Designing Interactive Distance Cartograms to Support Urban Travelers

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Abstract

A distance cartogram (DC) is a technique that alters distances between a user-specified origin and the other locations in a map with respect to travel time. With DC, users can weigh the relative travel time costs between the origin and potential destinations at a glance because travel times are projected in a linearly interpolated time space from the origin. Such glance-ability is known to be useful for travelers who are mindful of travel time when finding their travel destinations. When constructing DC, however, uneven urban traffic conditions introduce excessive distortion and challenge user intuition. In addition, there has been little research focusing on DC's user interaction design. To tackle these challenges and realize the potential of DC as an interactive decision-making support tool, we derive a set of useful interactions through two formative studies and devise two novel techniques called Geo-contextual Anchoring Projection and Scalable Road-network Construction. We develop an interactive map system using these techniques and evaluate this system by comparing it against an equidistant map (EM), a widely used conventional layout that preserves the geographical reality. Based on the analysis of user behavior and qualitative feedback, we identify several benefits of using DC itself and of the interaction techniques we derived. We also analyze the specific reasons behind these identified benefits.

Keywords: Distance Cartogram, Geo-contextual Anchoring Projection, Scalable Road-network Construction, Map Interaction

Index Terms: H.5.2. [Information interfaces and presentation]: User Interfaces – *Graphical User Interfaces (GUI)*

1 Introduction

Researchers have shown long-standing interest in understanding how people perceive environmental distance [1]. Understanding cognitive distance has been considered a fundamental aspect of explaining travel behaviors, as people rely on the cognitive distance to weigh the relative costs of travel to different locations and to then make decisions about where to go [2]. Among many factors that influence cognitive distance, travel time has been considered a dominant one [2, 3]. The importance of travel time is notable within urban areas, where highly variable and ever-changing traffic conditions result in increased travel time uncertainty [4]. 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. Many of these decisions are made using destination recommender systems (DRS) and map services, such as Yelp, Google Maps, Zillow, Uber, etc. [5]. Due to the importance of travel time for spatial decision-making, numerous techniques exist to visualize travel times [3, 4, 6]. However, encoding the travel time on a map and creating tools that aid users in using this information to make travel decisions presents substantial challenges [7, 8].

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We discuss two general categories of methods for visually encoding travel time: equidistant maps (EM) and distance cartograms (DC). In general, traffic conditions can be encoded in EM using color-coded road segments [9], or as heat maps [10]. Such approaches effectively convey ordinal-level details of the traffic (e.g., slow, fast). However, a map user may face difficulties in decoding the exact *amount* of travel time [11] when relying only on colors, as this visual channel is known to be limited in encoding quantitative information [12]. One will be able to see exact travel times if the interface also provides the time as text (e.g., through printed values on the map). Still, the existing services typically require users to complete additional steps to obtain specific travel time information (e.g., type the address of the destination, or select a marker on a map) [4]. These steps can be cumbersome if the user needs to compare multiple travel destinations [13].

On the other hand, DC warps EM to help a user to decode travel time with a higher degree of precision [14]. DC sets one location as an *origin* and rearranges the positions of all other map features so that the distances between the origin and each of the rearranged features indicates absolute travel time [15, 16]. With DC, travelers can visually decode precise travel time information because the travel times are encoded by *position,* which is shown to be the most precise visual channel for encoding quantitative information [12]. In addition, travelers can compare time between different destinations with lower cognitive effort as they can accomplish time-related decision-making without relying on extra steps or having to memorize the travel time to each location [4].

While these benefits are notable, constructing a visually straightforward DC is challenging [7]. Designing DC requires deforming the *physical space* (which represents geographic reality) on a map in order to present the *time space* (which represents travel time from the origin to every location) [4]. Unevenly distributed road infrastructure and irregular urban traffic contribute to increasing discrepancies between the two spaces. When the discrepancies become extreme, DC becomes indecipherable [17]. These perceptual challenges have been indicated in several studies and limit the deployment of DC in practice [16]. Building robust DC that can be used in realistic settings requires improving the external representation of DC, such that it better aligns with the user's understanding of urban spaces [18]. Another challenge for DC is the lack of studies focusing on quality interaction design for DC. [19]. To support users in making high-quality decisions, an interaction mechanism that helps travelers discover meaningful destinations among several candidates is required [5].

The goal of this work is to design an interactive map system that utilizes DC to better support urban travelers who are mindful of travel time when finding travel destinations. To design the system, we devise two techniques that each respectively overcome the two challenges we noted earlier. First, to improve the quality of *external representation* of DC, we propose *Geo-contextual Anchoring Projection* (GAP). GAP ensures that DC retains topological relationships of the underlying road network in order to attain a higher level of map recognizability. Second, we conduct a survey on Amazon Mechanical Turk (AMT) and a subsequent focus group interview to derive a useful set of *user interactions* that improve the utility of the DC in decision making, such as a smooth transition between EM (e.g., Fig.1(a)) and DC (e.g., Fig.1(b)). To seamlessly

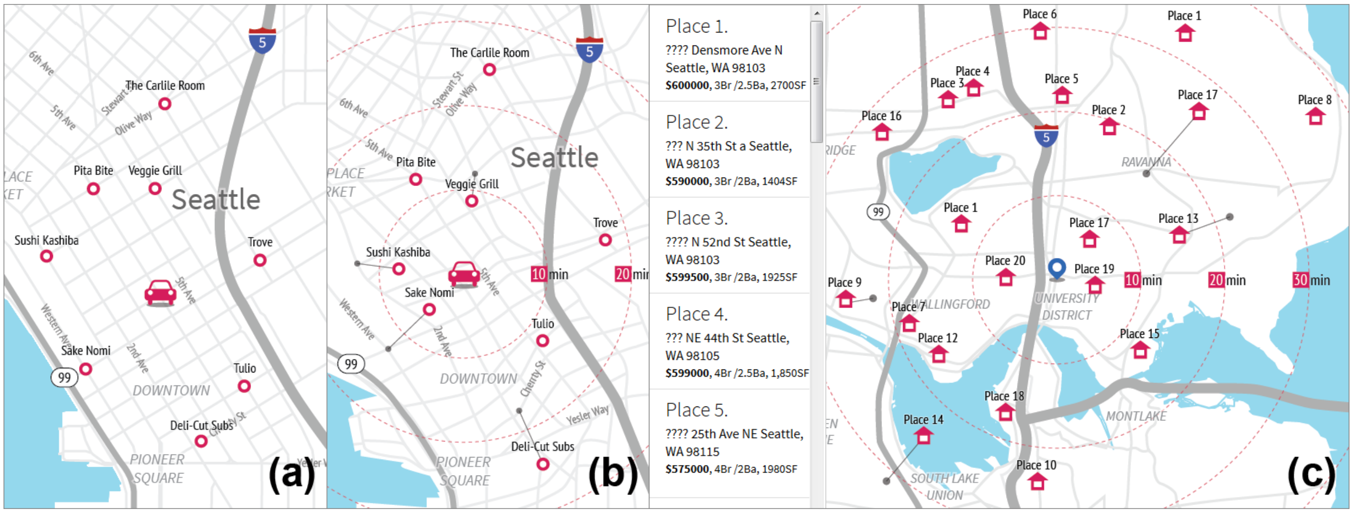

Figure 1: Restaurants in downtown Seattle shown with (a) EM, and (b) DC. (c) An interface used in study for finding a place to stay. DC is used.

provide a set of desired user interactions, we devise *Scalable Road-network Construction* (SRC). SRC reduces the computational cost of calculating the DC on a road network by generalizing the road network based on each road's perceptual saliency.

We evaluate the quality of the two techniques and the interactive map system we designed through two studies. In the first study, we conduct interviews to examine user's perceived preference and usefulness of DC compared to EM. Overall, 71% of participants preferred DC whereas 16% preferred EM. We also identify the most common reasons why participants felt DC was more useful. They 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%). In the second, controlled, study, we examine the adoptability and practical implications of our system and its map interactions in realistic settings. As a result, participants made decisions significantly faster and with lower cognitive effort using DC versus EM. Participants were also significantly faster with the map interactions (transitions) than without them.

The contributions of this work are as follows: first, we devise novel techniques called GAP and SRC to design more interactive, scalable, and useful DC. Second, we derive a set of useful interactions of DC through two formative studies, and introduce the first interactive map system that smoothly transforms its cartographic layout to better support diversifying user map usage context. Third, we gain deeper understanding of why and how the DC and the interactions we derived aid travellers in finding their travel destinations through the two studies.

2 Related Work

2.1 Visualizing Travel Time in Cartographic Layout

We analyze techniques related to travel time visualization to identify the unique opportunities that DC can offer to users. In a meta-analysis of the techniques, we identify two notable factors that characterize perceptual strengths and weaknesses of each technique. These are: (a) geographic fidelity, or whether the technique *warps* the geographically accurate map and (b) whether the technique is based on a single *origin*. Based on these factors, we categorize previous techniques into four groups (see Table 1).

The techniques in Group 1 neither warp EM 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 travel speed and points with distinct symbols to identify travel impediments [9, 20], or replacing the road with a sinusoid curve (the curve's amplitude and frequency indicate the amount of travel time) [21]. Sometimes, heat maps [10] are used to display the traffic condition. In such visualizations, a user can easily perceive traffic conditions of specific roads or areas [9]. However, it may be difficult to determine exact travel time unless additional cues, such as text, are provided, as colors, patterns, or glyphs may have limited ability to convey quantitative information [12].

The techniques in Group 2 warp 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 reflects the travel time to the most accurate extent possible. Multi-dimensional scaling (MDS) has been widely adopted to shift locations, and a variety of applications have been suggested [14]. With the approaches in Group 2, a user can see travel times between multiple locations at once. However, MDS would compromise the accuracy of lengths between the locations to present a result in Euclidean space [7]. Also, a user may need to internally sum the lengths of multiple edges that connect the departure point and the destination to identify the amount of travel time, since travel paths are typically not a single straight line.

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 [6]. With this approach, travelers determine approximate travel time from the origin to each location [16]. Still, travel times are only accurate when the destination-of-interest falls exactly on an isochrones because travel time between two contours is not linearly interpolated. Consequently, a user may need to assume the travel time to any location that is not on isochrones (e.g., a travel time to a point located between 10 and 20 mins. isochrones can be 11 or 19 mins., or somewhere in-between). Another method is a 3D time-space cube to present travel time along a path, using height as the time [22]. Still, this method is not designed for presenting the travel times to multiple destinations.

Table 1. Categorization of travel time visualization

	Map is not warped	**Map is warped**
Origin is not specified	**Group 1:** Color-coded roads [9, 20], heat map [10], sinusoid curve roads [21]	**Group 2:** MDS based approaches [14]
Origin is specified	**Group 3:** Free-form isochrones [6, 16], Space-Time cube [22]	**Group 4:** Circular isochrones [4, 15, 16]

The techniques in Group 4 warp the map around a specified origin. These techniques are known as DC. Unlike the approaches in Group 3, DC presents circular isochrones which present travel times with linearly interpolated time space around the origin [4]. This characteristic ensures that distances between the origin and destinations are *identical* to the actual travel time between them. Because DC encodes time information via position, DC is efficient for visually conveying actual travel time [12]. Theoretically, DC can encode the time without error (unlike Group 2), and a reader can decode travel time with a higher degree of precision (unlike Group 1, 2, and 3). Previous studies have shown that using DC can support a fast and accurate decoding of time information [4].

Although DC may not able to offer all of the benefits that the other groups provide (e.g., provide the traffic condition of certain areas), travelers who use this layout can visually decode the precise amount of travel time with less cognitive effort. Through the analysis, we conclude that such characteristics can be suitable for supporting urban travelers who evaluate and compare the cost of travel for making their travel decisions. However, constructing a visually straightforward and interactive DC presents challenges, as we discuss in the following subsections.

2.2 Presenting Time Space in Distance Cartogram

Bunge and Tobler were one of the notable pioneers who contributed to introducing DC to researchers [23, 24]. Their early work presents DC of Seattle with circular isochrones denoting locations that can be reached from the map origin in the same travel time. Then a few years later, Angel and Hyman noted that the times are distributed *discontinuously* across space [17]. Even if two given points are physically located in close proximity, travel times from the origin to the points can differ greatly, because: (a) the Euclidian distance (as known as *crow's distance*) between two locations and the network travel distance are generally different [6], and (b) uneven traffic will lead to variation in travel time [4]. One notable implication of Angel and Hyman's work is that the discontinuity of time space would make it impossible to project the travel time on Euclidean space without overlapping map features which can deteriorate the interpretability and recognizability of DC

Construction of DC is a process of warping *continuous* physical space to represent *discontinuous* time space [15]. In order to warp the physical space, it is necessary to determine a *key structure,* which defines the locations to shift and the topological relationships between the locations (e.g., adjacency and connectivity between locations) [25]. The road network, which represents a real-world road infrastructure with a set of edges (which indicate a road) and the nodes (which indicate the crossings), has been widely used as a key structure [4, 16]. While shifting the nodes of the road network, a node can easily intrude on the adjacent nodes and edges and violate the topology of the key structure [7]. Such violation means 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. These violations destroy the planarity of external representation of DC by overlapping the map features. As Dorling remarked, "where the travel time space is inverted, however, even depiction of a single point may not be possible" [7].

A recent break-through has been suggested by [15], which uses a star network for defining a key structure. A star network is constructed by connecting the origin and every travel destination on a map [15]. Figuratively speaking, the structure of a star network is like spokes of a wheel, and each node in the network can move along its own spoke to reflect time space. Such structure is advantageous for maintaining the planarity of DC while the deformation, as the node's radial shift, will not be able to violate adjacent edges. In some cases, however, the discontinuity of the time space can invert the relative position of locations to such a

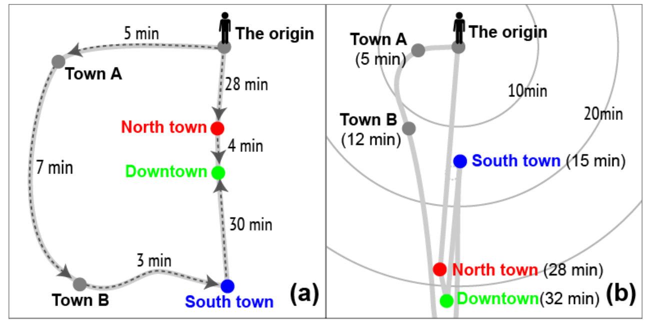

Figure 2: The locations of towns in (a) a physical space, and (b) a time space. The relative positions between South town, Downtown, and North town are inverted in time space.

severe degree that it confuses readers in reading the map. Fig. 2 demonstrates such possibility. In the physical space in Fig. 2(a), South town is located *further* from the origin than both North town and Downtown. However, travel time to South town is *shorter* than the travel time to the North town and to Downtown. As a result, the time space in Fig. 2(b) locates South town to the North of North town. The disrupted relative positions can confuse travelers. To generate more robust DC that can work in real-world settings, we need to better understand how much and what type of locational shifting is feasible before the DC becomes a poor fit with the user's internal representation of the space.

In short, directly using a road network as a key structure can cause overlapping of map features and impair the recognizability of DC. Using a star network can eliminate such overlaps, yet this method may not impose enough constraints to prevent possible perceptual disruptions between the locations. Consequently, we see the necessity to devise a new way to improve the presentation of time space in constructing DC to attain a broader adoptability.

2.3 Designing Interactions for Distance Cartogram

Several studies have been conducted previously to improve various aspects of DCs. Some have designed algorithms to improve performance [14], and some focused on improving visual quality of DC [4]. To date, however, the majority of approaches have focused on creation of static images, not interactive DCs as travel-related decision-making tools [4]. Hong et al. suggested one of the earliest interactive DCs which allows users to set the origin and time of weekday (e.g., 5:30 P.M. on Monday) [4]. Still, the tool restricts users' exploration with a fixed zoom level and constructs DC based on a static road network. The limited scalability of a road network used in earlier work may not be able to provide sufficient detail for mapping urban areas [25].

To unravel the potential of DC as an exploration tool, we see it is important to (a) derive a useful set of user interactions that can facilitate travelers' spatial exploration, and (b) construct DC within acceptable response times to retain the "flow of thought" of users while interacting with a system [26]. The biggest obstacle to supporting such requirements is the high computational cost for yielding travel time. Dijkstra's algorithm, the most widely used algorithm in DC, has $O(n^2)$ complexity [27]. Dynamic Delaunay Triangulation requires $O(n^3 \cdot 2^{\alpha(n)})$ of cost ($\alpha(n)$ is the "slowly growing functional inverse of Ackermann's function") [15]. To overcome this challenge, we see it is necessary to devise a technique that can flexibly define a key structure by abstracting perceptually dominant road structure of a given area [28].

3 Formative Studies

Due to the limited prior work focused on user interaction design for DC and specifically for the interactive map system we aim to design, we conducted two formative studies to better define the need and scope for the remainder of the work. In the first study, we conducted an online survey with urban travelers recruited on AMT (hereinafter Turkers) to understand the *general importance* of travel time and the *challenges* that map users currently face in accessing it. We 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 the Turkers were rewarded $1.50 for their participation. In the second study, we used a focus group session to *identify the necessary interaction design requirements for DC*. 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 elicit viewpoints of Turkers and Experts, we choose to focus on mobile platforms in both studies. Finding local services as well as travelling and commuting on short distances are the two most popular mobile phone use cases [29], that together cover almost 45% of all user interactions with mobiles. In addition, due to the novel nature of DC to audiences, we present concrete scenarios in which understanding travel time is an important part of the decision making process. We developed five scenarios for the study: (a) spontaneously finding the next travel destination while on the move, (b) deciding on a place to go to while considering multiple factors (e.g., ratings, travel time), (c) changing the travel destination while already heading somewhere, (d) familiarizing oneself with new surroundings, (e) and 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 [29] 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, we asked Turkers to indicate the frequency of experiencing such scenario as well as the degree of importance of the scenario. Finally, we also asked Turkers to report important factors for them in making short-distance travel decisions. Major findings are as follows:

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%). Based on the provided 5 common mobile phone use problems they indicated the following there as 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, Experts' comments from the focus group session pointed to a potential advantages of DC as follows: helping travellers 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 geographical reality is crucial. The discussion in the focus group session revealed that EM 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 DC exclusively. Furthermore, three experts expressed concern that the users may experience adoption barriers in using DC, as the layout will likely be novel to them. This chain of thought led Experts to suggest that devising a visual representation of 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. Users would expect common interaction types supported in existing map services. The focus group session also suggested that DC can be useful as an extension or additional layer on top of EM (4 Experts). Consequently, when interacting with DC, the users will likely have similar expectations related to interacting with EM. Therefore, the interface should allow users to interact with DC through widely used interactions such as zooming, panning and setting the origin. Two Experts mentioned that devising these familiar interactions in DC would increase the chance of easy adoption.

Based on the findings from the survey, we determine that obtaining precise travel time is important yet cumbersome. Consequently, we identify opportunities for redesigning DC as a decision-making support tool. The findings from the focus group interview indicate the necessity of (a) devising a presentation and an interaction that can help users relate destinations' locations in EM and DC, and (b) providing a series of map interactions to help travelers explore the space equally well with EM and DC. Designing an interactive map system that meets such requirements may improve the overall quality of a conventional map system.

4 System

We identified the three challenges arising when designing an interactive DC. The first challenge is to construct visually straightforward presentation of DC. In section 4.1, we elaborate on how GAP tackles this challenge and improve DC's visual representation. The second challenge is to handle the computational overhead that occurs when using a large scale of a road network. In section 4.2, we present how SRC manages the overhead and provide the seamless system interactivity. Third, in section 4.3, we elucidate the user interface (UI) design and the implementation of interactions of our system. To construct DC, we adopt a widely used road network based method. First, the process defines DC's key structure from a road network. Then it calculates the travel times from the origin to every node in a key structure via Dijkstra algorithm. Finally, it renders DC by shifting every node's position based on the calculated travel times (see [4, 14, 16] for details).

4.1 Geo-contextual Anchoring Projection

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*) [28]. Such topological relationships serve as a fundamental cognitive anchor that people rely on to establish the relationship between reality and the scaled map model [30]. However, if one uses a road network as a key structure to construct DC, preserving the topological relationships of a key structure becomes a conundrum [16]. This is a natural consequence of the fact because the physical distance between two points is generally *not proportional* to the travel time between them. Consider the case where the traffic congestion causes increased travel time from the origin to one destination which will result in the destination to be away from the origin. On the contrary, if one can reach a distant destination within a comparatively short amount of time, the destination will shift toward to the origin. If these shifts intrude adjacent nodes or edges in a key structure and create a new intersection between edges, the topology of a key structure is said to be violated. As noted, a topological violation can severely impair the map recognizability [7]. Fig. 3 (a, b) demonstrates such possibility: Fig. 3(a) shows the physical space, with a topology of a simplified road network used

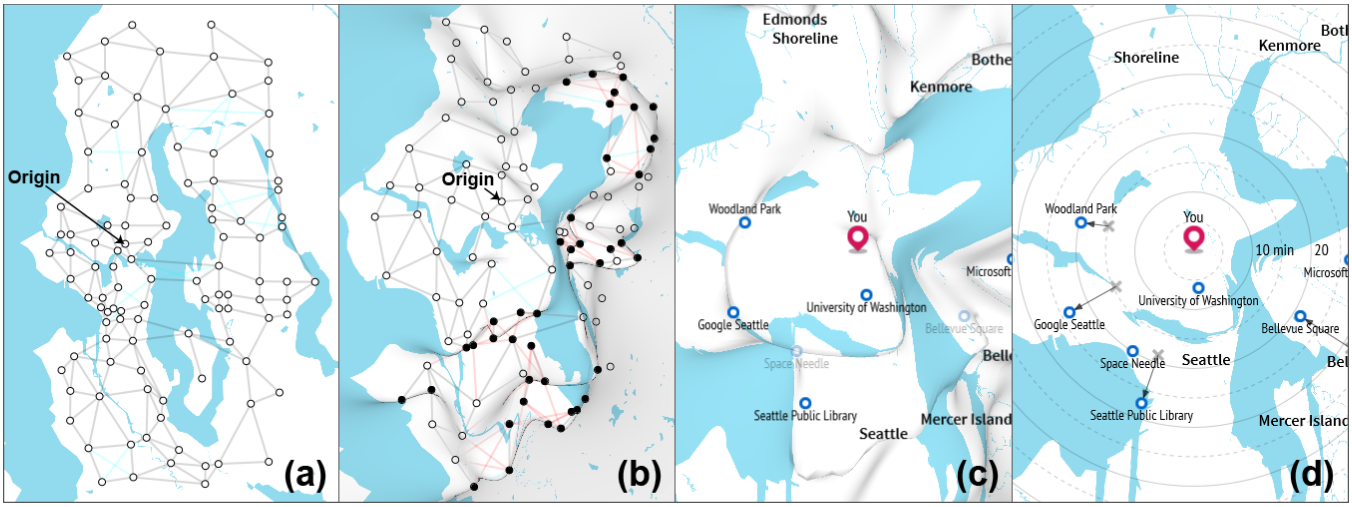

Figure 3: (a) EM and a key structure used in [4] (b) DC and a rearranged key structure: black nodes violates the topology of a key structure (c) DC constructed without GAP: the overlaps appear (d) DC constructed with GAP: overlaps are removed and replaced with anchors

in [4]. Fig. 3(b) shows a node-shifted time space. In Fig. 3(b), white nodes preserve the topological relationships and readers may easily infer the corresponding nodes between Fig. 3(a) and Fig. 3(b). However, the same task becomes nontrivial in the black nodes. Black nodes denote the nodes contributing topological violations.

GAP is a projection method designed to shift every node's position in a key 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. 3 (c, d) present the visual distinction between the result without GAP (Fig. 3(c)) and with GAP (Fig. 3(d)). In Fig. 3(c), the makers for "Space Needle" and "Bellevue Square" are presented with less transparency because uneven travel times cause topological violation and lead them to be submerged by landmass nearby. Fig. 5(b) remove these overlaps by replacing these with anchors.

Fig. 4 presents the pseudocode of GAP. O_i denotes the original position of node n_i in a key structure G, T_i denotes the target position of n_i. We derive n_i's target position via Dijkstra 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 [31]. To check for topological violations, we find all edges that are connected to a node. Then for each incremental shift in 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 two edges has changed from the previous step. (i.e., if the determinant of two lines is zero, that means the two lines are parallel or coincident).

```
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
        A_i = getAnchor(T_i, N_i)
        break
  end
end
```

Fig. 4: Pseudo code of GAP

It is worth noting that the use of anchors allows depiction of precise travel time, even *without* shifting the nodes' locations. However, we see anchors will likely to appear at every node, and some nodes may stretch excessively long anchors and impair the visual quality the result (Fig. 5(a) in [4] can be an example).

4.2 Scalable Road Network Construction

The goal of SRC is to derive a key structure of DC from a raw road network. The derived key structure should (a) capture major features of a raw road network so that a user can easily interpret the features in DC, and (b) maintain adequate amount of nodes and edges to ensure a reasonable response time when construction of 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 use of a map [25]. In designing SRC, we see the following two principles as closely related to achieving our goal. **P1:** when designing a map with distortion, presenting the accurate topological relationship between roads is critical [33]. **P2**: travelers perceive the urban space hierarchically [34]. That is, the types of roads (e.g., highways, arterial roads, residential streets) are perceived with different degree of saliency.

The SRC presents a key structure that has a different degree of details depending on zoom level a user specifies. SRC includes six subroutines. They are: (a) Raw paths obtaining, (b) T-splitting, (c) Dead-end pruning, (d) Chained path merging, (e) RDS, and (f) Hierarchical clustering. The pipeline for SRC is shown in Fig. 5 (c).

In **Stage 1**, SRC obtains a raw road network from OpenStreetMap (OSM). OSM provides one of the richest and extensive open map data to public, and the map features in OSM have been identified as reasonably accurate for general map users [35]. OSM includes various types of *pathways* (i.e., an ordered list of *nodes* – each defined by longitude and latitude – that is used in

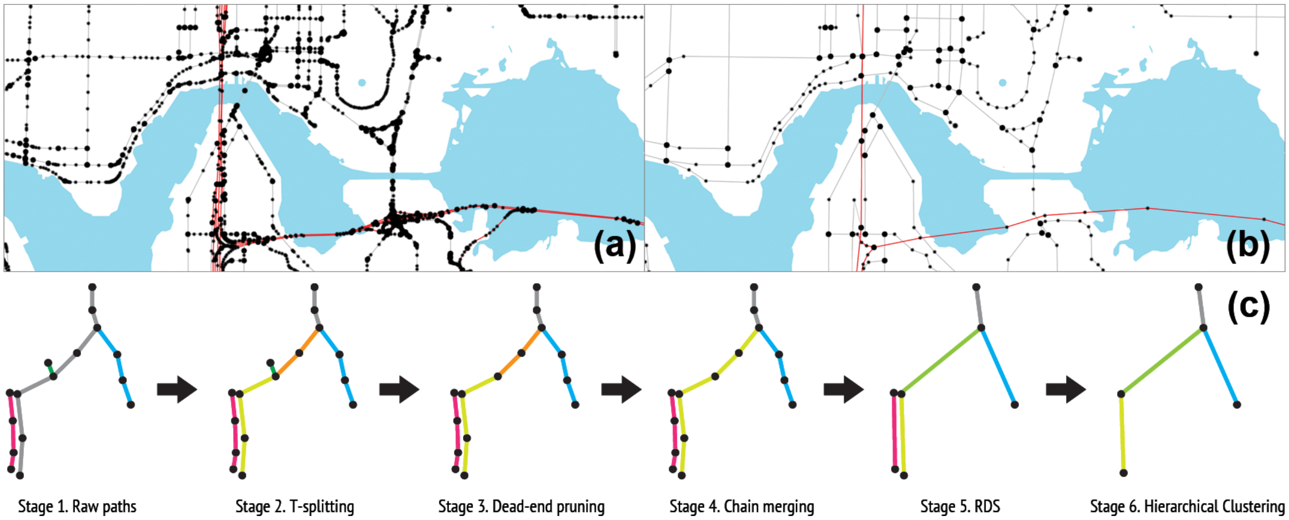

Figure 5: (a) A raw road network obtained from OSM, and (b) the derived key structure with SRC. Red paths indicate the highways. Bigger nodes are terminal nodes, and smaller nodes are intermediate nodes. (c) Six stages of SRC: each *pathway* is encoded with a different color.

OSM), such as highways, arterial roads, and bicycle roads. Among these, we collect the pathways related to vehicle traffic. They are: (a) *highway* (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**). Using the OSM API, we collected pathways in the greater Seattle area, between -122.440 and -122.075° longitude, and 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* pathways obtained from OSM to enforce 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 in 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 threshold). In **Stage 4**, we concatenate two pathways if one of the terminal nodes in each pathway is the same (i.e., that has the same longitude and latitude), and no other than the two pathways in a network share a node.

In Stage 5 and 6, SRC starts modifying a key structure by adding or removing nodes in a pathway or shifting a node coordinates. In **Stage 5**, SRC executes Ramer-Douglas-Peucker (RDP) line simplification [36] for each pathway. The purpose of RDP is to remove the intermediate nodes that are aligned in a straight line and prefer not to lose much of geographical accuracy. We used 5 meters for 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 [37]. In this process, the two nearest nodes in the same group of pathways are merged to one. This process continues until distances between every two nodes are above the threshold. The result is shown in Fig. 5(b). The number of pathways shrinks to 5,785, and nodes are reduced to 4,405 (93% of nodes are pruned compared to a raw network).

In **Stage 7**, to construct a DC's key structure, the system glues several types of pathways in different classes derived from SRC based on a zoom level and a focal point of on a map screen. With this class-based method, the key structure can present an accurate topological relationships of perceptually salient roads in an area (for holding P1 and P2). It can also control the order (i.e., number of nodes) and size (i.e., number of edges) of a key structure to such a degree that the system can present seamless interactivity to users.

We used SRC as a pre-processing for preparing a key structure. That means, only Stage 7 is executed while users interact with our system. SRC implementation yields 491 seconds of calculation time with all pathways of the Greater Seattle on a computer with 2.4G Intel i7 CPU and 8 GB RAM. Also, even though SRC significantly reduces a size of a key structure, there are cases where the size exceeds to a degree where the system cannot finish Dijkstra within a second. To guarantee the interactivity of the system, we periodically pre-calculate travel times for some parts of the structure, which is used in [4].

4.3 User Interface and Interaction of Mobile System

We design an interactive mobile map system where travelers can discover various types of local businesses in the greater Seattle area. The system presents 8,572 real local businesses around the target area which were gathered via Yelp API 2.0. The types of locations available are restaurants, bars, movie theaters, museums, coffee and desserts, groceries, and places for sports activity.

To support effective destinations discovery with the system, we designed a UI where a user can choose one of the location categories on the list (Fig. 7 (a)). Once a user selects a category, the

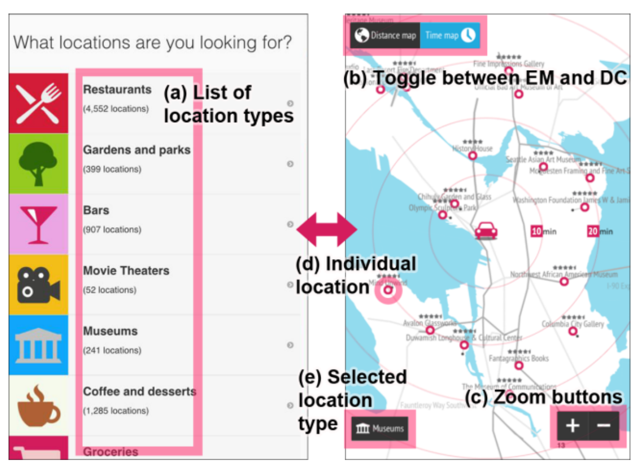

Figure 6. Mobile UI: A user can select a type of location (left), and explore areas in the greater Seattle area (right)

map is displayed. Five interactions are available in the map screen. First, a user can switch the cartographic layout between EM and DC with a toggle, as shown in Fig. 7 (b) (we call this EM+DC). Second, a user can use zooming interaction with buttons (Fig. 7 (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 7. (e)). When the user taps this button, the screen returns to the initial list. Finally, map panning is available.

The formative studies reveal that EM+DC can potentially help users to quickly access both geographical and temporal information and make a better decision. To implement EM+DC, we use a smooth *animated transition* between EM and DC to help users to retain their physical context in EM. There are techniques other than animated transitions, such as a juxtaposed view, lens view, overlay, or swipe interaction [38]. But the visual representation of DC can be highly different from EM, and the animated transition can help users to easily track the changes between the two stages [39].

To implement the transition, we use linear interpolation between EM and DC. The duration has been set to one second to help users to maintain their *focus* [26] while interacting. The EM+DC can be implemented with the following steps: (a) for each node N in a key structure of EM, N 's Cartesian coordinate $N_{start}(x, y)$ is converted to a polar coordinate $N_{start}(r, \varphi)$ from the origin O. Next, (b) the destination of $N_{start}(r, \varphi)$, $N_{end}(r', \varphi)$, where the distance r' indicates travel time from O is derived. Specifically, 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} . Finally, (c) $N_{end}(r', \varphi)$ is converted to a Cartesian coordinate $N_{end}(x', y')$. Once $N_{end}(x', y')$ is defined, the system linearly interpolates N's location from $N_{start}(x, y)$ to $N_{end}(x', y')$. Fig. 7 briefly explains this conversion.

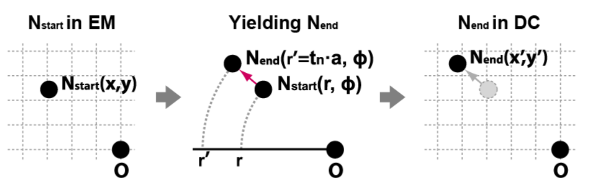

Figure 7: Yielding $N_{end}(x', y')$ by converting a coordinate system

5 Evaluation

We conducted two studies to evaluate our techniques and the system. In the first study (S1), we design 3 sets of static maps to understand the impact of DC constructed with GAP. Our goal was to see whether GAP can support people enough to overcome the novelty of DC and find benefit of using DC over EM 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.

5.1 S1: Understanding the Adoptability of DC

5.1.1 Method

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 the University of Washington. No participants reported they knew DC. All were 18 or older and resided in the Seattle area. The study was conducted in a lab, using a single computer.

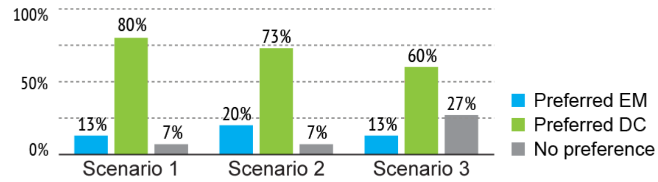

Figure 8: User preference results in Study 1

To understand the adoptability of DC, 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 time (*1 factor* to consider, among *7 candidates*).
- **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 (*2 factors* to consider, among *14 candidates*).
- **Scenario 3.** A person finds a new place to stay by considering price, size, travel time to an office, and neighborhood (*4 factors* to consider, among *20 candidates*).

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 (the interface in Fig. 1 (c) is used as a DC condition in Scenario 3).

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 EM and 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 DC (Aspect 1), whether they found 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 DC's usefulness (Aspect 3).

5.1.2 Results

Overall, the participants preferred DC over EM in every scenario. Fig. 8 shows in how many cases EM or DC were preferred for each scenario. In total, they preferred using EM 7 times (16%), DC 32 times (71%) and they expressed no preference 6 times (13%).

Aspect 1. Obtaining relevant information using DC: In terms of how participants interpreted information using 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 became clear as they experienced more scenarios. Only one participant felt anchors made it difficult to understand the information.

Aspect 2. Adoptability of DC and reasons: Regarding adoptability, 12 participants (80%) reported they would like to adopt DC. They found DC more useful than EM in accomplishing the scenarios. Analysis of feedback from the participants about the usefulness of 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 DC, and found this characteristic helped them make decisions quicker. The *include-and-exclude* group found 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 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 DC was useful. 6 participants (40%) reported DC was more useful in simple scenarios (i.e., the *simpler-the-better* group). They reported that 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 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 DC is useful and (b) their preference regarding the task complexity. In other words, 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.

5.2 S2: Exploring the value of DC interactions

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., DC, or EM+DC) alleviate some of the problems commonly faced by EM users? DC present precise travel time which enables instantaneous comparisons between locations without the need for holding any additional information in memory. We, therefore, expect that it 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 DC or EM+DC will be lower in comparison to EM alone.

As DC allows users to consider more options with a lower attention burden, we expect that decision time and decision accuracy would both be higher when using DC or EM+DC than using EM.

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

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

5.2.1 Method

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 system we designed in section 4.3 against another system where only EM is available. The former provides travel time with DC as well as the text upon a user request, whereas the EM-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 DC to participants. Then we gave 2 short tutorial tasks to verify their understating of 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 EM to 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 EM or DC respectively. After completing two scenarios, participants filled out a survey asking for direct comparisons between EM and DC on a number of aspects described in details in section 5.2.2. Then we briefly introduced EM+DC to participants.

Stage 2. Comparing EM to EM+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 EM+DC detailed in the dependent measures section. After this stage, we conducted a semi-structured interview.

5.2.2 Dependent measures and analysis

For each scenario, we measured the perceived cognitive load (H1.1) using items from NASA TLX questionnaire [40]. These are: (a) mental demand, (b) overall performance, (c) frustration level, and (d) effort. Following indications from [40], 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 EM+DC 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., EM and DC in Stage 1 and EM and EM+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 DC and EM+DC. We analysed the feedback by coding the quotes and organizing the codes into themes with affinity diagramming.

5.2.3 Results

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

H1.1: For three of the four measured aspects of the cognitive load, the DC and EM+DC offered a significant improvement. In

Stage 1, mental demand has been significantly lower for DC (M=3.38, SD=1.59) as compared to EM (M=5.19, SD=2.26) ($p<0.01$). Similarly, effort in DC (M=2.88, SD=1.09) has been significantly lower than in EM (M=5.19, SD=1.87) ($p<0.01$). Finally, the level of frustration reported for DC (M=2.38, SD=1.54) was also significantly lower as compared to EM (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 EM+DC (M=4.44, SD=2.22) as compared to EM (M=5.75, SD=1.84), p=0.04; effort significantly lower in DC+EM (M=4.06, SD=2.02) as compared to EM (M=6.44, SD=2.13), $p<0.01$; and frustration significantly lower in DC+EM (M=2.62, SD=1.71) as compared to EM (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 DC (M=44.88, SD=18.43) as compared to EM (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 EM+DC (M=133.36, SD=44.78) as compared to EM (M=160.63, SD=46.28) with $p<0.05$. These results indicate that the DC and EM+DC indeed allowed users to take advantage of the visual support for comparing multiple locations and make faster decisions. H1.2 is fully supported.

H1.3: There was no significant difference in the accuracy between DC and EM in Stage 1 and between EM and EM+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 the switching interaction and the interview data.

Finding 1. EM+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.

"Definitely easier as I can clearly see which places I needed to consider inside the time circle." – P11

Adding the EM+DC in Stage 2, made the preference for DC based solution even stronger with all the participants preferring EM+DC and 38% preferring it strongly. Participants specifically commented that having an ability to switch was helpful for understanding how the two maps are connected.

"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." – P16

Finding 2. EM+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 EM 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 EM was more familiar.

"In the time map, many geographical features were transformed, so I wouldn't believe them as is." – P6

In Stage 2, when they worked with even more challenging scenarios requiring a precise understanding of geographical reality, but also used EM+DC, the ratio of participants that preferred EM for this aspect shrunk to just 38%. Participants who expressed such increased confidence in understanding the geographical reality reported that using EM+DC was easy and comfortable. They felt that EM+DC provided more clarity and a deeper understanding of the relation between EM and DC.

"Using both maps provided more clarity and deeper understanding of the areas than using just distance map." – P9

Table 2. Experimental results from Study 2

Measure	Stage 1 EM	Stage 1 DC	Stage 2 EM	Stage 2 DC+EM
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: ** $p<0.01$, *$p<0.05$

Finding 3. EM+DC improves usefulness and increases the adoption. The survey after the Stage 2 revealed various positive aspects of EM+DC. More than 90% of the participants considered EM+DC useful and 81% considered it important. 64% of participants reported that they used EM+DC frequently while accomplishing the task. Also, 86% felt it helped them clarify their understanding of the information.

"(...) 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." – P15

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

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

5.3 Discussion

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

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

6 Conclusion

A number of important challenges for improving the quality of DC still persist. First, preservation of topology is essential for building high quality DC, however, that does not necessary mean that the result is always recognizable. The *shape* of a road network has been considered as important as the topology (See Fig. 3 (c), (g) in [41]). Research regarding this aspect would improve the perceptual quality of DC. Second, there are cases where a key structure derived from SRC contains too many pathways and fails to present results within a second. To design a fully scalable DC that works in any conditions, it is necessary to improve the algorithm for constructing DC. Third, travel decision-making is known to be an intricate cognitive process requiring consideration of a variety of factors [5]. Identification and visualization of relevant thematic spaces other than time space can better support travelers in broader context.

Map usage context and user needs are increasingly diversifying. Designing map systems that offer flexible user interactions with dynamic presentation of information can improve overall user satisfaction of map systems. Our findings indicate that the techniques and interactions we offered were successful design choices along this path. In conclusion, we see DC as a useful additional layer on top of the existing map applications and DRS.

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