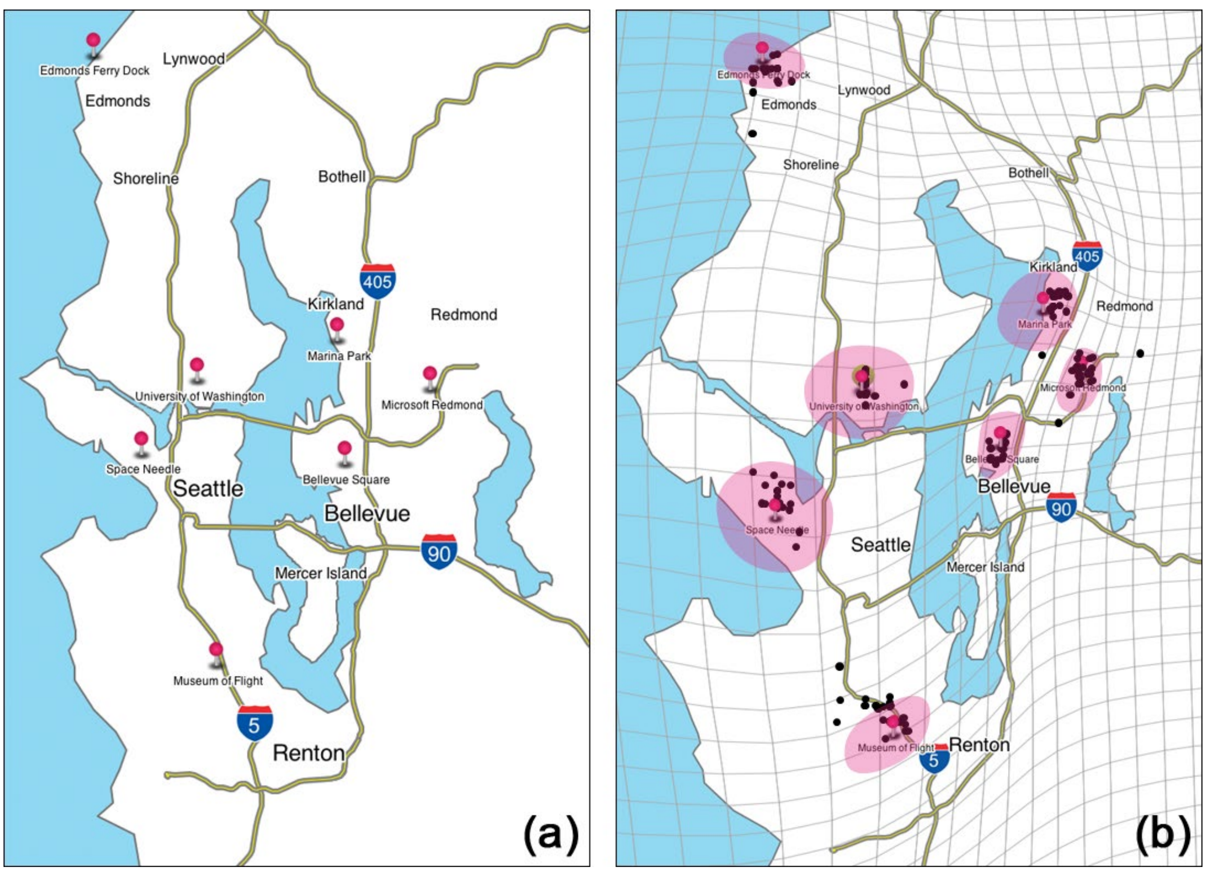

Figure 7.1. Landmark matching:

(a) Landmarks plotted on a WM, (b) Landmark matching results

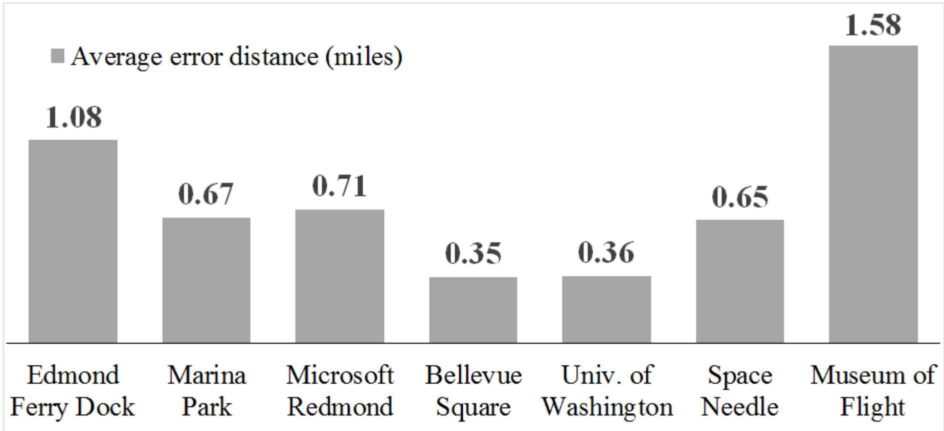

Figure 7.2. Average error distance on Task 1.

temporal disparities (such as a congested route or speed limits) may cause the isochrones to contort in a highly eccentric manner; in this case, the distortion will obviously break spatial integrity. For more realistic applicability. however, Traffigram must provide information without hampering readability. We used one of the most distorted results to make the experiment more challenging and to account for this possibility.

Figure 7.2 shows the test result. The average time on the task was 66.7 sec. (SD = 31.0). Fig. 8 depicts a result of this task. Magenta circles represent a 1.5-mile spatial radius for each landmark. To analyze task error, we used average Euclidian distance of discrepancy between user's selected point and actual point. In this task, we hoped to avoid the issue that smaller less-congested grid areas might be harder to identify with their icons. Interestingly, we found that this was not the case, since we observed the highest user errors for the Museum of Flight, which was only the fifth most congested area out of seven spots, which in part seems to dismiss our rationale. These errors may be due to the fact that there are very few visual references (coastlines, crossings, bridges, etc.) by the museum. In contrast, Bellevue Square has the second smallest grid area, but none of the participants identified the place incorrectly. The proximity of the city name may also have helped in this case.

Task 2: Where do we meet: In task 2, I studied how efficiently a DC provides directions when two or more people have different initial positions, yet want to know the traffic situation for a given time. Our hypothesis was that users would recognize traffic situations more easily with Traffigram than with a map utilizing a color-coded road segments. The scenario was presented to the subject as follows: one person is at one location in the University District, and one person is at one location in Redmond, and they want to meet on Wednesday at 4:00 p.m. at whichever place is closest (temporally) to the other. We then presented two Traffigram visualizations with origins at, respectively, the location in University District (see Fig. 7.3 (a)) and the location in Redmond (Fig. 7.3. (b)) and a visualization with color-coded road segments (Fig. 7.3 (c) – Google Maps were used to construct this view) in rotation. The visualization with color-coded road segments depicts an asymmetric traffic condition; the bridge connecting the two areas has different amounts of congestion depending on the direction of travel. Participants were asked to determine which commute was shorter based on time and relevant traffic issues. This task illustrated the degree to which Traffigram aided the correct decision (meeting at the location in Redmond) and how efficiently it led to understanding compared to the use of a traditional traffic visualization.

Table 7.5 relays the experiment results. Time-on-task between a visualization built by color-coded road segments and a DC were significantly different ($t=-3.06$, $p<0.05$) and the correct answer ratio of condition in a DC (96%) was also higher than the ratio in the visualization with color-coded road segments (72%). The information decoding time on color-coded road segments

Table 7.5. Time on task and correct answer ratio on Task 2

	Average time on task	Correct answer ratio
Color-coded road segments	25.3 sec.	72%
A DC	14.3 sec.	96%

and a DC between American and Korean was not significant ($F(1,23) = 1.46$) which denotes the participants' prior knowledge didn't affect the outcome. As the task 1 didn't ask participants to read travel time through a DC, they started reading travel time using DC for the first time in the task 2. Through the sessions, we observed that the participants understood the concept of Traffigram as they counted rings on the map or estimated length between two places to answer quickly.

Task 3. When should I head home: Even when the origin does not change, traffic is a time-dependent metric. The third task was devised to evaluate whether a DC could enable users to understand ever-changing traffic information. In this task, participants were asked to decide when they would like to return home from work. On a computer screen, we presented one WM (see Fig. 7.3 (a)) and three DCs centered on their fictional work location of one location in Fremont from 4:30 p.m., 4:45 p.m., and 5:00 p.m. (see Fig. 7.3 (b), (c), and (d)). We then asked participants which departure time minimizes their time on the road. 23 out of 25 participants (92%) provided the correct answer of 4:30 p.m. The difference between Americans and Koreans was not significant ($F(1,23) = 1.92$, n.s.). We also evaluated how users became familiar with DCs through this task as well, as the average time-on-task decreased 38% compared to Task 2, even though this task involved an additional image (On the previous task, participants spent on average 14.3 seconds, and for this task, 8.9 seconds). 24% of the participants chose their answer within 6 seconds. 52% of participants stated they found this task the most useful among all the tasks they had conducted.

Task 4. Pizza Delivery: The main purpose of this experiment was to understand DCs' utility when a user is considering multiple potential destinations. A fictional pizza restaurant owner runs a delivery service near the University of Washington. The task is to sort the closest delivery location based on travel times. In practice, this task is somewhat artificial since an algorithm could

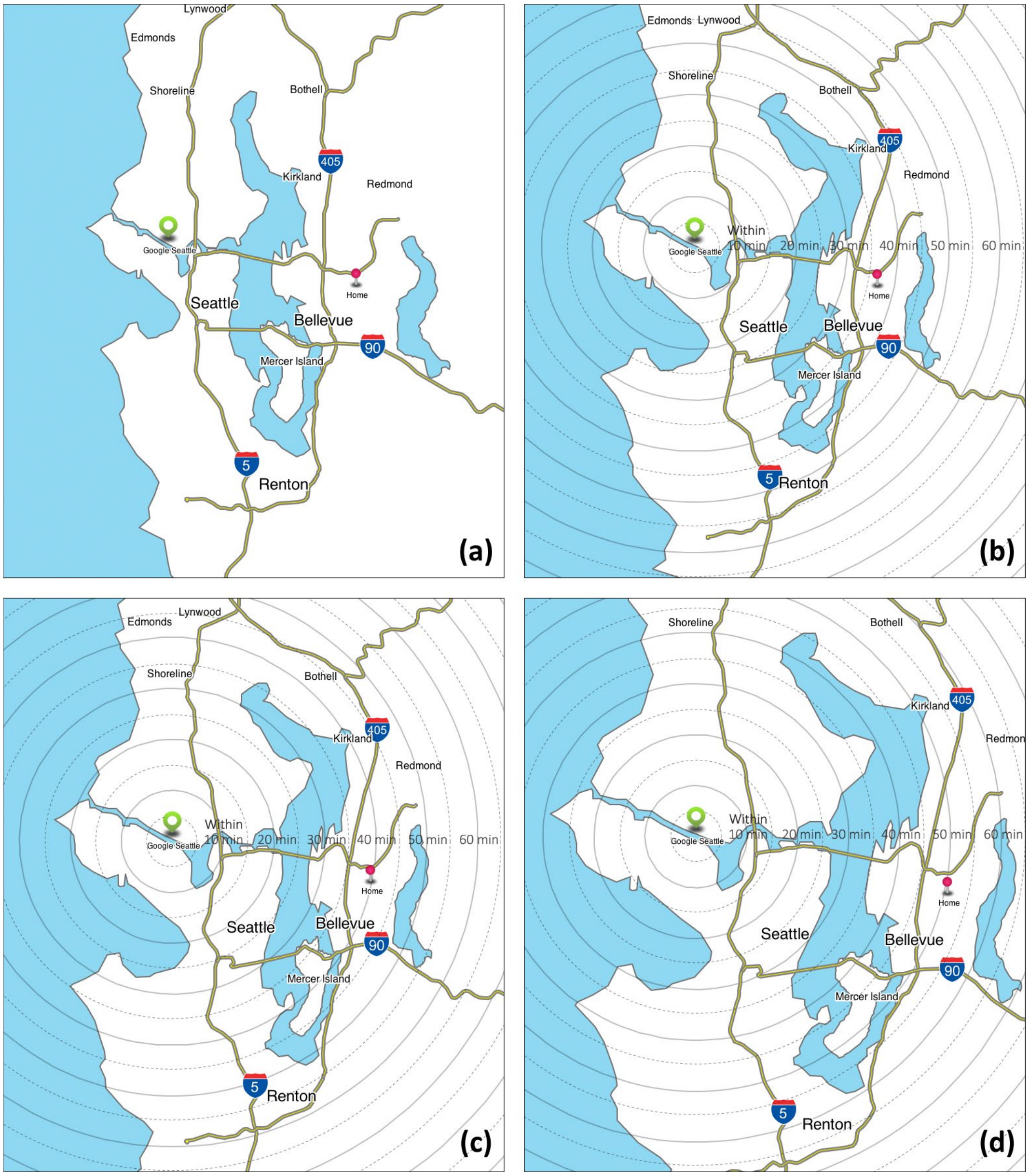

Figure 7.3. When should I head home?

(a) a WM, (b) a DC at 4:30 p.m., (c) a DC at 4:45 p.m., and (d) a DC at 5:00 p.m.

easily sort the orders. However, we wanted to test the situation where users were selecting from among multiple destinations visually. A better task, and one to be studied in future work, would be to select from multiple rental homes assuming a fixed work location. After explaining the scenario, we asked participants to sort pizza orders from longest to shortest travel time using two different visualizations; a DC (Fig. 7.4 (left)) and a list view with address (Fig. 7.4 (right)).

The difference between the task times presented in Table 7.6 is significant (p < 0.0001). The time difference between American and Korean participants was not significant (F(1,23) = 0.03, n.s.). Participants completed the task 1.7 times faster with the DC. We also asked the participants how stressed they were during each sub-task using a Likert scale from no stress to highly stressed and 88% of participants answered using a DC was less stressful. Even though a DC lacked the capacity to inform users of the exact travel time, participants still felt less stressed completing the task with the visualization. Thus, we identify the potential usefulness that a DC has when a user is located in one spot and (s)he has multiple choices of destination.

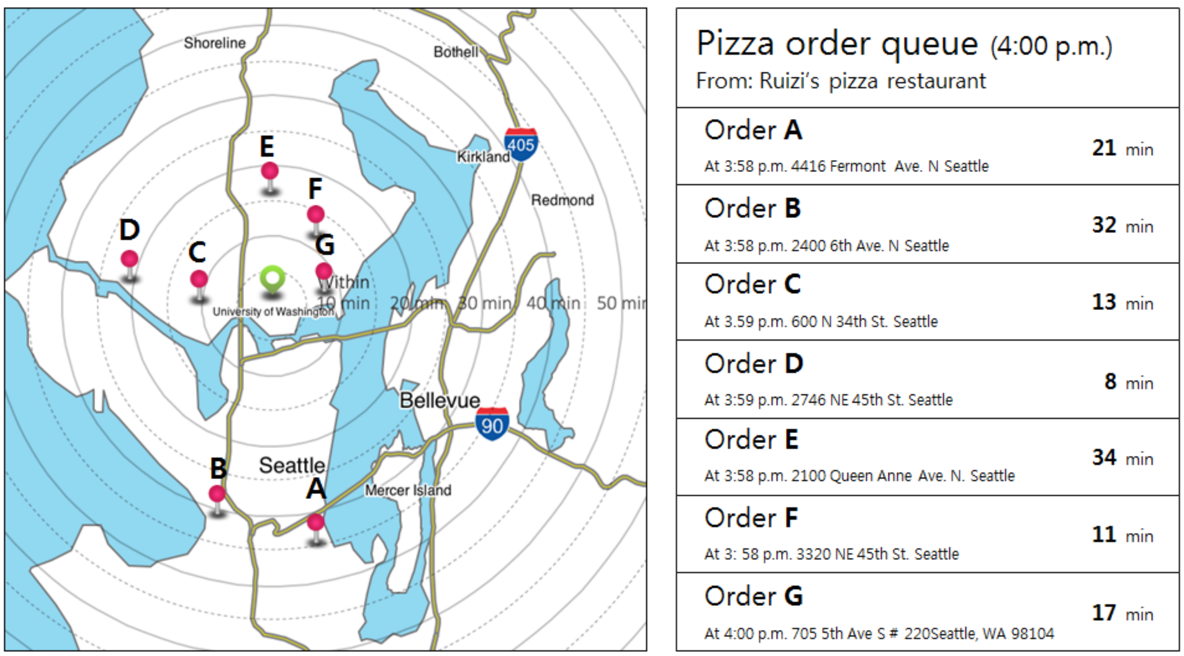

Figure 7.4. Pizza order screen constructed with a DC (left),
List of destinations for pizza order (right)

Table 7.6. Time on task and correct answer ratio on Task 2

	Average time on task	Correct answer ratio
List view	36.7 sec.	92%
A DC	21.9 sec.	96%

Post-task survey: After completing the four tasks, we surveyed participants' design preference from among variations Fig. 6.6 (b) – Fig. 6.6 (f). We asked participants to choose one or two design variations that were visually intriguing. After that, we asked them to select the most practical design variation. The result of this preference survey and some of their insights are listed in Table 6.7. Fig. 6.6 (c) received the highest number of votes for both criteria; several subjects mentioned that 6.6 (c) clearly explains travel time and is easy to recognize. Furthermore, many subjects mentioned that they found 6.6 (c) to be aesthetically beautiful. Meanwhile, many participants responded negatively to design variations 6.6 (e) and 6.6 (f). Responses included: 6.6 (e) is not detailed and is difficult to recognize the difference between normal maps. One subject mentioned that he couldn't find any information he wanted to know in 6.6 (e). Three participants remarked they didn't prefer 6.6 (f) because it was visually too busy. For the aesthetic criterion, survey results depicted participants' varied preferences compared to the practical criterion; many people had difficulty deciding among 6.6 (b) through 6.6 (d). From the aesthetic perspective, people mentioned that colored circles are clear, easy to perceive, and more attractive than interlaced thick and thin lines. Some people remarked that 6.6 (d) has potential because it supports their need for a sense of distance. For the practical criterion, more than 50% of participants chose 6.6 (c). Many remarked that the power of Traffigram lays in enabling people to understand the variation in travel time from their place of origin to their destination. Participants felt that

Table 7.7. Design preference (Voting portion)

	6.6 (b)	6.6 (c)	6.6 (d)	6.6 (e)	6.6 (f)
Design Variation					
Aesthetic preference	17%	39%	28%	11%	4%
Practical perspective	20%	52%	20%	0%	8%

concentric circles (i.e. isochrones) helped achieve this goal. Interestingly, in both groups, participants suggested a new design variation; combining 6.6 (c) and 6.6 (d), so that users can perceive travel time and distance concurrently.

7.1.1.2 Discussion

Implications for Design: The first study was conducted to learn the potential usefulness of DCs compared to the existing solutions that support similar tasks. Results of the studies stresses the perceptual efficiency of using DCs when a user compare travel times to multiple destinations. We present some of the recurring feedbacks we got from our participants which the researchers who study DCs can consider:

- **Present equidistant maps and a DC simultaneously when necessary:** Seven participants mentioned that a DC would be more useful if an equidistant map (such as a WM) is placed next to the DC so that the they can get a sense of both distance and time. Two subjects mentioned their worry about the possibility of illegibility caused by severe distortion. We believe this design decision could relieve that problem.

- **Time and the origin setting is considered as useful from participants:** Five participants mentioned preferences for inputting position or time while the tasks (the features are supported in Traffigram 1.0, but note that participants used static DCs and they did not have a chance to use Traffigram ver. 1.0). Two of them proposed a specific user interface.
- **Interactivity and seamless experience**: Five participants were concerned about the interactivity of the map if they were to frequently change user origin and time information. This implies the necessity of developing techniques that enables DCs to become more interactive.
- **Visual style preferences**: Participants preferred 6.6 (b): concentric circular view, 6.6 (c): color-interlaced concentric circular view and 6.6 (d): grid view. The three styles take 85% of voting from the participants for aesthetic and 92% for practicality in the post-task survey.

According to an annual study of national driving patterns, US residents have wasted $121 billion due to traffic congestion in 2011, and this number is rising. A tool for understanding traffic patterns could have a positive impact on sustainability. Our user study focused on the potential applicability of a DC in real life situations. Participants stated DCs could be a practical tool when they choose departure time or location based on traffic conditions. The variable nature of the time between urban locations often frustrates urban travelers. DCs could assist in clarifying this traffic uncertainty. Finally, we identified that DCs can be especially useful when users have to select one destination from among multiple choices; for example, recently-hired employees looking for a place to live in their new community or people selecting a restaurant during rush hour. Commonly-used maps utilizing equidistant cartography are not optimal for presenting multiple destinations and travel times simultaneously. The study also revealed some limitations of ver. 1.0 which I aimed to improve in ver. 2.0 (e.g., implementing techniques for enabling construction of interactive DCs).

7.1.2 *Evaluation (Traffigram Ver. 2.0)*

In the second round of evaluations, I examined effects of some techniques and interaction types introduced in § 3 and § 4 (e.g., GAP and switching interaction) in more interactive settings using Traffigram ver. 2.0. This round of evaluation consists of the two studies. In the first study (S1), I design 3 sets of static maps to understand the impact of DC constructed with GAP with my collaborators. Our goal was to see whether GAP can support people enough to overcome the novelty of DCs and find benefit of using DCs over EMs within their everyday map use scenarios. We conducted qualitative interviews to capture users' subtle impression. Then we conducted a controlled study (S2) using a working mobile platform (i.e., Apple iPhone 6) where users can fully experience the interaction with the system. The goal was to see how and to what extent DC and the interaction deign improve the quality of a map system in realistic settings.

7.1.2.1 S1: Understanding Adoptability of DCs constructed by GAP

In S1, we conducted semi-structured interviews with 15 participants (5 females, 9 males, and one chose not to report gender) recruited through email lists that are used for recruiting subjects at a university in the Seattle area. No participants reported they knew about DCs. All were 18 or older and resided in the Seattle area. The study was conducted in a lab, using a single computer.

To understand the adoptability of DCs constructed by GAP, we derived three scenarios that the participants are likely to experience in their everyday life:

- **Scenario 1:** A taxi driver finds the customer (s)he can reach in the shortest amount of travel time (*1 factor* to consider, among *7 candidates*). Fig. 7.5 (a) and (b) are used.
- **Scenario 2:** A person selects a restaurant where (s)he will dine with family on a Friday evening. The person considers review ratings and travel times (<20 min.) (*2 factors* to consider, among *14 candidates*).

- **Scenario 3**: A person finds a new place to stay by considering the price, size, travel time to an office, and neighborhood (*4 factors* to consider, among *20 candidates*). The interface in Fig. 7.5 (c) is used as a DC condition in Scenario 3).

Figure 7.5. Restaurants in downtown Seattle shown with (a) WM, and (b) DC. (c) An interface used in S1 for scenario #3 (DC).

Depending on the scenario, the participants considered a varying number of factors and candidates; as they proceed, the complexity of the decision increases. For each scenario, we prepared a set of map interfaces; one projecting the destinations with EM and the other using GAP. Because Scenario 2 and 3 require the participants to consider more than just travel time, we presented a separate list that shows every marker's attributes along with a map.

At the beginning of the session, the participants received a brief verbal explanation of the core concepts of DC. Specifically, they were told about: (a) the existence of the origin in DC, (b) the meaning of isochrones, and (c) the fact that the distance between the origin and each marker denotes travel time in DC. Then, for each scenario, the participants were asked to make decisions with a WM and a DC respectively. The two conditions were presented in a reverse counterbalanced order. Once the participants finished each scenario, they were asked if they preferred either of the map interfaces, and if so, why. The participants had a follow-up interview after they finished every scenario. The main aspects asked were: whether they had difficulties in obtaining relevant information in a DC (Aspect 1), whether they found a DC useful and would like to adopt it in real world situations, and if so, why (Aspect 2), and how the degree of complexity of the decision influenced a DC's usefulness (Aspect 3).

In terms of the results, the participants preferred a DC over a WM in every scenario. Fig. 7.6 shows in how many cases a WM or a DC were preferred for each scenario. In total, they preferred using a WM 7 times (16%), a DC 32 times (71%) and they expressed no preference 6 times (13%).

Aspect 1. Obtaining relevant information using a DC: In terms of how participants interpreted information using a DC, 10 participants (67%) reported they found it straightforward enough to understand from the beginning. One challenge in interpretation that was noted was the use of the anchors. Four said that the meaning of the anchors was not clear at the beginning, but it

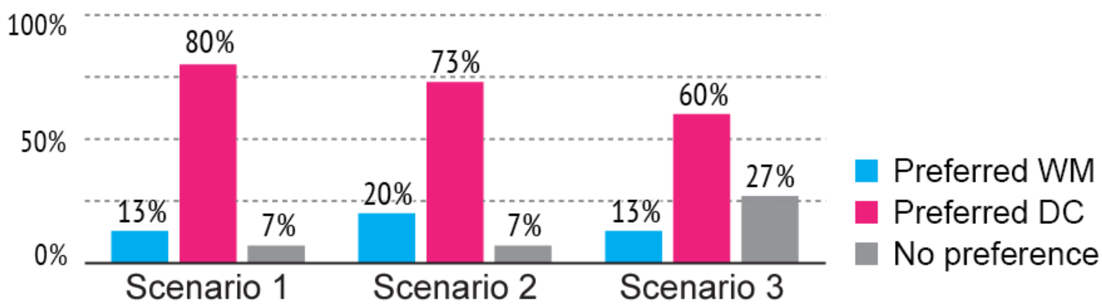

Figure 7.6. User preference results in Study 1

became clear as they experienced more scenarios. Only one participant felt anchors made it difficult to understand the information.

Aspect 2. Adoptability of a DC (and reasons): Regarding adoptability, 12 participants (80%) reported they would like to adopt a DC. They found a DC more useful than a WM in accomplishing the scenarios. Analysis of feedback from the participants about the usefulness of a DC revealed two general groups: *at-a-glance* group (7 participants) and *include-and-exclude* group (5 participants). The participants in the *at-a-glance* group mentioned that they were able to grasp travel time at a glance in a DC, and found this characteristic helped them make decisions quicker. The *include-and-exclude* group found a DC particularly useful when visually grouping the candidates. These participants felt that such grouping made it easier for them to exclude candidates that did not meet their criterion in terms of travel time, which allowed them to pay more attention to other factors. Three participants (20%) mentioned that they are not interested in adopting a DC since they decide a destination before they travel, or don't think travel time is an important factor for choosing a destination.

Aspect 3. Decision's complexity and impact on usefulness: We were particularly curious as to whether the level of complexity of the decisions influenced the extent to which the participants felt a DC was useful. 6 participants (40%) reported a DC was more useful in simple scenarios (i.e., the *simpler-the-better* group). They reported that a DC helped them make travel decisions faster, but as they were asked to consider factors other than just travel time, they felt less gain. On the other hand, the other 5 participants (34%) thought a DC was actually more helpful in complex scenarios (i.e., the *complex-the-better* group). They said they could simplify the decision by excluding places located “outside of the circle”.

Relations between Aspect 2 and Aspect 3: While participants’ opinions diverged in Aspect 2 and Aspect 3, we realized that 5 out of 6 participants in the simpler-the-better group were also in the at-a-glance group, and 4 out of 5 in the complex-the-better group were in the include-and-exclude group. This strong inter-group relationship implies that there are strategy similarities between the reasons (a) why participants felt a DC is useful and (b) their preference regarding the task complexity. In other words, the DC’s visual glance-ability helped users make quicker decisions in simple tasks, whereas the visual grouping aspect helped reduce the effort needed for more complex tasks.

7.1.2.2 S2: Exploring effect of interaction design of DC

In S2, we aim to fortify the findings from S1 and evaluate the quality of interactions of our system in realistic settings with a measurable user behavior. The specific RQs are as follows:

RQ1: Can the DC based solutions (i.e., DCs, or DCs *with* switching interaction – we call this as WM+DC) alleviate some of the problems commonly faced by WM users? DCs present precise travel time which enables instantaneous comparisons between locations without the need for holding any additional information in memory. Therefore, I expect that using DCs or WM+DC would decrease the perceived cognitive load in scenarios where comparisons-and-selections involving travel time are needed.

- **H1.1:** The perceived cognitive load of using DCs or WM+DC will be lower in comparison to WM alone. As DCs allow users to consider more options with a lower attention burden, we expect that decision time and decision accuracy would both be higher when using DCs or WM+DC than using WM alone.

- **H1.2:** The amount of time needed for accomplishing the task using DCs or WM+DC will be lower compared to WM alone.
- **H1.3**: The decision accuracy using DCs or WM+DC will be higher than using WMs alone.

RQ2: What is the value of switching interaction? In scenarios where information about the precise geographical surroundings is required, DCs may not be useful and a combination of DCs and WMs may be required. Consequently, we explore the value of the switching interaction in scenarios where both precise geographical and temporal information is needed.

In terms of study methodology, we recruited 16 participants (8 females and 8 males) through the same email lists we used in S1. All were 18 or older with a mean age of 29.7 years. 87% held a graduate or professional degree. The study took under 1 hour and every participant was rewarded $15 for participation. We conducted a within-subject lab study to compare the Traffigram ver. 2. 0 against another system where only WMs are available. The former provides travel time with DCs as well as the text upon a user request, whereas the WM-only system provides travel time by the text only. Every participant used the same mobile phone we provided. At the beginning, we briefly introduced our mobile map system and the concept of a DC to participants. Then we gave 2 short tutorial tasks to verify their understanding of a DC. These were: finding the nearest location, and counting the locations reachable within 10 mins. After that, the participants went through the following stages:

Stage 1. Comparing a WM to a DC: We asked participants to complete two similar comparison-and-selection scenarios in which a user considers (a) travel time, (b) ratings, (c) number of reviews, and (d) geographical reality aspects at a coarse level of detail (i.e., understanding general areas of certain neighborhoods or geographical aspects, e.g., the destination placed at seashores) of destinations for making a decision. We created two such scenarios that asked participants to find a particular restaurant or a bar. We presented these scenarios in a reverse counterbalanced order, which means each participant made decisions on one restaurant and one bar using a WM or a DC respectively. After completing two scenarios, participants filled out a survey asking for direct comparisons between a WM and a DC. Then we briefly introduced switching interaction to participants.

Stage 2. Comparing WMs to WM+DC: The procedure was the same as in Stage 1, with two changes: (1) we used the scenarios, in which understanding the geographical reality is needed at a high level of detail on top of travel time information (i.e., relative physical proximity of multiple locations). We created two similar scenarios that required the users to make a quick travel plan for exploring nearby parks or museums by selecting the closest ones in terms of travel time, then further to identify another park or museum that is geographically closest to the selected ones, so that walking is possible; (2) we added questions related to the use and benefits of the switching interaction. After this stage, we conducted a semi-structured interview.

Analysis: For each scenario, we measured the perceived cognitive load (H1.1) using items from NASA TLX questionnaire [77]. These are: (a) mental demand, (b) overall performance, (c)

Table 7.8. Experimental results from Study 2

	Stage 1		Stage 2	
Measure	WM	DC	WM	DC with switching interaction
Task time (sec)	95.45	44.88**	160.63	133.38*
Accuracy (%)	93.75	93.75	88.00	94.00
Mental demand	5.19	3.38**	5.75	4.44*
Effort	5.19	2.88**	6.44	4.06**
Performance	6.67	7.38	5.75	6.88
Frustration	3.88	2.38*	4.94	2.62**

Significance against EM in each stage: ** $p<0.01$, *$p<0.05$

frustration level, and (d) effort. Following indications from [77], we dropped other individual subscales. We measured task time (H1.2) using a stopwatch, and accuracy (H1.3) by recording correct answer ratio. For direct comparisons between the conditions, we used (a) preference, (b) ease of accessing the information, (c) ease of understanding the information, (d) confidence in understanding the geographical surroundings, and (e) confidence in understanding the temporal surroundings. Additionally, for the second stage, where the switching was introduced, we asked for the evaluation of a number of aspects of the switching interaction on a 7-point differential scale. For analysis, a paired-samples t-test was used to compare the impact of map interfaces (i.e., WMs and DCs in Stage 1, and WMs and WM+DC in Stage 2) on dependent measures. We also collected qualitative feedback from the survey and the semi-structured interviews to understand the usefulness of DCs and WM+DC. We analyzed the feedback by coding the quotes and organizing the codes into themes with affinity diagramming.

Results: Table 3 shows a summary of the behavior and perception measures in both stages. Stage 1 refers to the comparison between WMs and DCs, while Stage 2 refers to the comparison between WMs and WM+DC.

H1.1: For three of the four measured aspects of the cognitive load, the DC and the DC with switching interaction offered a significant improvement. In Stage 1, mental demand has been significantly lower for a DC ($M=3.38$, $SD=1.59$) as compared to a WM ($M=5.19$, $SD=2.26$) ($p<0.01$). Similarly, effort in a DC ($M=2.88$, $SD=1.09$) has been significantly lower than in a WM ($M=5.19$, $SD=1.87$) ($p<0.01$). Finally, the level of frustration reported for a DC ($M=2.38$, $SD=1.54$) was also significantly lower as compared to a WM ($M=3.88$, $SD=2.33$), with $p<0.05$. However, no significant difference in perceived performance has been found between the conditions. For Stage 2, it can be seen that the tasks were, in general, considered more difficult.

The comparison results were, however, similar to Stage 1: mental demand significantly lower in a DC with switching (M=4.44, SD=2.22) as compared to a WM (M=5.75, SD=1.84), $p=0.04$; effort significantly lower in a DC with switching interaction (M=4.06, SD=2.02) as compared to a WM (M=6.44, SD=2.13), $p<0.01$; and frustration significantly lower in a DC with switching interaction (M=2.62, SD=1.71) as compared to a WM (M=4.94, SD=2.02), $p<0.01$. The difference in perceived performance was not significant either. H1.1 is partially supported, as the difference in the perceived performance was not significant.

H1.2: The measured task completion time in Stage 1 was significantly lower for a DC (M=44.88, SD=18.43) as compared to a WM (M=95.19, SD=62.26) with $p<0.01$. Similar results were observed in Stage 2, where task completion time was also significantly lower for WM+DC (M=133.36, SD=44.78) as compared to a WM (M=160.63, SD=46.28) with $p<0.05$. These results indicate that the DC and the DC with switching interaction indeed allowed users to take advantage of the visual support for comparing multiple locations and make faster decisions. H1.2 is supported.

H1.3. There was no significant difference in the accuracy between a DC and a WM in Stage 1 and between a WM and WM+DC in Stage 2. As we did not limit the task completion time, and the differences in task completion times are significant, it is likely that the participants spent more time to achieve the same level of accuracy in both conditions. H1.3 is rejected.

To address RQ2, we turn to interface comparison measures, feedback about switching interaction and the interview data.

Finding 1. WM+DC generally preferred over DC: In terms of general preference, in Stage 1, 87% of the participants preferred DC and 25% preferred it strongly. A similar preference was expressed in terms of other comparison measures we used, except for confidence in understanding the geography. The participants indicated that DC simplified the comparison process and that they liked the ability to see the time information directly. P11 remarked: *"Definitely easier as I can clearly see which places I needed to consider inside the time circle."*

Adding the DC with switching interaction in Stage 2 made the preference for DC based solution even stronger with all the participants preferring DC with switching interaction and 38% preferring it strongly. Participants specifically commented that having the ability to switch was helpful for understanding how the two maps are connected. P16 mentioned: *"It was interesting to see how the map was distorted as I was using the time map. It actually can be helpful if time is one of my priorities."*

Finding 2. WM+DC improves understanding of geographical surroundings. In Stage 1, despite working with scenarios that prioritized travel time, 70% of participants still expressed the preference for a WM when rating confidence in understanding the geographical reality. They stated that the distorted geography could be confusing especially for areas they are unfamiliar with and also felt that a WM was more familiar. P6 said: *"In the time map, many geographical features were transformed, so I wouldn't believe them as is."*

In Stage 2, when they worked with even more challenging scenarios requiring a precise understanding of geographical reality, but also used a DC with switching interaction, the ratio of participants that preferred a WM for this aspect shrunk to just 38%. Participants who expressed such increased confidence in understanding the geographical reality reported that using WM+DC was easy and comfortable. They felt that DCs with switching interaction provided more clarity and a deeper understanding of the relation between WMs and DCs. P9 mentioned: *"Using both maps provided more clarity and deeper understanding of the areas than using just distance map."*

Finding 3. WM+DC improves usefulness and increases the adoption. The survey after the Stage 2 revealed various positive aspects of the DC with switching interaction. More than 90% of the participants considered the WM+DC useful and 81% considered it important. 64% of participants reported that they used the WM+DC frequently while accomplishing the task. Also, 86% felt it helped them clarify their understanding of the information. P 15 noted: *"(...) the details of the location provide the travel time regardless of its distance, but that conflicts to the visual information from the map itself. Switching reduces that kind of cognitive/perceptual conflicts."*

The analysis of the follow-up interviews revealed more specific reasons why the participants generally felt the WM+DC was useful and important. 88% of participants felt (a) the DC with switching interaction was useful because it helped them easily track the placement of the particular location between time and space. Also, (b) 75% mentioned the DC with switching interaction helped them obtain the information needed for accomplishing the task with less effort. Finally, (c) 69% found the DC with switching interaction useful for preserving the overall understanding of the map for space and the time.

We observed that many participants were initially skeptical about using a DC due to its novelty. However, most found the DC with switching interaction to be useful in alleviating the initial adoption barrier. For example, P12 said she didn't expect the DC to be useful in the beginning. After the study, however, she reported that the DC with switching interaction helped her track the locations of interest between the two layouts and made her feel "relieved" while using DC. Also, 8 participants said WM+DC helped them familiarize with the DC layout which they have never experienced before. Interestingly, P1 and P3 reported that with an animated transition, the DC felt less distorted than they expected.

7.1.2.3 Discussion

In general, the user preference indicated between WM and DC in S1, as well as the user behavior metrics and qualitative feedback in S2 are both favorable towards DCs. Such similar results in both studies suggest that urban users can get practical benefits from using DC-based solutions in similar use cases. The potential reasons *why* and *how* DCs can aid users were specifically identified in S1 (i.e., relations between Aspect 2 and 3).

Even though we expected the potential of using DCs, we thought the novelty of DCs to the general users is the most challenging barrier that the new design should overcome for facilitating user adoption of a DC in everyday decision-making. Consequently, the design motivation behind GAP and the WM+DC was to lessen the negative side effects that stem from the unfamiliar aspects of a DC to the extent possible. In designing GAP, the primary goal was to understand a way to minimize the amount of such distortion from a WM to help the users retain the geographical context. In addition, a DC with switching interaction was designed to provide the choice of layout most adequate for user's situation and to help easily relate the context between WM and DC while transitioning between the two. The high adoption intention in S1 and the positive user feedback about the DC with switching interaction in S2 (i.e., Finding 3) support the claim that GAP and the DC with switching interaction can help people familiarize with DCs and increase the chance of adoption.

7.2 In-the-Wild

7.2.1 *Evaluation (Traffigram Ver. 3.0)*

7.2.1.1 Methodology

In 2017, I used Traffigram ver. 3.0 to run a deployment with my collaborators. We sought to understand whether the perceived benefits of using DC outweigh the barriers of DC *adoption* for use in the wild, and whether users are motivated to continue using DC in the long run. To answer these questions, we conducted a 4-week field deployment study focusing on understanding *perceived usefulness* and *ease of use* of DC and Traffigram. To conduct the study, we recruited participants through email lists used at the University of Washington in Seattle for recruiting study participants. We asked interested participants to complete an initial screening survey. We selected participants who (1) reported frequent travel by car, bike, or on foot, (2) would be physically present in the Seattle during the study period, and (3) were willing to participate in a 4-week study. As a result, we recruited 26 participants (13 female, 1 non-binary). Participants' ages ranged from 20 to 48 (M=30). Prior to participating in the study, participants were asked to complete an orientation material designed for introducing core features of Traffigram that might not be familiar to them (i.e., the concept of DCs such as isochrones and anchors, and UI features presented in Traffigram, such as map interaction types and destination types). At the end of the material, participants were required to correctly answer 10 quiz questions that test participants' understanding of DC and Traffigram. Every participant completed the orientation material in approximately 15 minutes.

After finishing the material, the participants were able to access Traffigram via a mobile web app and a website for desktop use. We captured participants' qualitative and quantitative data from four sources: survey, behavioral metrics, closing survey, and interviews. First, the participants were asked to complete minimum two surveys about their usage per week. All surveys were identical and emailed to the participants every evening. Participants provided consent for logging their behavior metrics regarding time spent on each map mode (i.e., WM or DC), as well as map interaction types they used and usage frequency during the study period. To account for potential ordering effects of map presentation, Traffigram opened the WM map by default for half of the participants and the DC map for the other half. Participants were not restricted to using their default map and could easily switch to a different map mode if desired. After using Traffigram for the four weeks, participants completed a closing survey. The closing survey included multiple five-level Likert scale questions about the participant's opinion on Traffigram. They also answered open-ended questions about their overall experience and thoughts on DC and Traffigram's UI features. Finally, we recruited 9 participants who volunteered to have a closing interview. The interviews took place within a week of their study completion. Each interview lasted approximately one hour. Interviews were transcribed for thematic analysis [78].

We used quantitative and qualitative methods to examine our inquiries. Of the 26 participants, 6 participants were removed from analyses for the following reasons: two submitted too few or no surveys, two were not in Seattle for sufficient periods of time during the study, one participant's logging data showed only a few seconds of usage despite many survey responses, and one requested to leave the study. We thus collected 171 survey responses from 20 participants over the course of 4 weeks. Each of the 26 participants was compensated with $125; the 9 interviewees for the closing interview also received an additional $25.

7.2.1.2 Results

We analyzed the four sources of data we collected from the study to examine the *perceived usefulness* and the *ease of use* of the distortion applied in DC, and UI features that Traffigram offers, such as the map interaction types. Specifically, we investigated the perceived usefulness of DCs and Traffigram by examining whether real world users can find scenarios in which they believe using DCs would improve their location searching performance. Prior lab studies suggest DCs can be an efficient tool for comparing travel times (e.g., [6, 72]), but it is not well understood as to whether such perceptual efficiency would generalize to real environments. Second, we examined ease of use of DCs and Traffigram by investigating how users perceive the DCs' distortion and utilize a set of map interaction types.

Perceived usefulness of DCs: Perceived usefulness is defined as "users believe that using a system can attain *better performance* on their tasks" [71]. To understand the perceived usefulness, we first analyzed interviews. Then we further examined participants' usage time between the two map modes (i.e., DC and WM), and their responses in the closing surveys.

Through the interviews, we identified participants noted five *use cases* (UC), in which using DC was particularly helpful for them for improving search performance, compared to the current search method. Many interviewees noted that they used DC to confirm expectations of travel time and to minimize the likelihood of being caught in traffic (everyone except P2, **UC#1**). For example, P4, P8, and P9 specifically noted that the ease of calculating travel time in DC influenced their decisions. P3, P4, and P9 noted that using DC was useful in calculating expected travel time to their destinations while they travel. Interestingly, P9 noted that she frequently compared *anchor lengths* and switched back and forth between DC and WM to estimate the traffic that she might experience. *"Actually, even though it is within the same concentric circle (the isochrone), if it is much more distorted, then I would go to the less distorted one, because it will mean that I will have to experience a lot of traffic."* P3, P5, P7, and P8 noted they perceived DC to be especially useful in situations when they were finding a location that offered similar value (e.g., Costco, Starbucks, post offices, or gas stations, **UC#2**). In such cases, they found travel time more important than other decision factors. "*I wanted a quick cup of coffee … I think those are the situations where I really, really want a quick thing*. (P5)", "*Three different Costcos provide the same value to me. The only factor I care about in that situation is travel time.* (P3)" P1, P3, P7 and P8 noted they used DC when they made immediate and instant decisions in unfamiliar neighborhoods (**UC#3**). P9 noted. "*I just moved neighborhoods, so I wasn't really sure what place might be convenient … I liked the time mode because it let me look at a couple of different places that might be convenient and where I could go based on that.*" P1 found DC was useful for minimizing walking distances during a date. P2 and P7 noted that DC was useful when considering multiple factors when finding a destination (**UC#4**). "*I'm sort of doing an optimization problem in my head. I kind of want a beer but not if I have to drive super far. So, I might start dragging the isochrone out until I see something good and then look at the isochrone and it says 11 minutes to drive to get to a place that looks suitable.* (P7)" Finally, a non-trivial minority of interviewees mentioned DC was useful when "a minute matters" (**UC#5**). For instance, P3 said she used DCs when she had to finish lunch within a certain threshold of time. The use cases participants mentioned in the interviews recurred in open-ended questions in the closing survey. For example, P15 mentioned UC#2 in the survey response: "*Most often I used Traffigram to find coffee shops or bars near my current location. I usually think about "near" in terms of how quickly I can walk there. Traffigram was perfect for that.*"

We were curious to see whether the interviewees perceived usefulness of DCs increased motivation to use DCs throughout the study period. Eight interviewees mentioned that they spent more time on DCs because they found DCs' unique features to be useful. P1 noted: "*The only reason that I used the standard map was … It was by default. The very unique characteristic of* *this app is the time map. Whenever I used this app it was only for time map and I would say my active use was 100% on time map."* The left chart in Fig. 8 shows proportion of time that every participant spent on WM and DCs On average, participants spent 57% of their time on DCs through the four weeks. The weekly proportion of time participants spent on DCs remained over 50% through the four weeks. (From week 1 to week 4: 57%, 51%, 62%, 58%).

Perceived ease of use of a DC and Traffigram: Perceived ease of use is defined as "users can *understand* the meaning of information and *discover* the actions they can take" [73]. We analyzed data from the interviews, behavioral logs, and closing surveys to understand the perceived ease of use of distortion applied in DCs and Traffigram.

All interviewees noted distortion appearing in DCs incurred little confusion. "*I think that the distortions were effective in showing the time distance without making the map hard to read*. (P9)" A few interviewees made recurring comments. Many found understanding the rationale behind the distortion helped them feel "comfortable" with distortion. "*I understand the purpose of a time map, and it doesn't detract from my use of it.* (P4)" Another group of interviewees noted that switching lead them to think less about distortion. "*I didn't think about the distortion that much, which is really strange. I remember when I first saw maps like this I was really interested in how the land morphed. Like right now, I'm clicking back and forth and just looking at Seattle stretching and compressing and that's interesting. But I definitely didn't give it [distortion] a thought, which is really weird.* (P7)" However, P2, P4, and P7 mentioned that anchors were confusing. "*At the beginning of the study, that I was a little concerned about the anchors. It doesn't latch on the distortion or something …. But, I didn't end up seeing very many of those when I was actually using it. So, it wasn't an issue.*" P4 also noted: "*So, I think with the anchors ... it represents the physical location on the time map? I guess I didn't see that many of them*." In general, we found participants found distortion applied in DCs with S-GAP to cause little confusion. However, anchors were perceived as not easy to understand their meaning for some participants. Aligned with the patterns we found in the interviews, 5-level Likert scale survey responses showed low confusion from DCs' distortion (M=2.15, SD=1.04) but found anchors tend to be more confusing (M=3.47, SD=1.07).

When participants used DCs, the interaction frequency of zooming and panning occupied 91% of all interactions through the study period. Switching amounted to 6%. Still, many interviewees (P1, P4, P7, P8, and P9) mentioned they found switching easy to understand, used it frequently, and found it useful for linking the temporal and spatial information between WM and DCs. P6

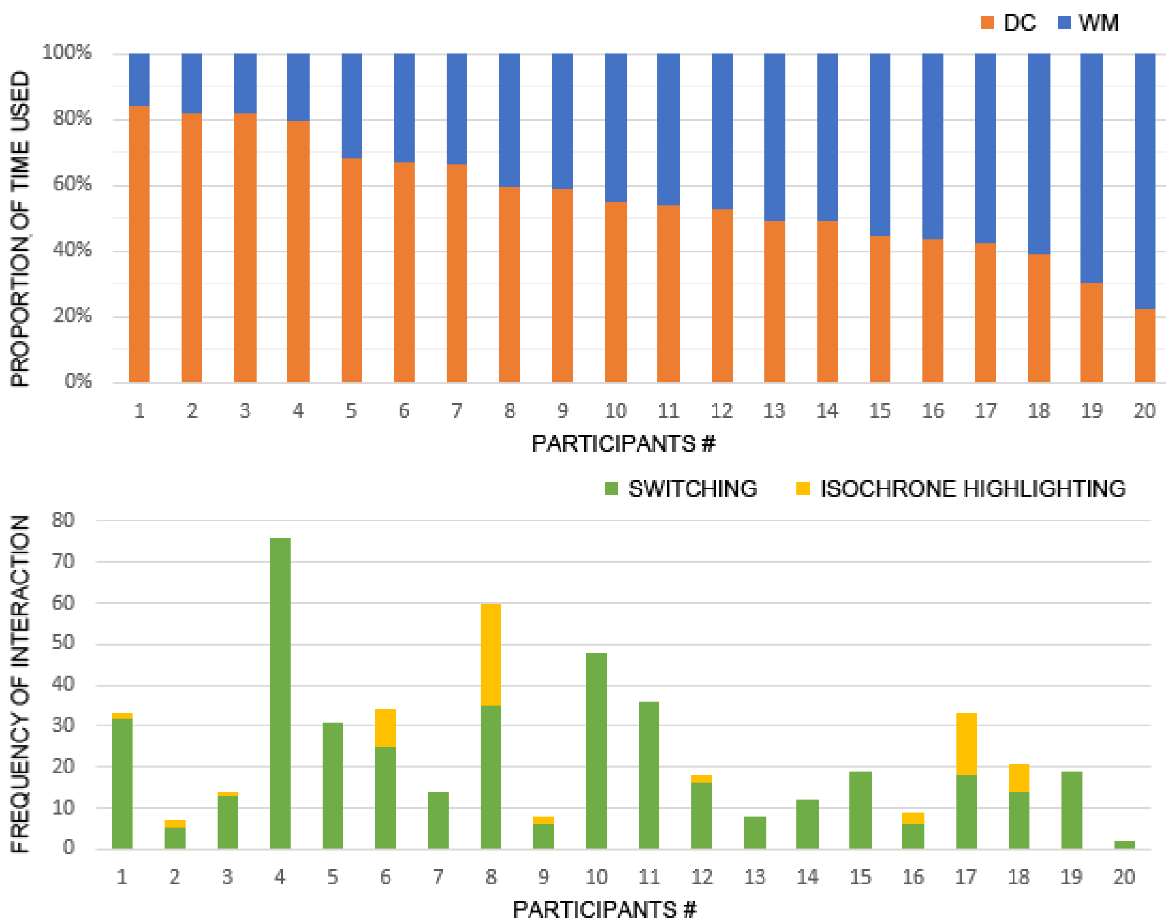

Figure 7.7. Map usage time proportions between DC and WM (top), Switching and Highlighting interaction frequency (bottom).

noted: "*I tried to just use the time mode because I liked that and I tried to navigate on foot based on the landmarks that I could recognize without switching the standard mode, but I think I would have had to switch to standard mode somewhere else where I didn't recognize the landmarks*." P8 said: "*Switching from the standard mode to the time mode was pretty useful because seeing how distorted it can be was easier for me to figure out if there is normal traffic, or it's actually really congested. I guess switching was what I used the most.*" Meanwhile, only 3% of all interactions were highlighting. The highlighting interaction was not perceived as intuitive by many participants and consequently garnered low usage. P2, P4, and P6 mentioned that weren't aware of highlighting or existing isochrones are already informative enough. For instance, P2 noted: "*It [highlighting] said seven minutes. But, I probably could've guessed that based on the fact that it's halfway between 5 and 10*." However, another group of interviewees (P3, P7, and P9) who were aware of highlighting found the interaction highly useful. P9 noted: "*I used the set ones to glance up but then the custom ones to judge the distance of a particular location or the range*." The right chart in Fig. 7.7 shows interaction frequency of switching and highlighting interaction being used. Every participant used switching, whereas only 8 used highlighting.

7.2.1.3 Discussion

Our inquiry started from whether DC's benefits can compensate for confusion caused by distortion and lead them to adopt DC. Through the study, we found notable use cases of DCs that reflect participants' real-life information seeking contexts. Previous studies found using DCs enabled users to grasp travel times to multiple destinations *at a glance,* which resulted in reduced time in making decisions, which in turn explains *how* DC can support efficient time-related decision-making (e.g., [1, 6, 72]). Built upon the existing results, our findings further explain *when* and *why* DC can aid user's spatial decision-making context.

Distortion applied in DC was well received in general, but anchors seemed counter-intuitive to many participants. This tendency is somewhat contradictory to the results of [1]. In addition, although we found S-GAP can create intuitive DCs, we heard from some interviewees that the DC were not always straightforward to read. S-GAP uses a static, heuristically derived parameter suggested in [49] for preserving shapes. Adjustment to this parameter changes the degree to which S-GAP retains geographical shapes. For example, a tighter parameter leads to better shape preservation while incurring more and longer anchors. We see that an ideal parameter is likely to vary depending on multiple factors, such as coastlines, degree of distortion, etc. In the future, we see it would be critical to develop a distortion model of DC that can be said to be "perceptually optimal" rather than "heuristic", which would require to reflect human information decoding accuracy, efficiency, and effectiveness in model development. The study also confirmed the usefulness of switching indicated in the previous study [1]. Unlike switching, however, we found that highlighting was used by only a subset of participants.

Meanwhile, we found participants encountered several issues while using Traffigram during the study period. For example, some mentioned they wanted to see travel time estimates for more flexible time requirements (e.g., seeing travel times 2 hours later, next Monday at 5:00 p.m., or uncertainty of travel time at a certain moment in the future). Some mentioned their desire to use a search UI instead of location type selection. Some reported occasional crashes of the mobile app. In the future, we plan to resolve these issues and build a system that robustly works in broader geographic areas. We aim to assess effects of using DC (e.g., use cases and context, observing usage patterns in longer period) with a larger user base. Also, observing usage patterns of special application contexts where time is critical, such as drivers who use autonomous vehicle, 911 dispatchers, or urban planners may open interesting research opportunities.

Perhaps one of the most encouraging perspectives we learned from the study is that using Traffigram made them feel differently about the city and space nearby. For instance, P2 mentioned: "*I think the time map definitely focused my attention on the travel time aspect of my search. It probably changed the way that I was thinking a little bit. I would say it was interesting and probably useful in some cases to actually see how long it would take to get to places. I remember one point I had been somewhere to a restaurant by car …. After I got back, I looked at it on Traffigram and it was like 'Oh, that was only 10 minutes away by car', if I switched to foot, it's like 45 minutes away or something. It really does change the landscape. It was interesting*." We found many interviewees felt they used Traffigram as a new way to explore spatial information, different from what they had been doing with their current practices.

7.2.1.4 Conclusion

I introduced a series of studies conducted to understand the impact of using DCs. The study with Traffigram Ver. 1.0 was conducted to identify specific tasks that using DCs can be helpful than using existing solutions in static setting and its effect. The results showed that DCs can help efficient decoding of travel time information than color-coded road segments or list. The second study was conducted to evaluate the effect of GAP and switching interaction in more interactive settings using Traffigram Ver. 2.0. Similar to results using Traffigram Ver. 1.0, 71% of participants preferred using DCs built based on GAP when finding locations with maps with considering travel times, whereas 16% preferred WMs. The most common reasons why participants felt DCs were useful are: (a) being able to grasp travel time at a glance and enable a quicker decision (47%) and (b) being able to visually include or exclude potential travel destinations and reduce decision complexity (33%). Aligning with this result, the study participants made decisions significantly faster and with lower cognitive effort using DCs than by using WMs. Finally, participants were also significantly faster with switching interactions than without them. The third study with Traffigram 3.0 showed some initial results that DCs can be a real-world solution. Through the four weeks of the field study, I found distortion in DCs constructed based on S-GAP caused little confusion for users in general. Participants found several use cases where they felt that DC was more helpful than tradition UIs for their spatial exploration tasks. I believe that the perceived usefulness and ease of use helped users retain motivation for using DC throughout the study period.

Chapter 8. CONCLUSION

This dissertation identifies the short-coming of the current design for visualizing travel time on cartographic layouts. That is, although travel time is the fundamental proxy for people to perceive their cost for travel, seeing the travel time with the current design is not easy. To tackle this design limitation, I proposed a series of computational techniques that enable using interactive and intelligible Distance Cartograms. Based on the techniques, I built three versions of the system named Traffigram and evaluated the potential of DCs through a series of studies in the lab and in the wild. The findings show the potential of DCs as a real-world solution for searching location, and present new interaction design paradigm for the future map design. In this section, I briefly review the thesis contributions. Then I present the limitations with the future research direction.

8.1 REVIEW OF THESIS CONTRIBUTIONS

Technical Contribution: In thesis problem section (§1.1), I posit that the most fundamental challenges for building a usable and useful DCs are improving *interactivity* and *intelligibility* of DCs. The contribution of this thesis starts from techniques that are devised to tackle these two challenges. Specifically, I proposed the two techniques that enable building interactive DCs; they are *Scalable Road-network Construction* (SRC, §3.2) and *Quadtree Time space Partitioning* (QTP, §3.3). In addition, to improve intelligibility of DCs, this thesis introduces two other techniques named *Geo-contextual Anchoring Projection* (GAP, §4.2) and *Shape-retaining Geo-contextual Anchoring Projection* (S-GAP, §4.3).

System Contribution: Although DCs have been studied for multiple decades, there have been a few systems that allow users to interact with DCs. Using the techniques introduced in §3 and §4 as a building block, this thesis introduces three versions of the system named Traffigram that each improves the previous version. Traffigram Ver.1.0 was built in order to explore the potential usefulness of DCs as a tool for exploring locations (§6.1). Traffigram Ver. 2.0 was built upon the Ver. 1.0, and there are three notable improvements (§6.2). Ver. 2.0 was the first system that presents commonly used map interaction types such as zooming or panning in DC modes, which was a core challenge due to the computational cost for building the time space. Aside from zooming and panning map interaction, the system also presents the switching interaction and helps users to use DCs or WMs depending on their use context. Finally, the system applied GAP to tackle the problem of topological violation which can hamper the intelligibility of DCs. Ver. 3.0 is the first system that is deployed "in the wild" and used by people in their ordinary spatial information-seeking tasks (§6.3). The system uses QTP to approximate time space based on real traffic information within a real time, which enables building an interactive system that shows real traffic information. In addition, the system applied S-GAP, which presents more severe constraint for applying distortions on maps than GAP.

Empirical Contribution: The thesis contributes to the DC research with reporting findings from a series of studies conducted to understand usability and usefulness of DCs using the three versions of Traffigram (§7). General patterns in the studies show that using DCs significantly shorten the task time for travel time information decoding and multiple location comparisons. In terms of decoding accuracy of travel time, using DCs significantly improves the accuracy of information decoding than existing solutions such as color-coded road segments. However, when comparing the decoding accuracy between DCs and text, there are no significant differences between the two conditions. Although there were no significant differences between DCs and text, participants' perceived cognitive load was significantly lower when using DCs than the condition where they used maps with text. The patterns I found in this quantitative analysis indicate that people can decode accurate information using current systems, but they still need to put a significant amount of time and effort in general. Using DCs may significantly shorten the time and cognitive effort for decoding travel times. Findings from qualitative analysis of these studies also indicate that people are favorable for using DCs when they consider travel time for finding locations. They felt using DCs was useful because of the "glanceability" and "filterability". In the recent deployment study, I found a series of notable use cases where the participants felt DCs was easy to use and they believed using DCs can help them can attain better performance on tasks they encounter. Such ease of use and perceived usefulness are the important factors for adopting the novel technology [68, 71]. Findings in the deployment study showed the potential of DCs as a useful map component in real situations.

8.2 LIMITATIONS AND FUTURE WORK

Through this thesis, I devised techniques, built systems, and sought findings for improving DCs, there are a number of challenges still exist. I highlight some of the challenges in this section.

8.2.1 *Technical perspectives*

The first limitation is the accuracy of a time space derived by QTP. The time space can be inaccurate. For example, QTP cannot guarantee that the algorithm can detect congestion happens in a small area than the grid applied in QTP. Lowering the time threshold can sensitively detect such a small congestion. However, smaller time threshold means more recursions which will increase the leading time for DC construction. The degree of accuracy of the time space and leading time for DC construction have a negative correlation. Because the leading time is something that cannot be sacrificed for building an interactive system, the next goal should be to improve the accuracy with fewer recursions. One possible way could be to accumulate across the time and construct a "spatiotemporal time space block". Using some slices in the block, QTP can intelligently decide which cell to recurse before casting request to traffic information APIs for getting the travel time information. Traffic patterns are repetitive in general and accumulating the past time space using QTP and use such information a prior for applying machine learning techniques could significantly improve the time space. The block may be able to construct present useful data also have different usefulness than merely DCs. Travel time is a critical proxy for measuring the cost of travel and useful information for many disciplines. But such a direction of research needs further investigation. These issues are some of the evident ones I noticed while applying DCs in location findings for casual users. The technique might be useful to some different audiences than the case I focused on this thesis. And depending on the scenarios and context, more adaptive techniques and interaction design might be necessary.

8.2.2 *Empirical perspectives*

One notable challenge remained is to understand the way to reflect on human's perception level of information in developing the model for applying distortion for DC construction. We identified that the preservation of topological relationships among features and regaining map shapes are some of the most critical factors for improving the map intelligibility when applying distortion. The core motivation for devising and proposing GAP and S-GAP was to build a DC that satisfies both aspects. In developing the two techniques, however, I used a mathematical notion of topological violation or heuristically developed parameters for preserving the shapes, and there is no human level of information decoding in the computational pipelines. As a matter of fact, depending on how tightly or loosely setting the parameters for S-GAP, the result of S-GAP can be nearly the same as the result with GAP or the result of WM with lots of anchors. In order to build a DC that can be said to be "perceptually intelligible", we need to apply human perception level of models in developing the distortion model for DC construction and test the model in rigorously designed studies. Such an approach should be precedented before we identify different use cases or scenarios.

8.3 Closing Remarks

Developing a tool that helps in understanding traffic patterns can have a positive impact on people's lives in general. This thesis focused on the potential applicability of DCs in real life situations, and my endeavor to develop a better system that can truly benefit real-world users is on-going. The variable nature of the time between urban locations regularly frustrates travelers. DCs could assist in clarifying this traffic uncertainty. I anticipate that this work will set up the possibility of a deeper understanding of identifying more use cases of DCs for different users and developing DCs' distortion model that may open new research opportunities.

BIBLIOGRAPHY

[1] R. S. Hong, R. Kocielnik, M. J. Yoo, S. Battersby, J. Kim and C. Aragon, "Designing Interactive Distance Cartograms to Support Urban Travelers," in *IEEE Pacific Visualization Symposium (PacificVis)*, 2017.

[2] A. M. MacEachren, How Maps Work: Representation, Visualization, and Design., Guilford Press., 2004.

[3] D. R. Montello, "The perception and cognition of environmental distance: Direct sources of information," *International Conference on Spatial Information Theory,* pp. 297-311.

[4] G. maps, "Google Maps," Google Maps, 8 1 2005. [Online]. Available: https://maps.google.com. [Accessed 25 12 2017].

[5] C. Lightfoot and T. Steinberg, "Travel-time Maps and their Uses," mySociety, 4 3 2006. [Online]. Available: https://www.mysociety.org/2006/03/04/travel-time-maps-and-their-uses/. [Accessed 25 12 2017].

[6] R. S. Hong, Y. S. Kim, J. C. Yoon and C. R. Aragon, "Traffigram: distortion for clarification via isochronal cartography," in *ACM conference on Human factors in computing systems (ACM SIGCHI)*, 2014.

[7] J. Mackinlay, "Automating the design of graphical presentations of relational information," *ACM Transactions On Graphics 5(2),* pp. 110-141, 1986.

[8] W. R. Tobler, Map transformations of geographic space, University of Washington, 1961.

[9] R. S. Hong, M. Yoo, B. Chinh, A. Han, S. Battersby and J. Kim, "To Distort or Not to Distort: Distance Cartograms in the Wild," in *ACM Conference on Human Factors in Computing Systems (ACM SIGCHI)*, 2018.

[10] W. Tobler, "Thirty five years of computer cartograms.," *ANNALS of the Association of American Geographers,* vol. 94, no. 1, pp. 58-73, 2004.

[11] S. Nusrat, M. J. Alam and S. Kobourov, "Evaluating cartogram effectiveness," *IEEE TVCG,* no. 99, 2016.

[12] C. Kocmoud and D. House, "A Constraint-Based Approach to Constructing Continuous Cartograms," in *Spatial Data Handling*, 1998.

[13] K. P. Goldsberry, Real-time traffic maps, ProQuest, 2007.

[14] G. Sun, R. Liang, H. Qu and W. Y. , "Embedding Spatio-temporal Information into Maps by Route-Zooming," *IEEE TVCG,* 2016.

[15] B. N. Hilton, T. A. Horan, R. Burkhard and B. Schooley, "SafeRoadMaps: Communication of location and density of traffic fatalities through spatial visualization and heat map analysis," *Information Visualization,* vol. 10, no. 1, pp. 82-96, 2011.

[16] E. C. o. Helsinki, "Traffic Noise in Helsinki during Daytime," 12 4 2018. [Online]. Available: http://cloudnsci.fi/wiki/demos/traffic_noise_helsinki_day_heatmap.html.

[17] k. Buchin, A. Goethem, M. Hoffmann, M. Kreveld and B. Speckmann, "Travel-time Maps: Linear Cartograms with Fixed Vertex Locations," *Geographic Information Science,* pp. 18-33, 2014.

[18] E. Shimizu and R. Inoue, "A New Algorithm for Distance Cartogram Construction," *International Journal of GIS,* vol. 23.11, no. 2009, pp. 1453 - 1470, 2009.

[19] S. Bies and M. Van Kreveld, "Time-Space Maps from Triangulations," in *International Symposium on Graph Drawing 2013*, 2013.

[20] D. F. L. Dorling, The visualisation of spatial social structure, University of Newcastle upon Tyne, 1991.

[21] A. C. Gatrell, "Concepts of space and geographical data," *Geographical Information Systems,* vol. 1, pp. 119-134, 1991.

[22] R. Ullah and M. Kraak, "An alternative method to constructing time cartograms for the visual representation of scheduled movement data," *Journal of Maps,* vol. 11, no. 4, pp. 674-687, 2015.

[23] A. Weber, Theory of the Location of Industries, University of Chicago Press., 1929.

[24] W. Bunge, Theoretical geography, Seattle: University of Washington, 1960.

[25] S. Angel and G. Hyman, "Transformations and geographic theory," *Geographical Analysis,* vol. 4, no. 4, pp. 350-367, 1972.

[26] J. C. Muller, "The Mapping of Travel Time in Edmonton, Alberta," *The Canadian Geographer/Le Géographe canadien,* vol. 22, no. 3, pp. 195-210, 1978.

[27] T. Carden, "Travel Time Tube Map," 2005. [Online]. Available: http://www.tom-carden.co.uk/p5/tube_map_travel_times/applet/.

[28] D. T. Lee and B. J. Schachter, "Two algorithms for constructing a Delaunay triangulation," *International Journal of Computer & Information Sciences,* vol. 9, no. 3, pp. 219-242, 1980.

[29] F. L. Bookstein, "Principal warps: Thin-plate splines and the decomposition of deformations," *IEEE Transactions on pattern analysis and machine intelligence,* vol. 11, no. 6, pp. 567-585, 1989.

[30] X. Chen, Seeing differently: cartography for subjective maps based on dynamic urban data, MIT, 2011.

[31] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische mathematik,* vol. 1, no. 1, p. 1, 269-271.

[32] S.-S. Lin, C.-H. Lin, Y.-J. Hu and T.-Y. Lee, "Drawing road networks with mental maps," *IEEE TVCG,* vol. 20, no. 9, pp. 1241-1252, 2014.

[33] W. A. Mackaness and K. M. Beard, "Use of graph theory to support map generalization," *Cartography and Geographic Information Systems,* vol. 20, no. 4, pp. 210-221, 1993.

[34] Z. Li, "General Principles for Automated Generation of Schematic Network Maps," *The Cartographic Journal,* pp. 356-360, 2013.

[35] J. Kopf, M. Agrawala, D. Bargeron, D. Salesin and M. Cohen, "Automatic generation of destination maps," *ACM TOG,* vol. 29, no. 6, p. 158, 2010.

[36] M. Haklay, "How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets," *Environment and planning,* vol. 37, no. 4, pp. 682-703, 2010.

[37] D. H. Douglas and T. K. Peucker, "Algorithms for the reduction of the number of points required to represent a digitized line or its caricature," *Cartographica: The International*

Journal for Geographic Information and Geovisualization, vol. 10, no. 2, pp. 112-122, 1973.

[38] O. Maimon and L. Rokach, Data mining and knowledge discovery handbook, 2005: Springer, 2005.

[39] H. Samet, "The quadtree and related hierarchical data structures," *ACM Computing Surveys (CSUR),* vol. 16, no. 2, pp. 187-260, 1984.

[40] S. D. Roth, "Ray Casting for Modeling Solids," in *Computer graphics and image processing*, 1982, pp. 109-144.

[41] B. Jenny, "Adaptive Composite Map Projection," *IEEE TVCG,* vol. 18, no. 12, pp. 2575-2582, 2012.

[42] N. Kadmon, "Cartograms and topology," *Cartographica: The International Journal for Geographic Information and Geovisualization ,* vol. 19, no. 3-4, pp. 1-17, 1982.

[43] J. Hadlaw, "The london underground map: Imagining modern time and space," *Design Issues,* vol. 19, no. 1, pp. 25-35, 2003.

[44] M. T. Gastner, C. R. Shalizi and M. E. Newman, "Maps and cartograms of the 2004 US presidential election results," *Advances in Complex Systems,* vol. 8, no. 1, pp. 117-123, 2005.

[45] C. William, "Rethinking the definition of the word 'map': an evaluation of Beck's representation of the London Underground through a qualitative expert survey," *International Journal of Digital Earth,* vol. 8, no. 7, pp. 522-537, 2015.

[46] S. M. Guseyn-Zade and V. S. Tikunov, "Numerical methods in the compilation of transformed images," *Mapping Sciences and Remote Sensing,* vol. 31, no. 1, pp. 66-85, 1994.

[47] D. M. Mark, "Spatial representation: a cognitive view," *Geographical information systems: principles and applications,* no. 1, pp. 81-89, 1999.

[48] Q. Bouts, T. Dwyer, J. Dyke, B. Speckmann, S. Goodwin, N. Riche, S. Carpendale and A. Liebman, "Visual Encoding of Dissimilarity Data via Topology-Preserving Map Deformation," *IEEE Transactions on Visualization and Computer Graphics,* 2015.

[49] D. A. Keim, S. C. North and C. Panse, "Cartodraw: A fast algorithm for generating contiguous cartograms," *TVCG, IEEE,* vol. 10, no. 1, pp. 95 - 110, 2004.

[50] C. Kocmoud, Constructing Continuous Cartograms: A Constraint-Based Approach, Texas A&M University, 1997.

[51] D. Dorling, A. Barford and M. Newman, "WORLDMAPPER: the world as you've never seen it before," *IEEE Transactions on Visualization and Computer Graphics,* vol. 12, no. 5, pp. 757-764, 2006.

[52] R. Diestel, Graph Theory (4th Edition), Springer, 2010.

[53] L. Kehrer and C. Meinecke, "Perceptual organization of visual patterns: The segmentation of textures," *Handbook of Perception and Action,* vol. 1, pp. 25-70.

[54] J. M. Lee, Riemannian manifolds: an introduction to curvature, Springer Science & Business Media, 2006.

[55] G. Wahba, Spline models for observational data, Society for industrial and applied mathematics., 1990.

[56] J. S. Yi, Y. Kang and J. Stasko, "Toward a deeper understanding of the role of interaction in information visualization," *IEEE Transactions on Visualization and Computer Graphics (TVCG),* vol. 13, no. 6, pp. 1224-1231, 2007.

[57] J. Heer and B. Shneiderman, "Interactive dynamics for visual analysis," *Queue,* vol. 10, no. 2, p. 30, 2012.

[58] K. Church and B. Smyth, "Understanding the intent behind mobile information needs," in *ACM conference on Intelligent user interfaces 2009*, 2009.

[59] M. J. Lobo, E. Pietriga and C. Appert, "An evaluation of interactive map comparison techniques," in *ACM SIGCHI 2015*, 2015.

[60] J. Heer and G. G. Robertson, "Animated transitions in statistical data graphics," *IEEE TVCG 13(6),* pp. 1240-1247, 2007.

[61] B. Tversky, J. B. Morrison and M. Betrancourt, "Animation: can it facilitate?," *International journal of human-computer studies, 57(4),* pp. 247-262, 2002.

[62] J. Nielsen, Usability engineering, Elsevier, 1994.

[63] A. MacEachren, "Travel time as the basis of cognitive distance," *The Professional Geographer,* vol. 32, no. 1, pp. 30-36, 1980.

[64] N. Ahmed and H. J. Miller, "Time–space transformations of geographic space for exploring, analyzing and visualizing transportation systems," *Journal of Transport Geography,* vol. 15, no. 1, pp. 2-17, 2007.

[65] D. R. Fesenmaier, K. W. Wöber and H. Werthner, Destination recommendation systems: Behavioral foundations and applications, Cabi, 2006.

[66] S. Greenberg and B. Buxton, "Usability evaluation considered harmful (some of the time)," in *ACM SIGCHI*, 2008.

[67] A. Henderson, "The innovation pipeline: design collaborations between research and development," *interactions,* vol. 12, no. 1, pp. 24-29, 2005.

[68] P. K. Chilana, A. J. Ko and J. Wobbrock, "From user-centered to adoption-centered design: A case study of an HCI research innovation becoming a product," in *ACM SIGCHI*, 2015.

[69] J. Lindley, P. Coulton and M. Sturdee, "Implications for Adoption," in *ACM SIGCHI*, 2017.

[70] F. D. Davis, R. P. Bagozzi and P. R. Warshaw, "User acceptance of computer technology: a comparison of two theoretical models," *Management science,* vol. 35, no. 8, pp. 982-1003, 1989.

[71] V. Venkatesh, M. G. Morris, G. B. Davis and F. D. Davis, "User acceptance of information technology: Toward a unified view," *MIS quarterly,* pp. 425-478, 2003.

[72] R. Ullah, E. Z. Mengistu, C. P. J. M. van Elzakker and M. J. Kraak, "Usability evaluation of centered time cartograms," *Open Geosciences,* vol. 8, no. 1, pp. 337-359, 2016.

[73] D. Norman, The design of everyday things: Revised and expanded edition, Basic Books, 2013.

[74] S. E. Battersby, M. P. Finn, E. L. Usery and K. H. Yamamoto, "Implications of web Mercator and its use in online mapping," *Cartographica: The International Journal for Geographic Information and Geovisualization,* vol. 49, no. 2, pp. 85-101, 2014.

[75] J. Nielsen and R. Molich, "Heuristic evaluation of user interfaces," in *ACM SIGCHI*, 1990.

[76] R. Ullah, M. J. Kraak and C. Van Elzakker, "Using cartograms to explore temporal data: Do they work," 2013. [Online]. Available: http://www.geomatik-hamburg.de/geoviz/online/Ullah_slides.pdf.

[77] S. G. Hart, "NASA-task load index (NASA-TLX); 20 years later," in *Human factors and ergonomics society annual meeting*, 2006.

[78] J. Aronson, "A pragmatic view of thematic analysis," *The qualitative report,* vol. 2, no. 1, pp. 1-3.

[79] S. M. Weir, "Getting around Town: Modifications in a Local Travel Time Space Caused by Expressway Construction," Doctoral dissertation, Pennsylvania State University, 1975.

[80] C. Kaiser, F. Walsh, C. J. Farmer and A. Pozdnoukhov, "User-centric Time-distance Representation of Road Networks," in *International Conference on Geographic Information Science*, 2010.

VITA

Ray Hong is a designer, engineer, and researcher who earned a Ph.D. degree in the Department of Human Centered Design & Engineering at the University of Washington. His research contributes to the field of human computer interaction and relevant other fields with (1) conceptualizing innovative designs that significantly improve current practices of information seeking and explorative visual analysis, (2) building state-of-the-art technologies that instantiate the novel designs to a form of scalable systems for users, and (3) discovering findings that extend our understanding of how people interact with the new techniques and systems and how such interaction changes current practice.