Visualizing Urban Accessibility: Investigating Multi-Stakeholder Perspectives through a Map-based Design Probe Study

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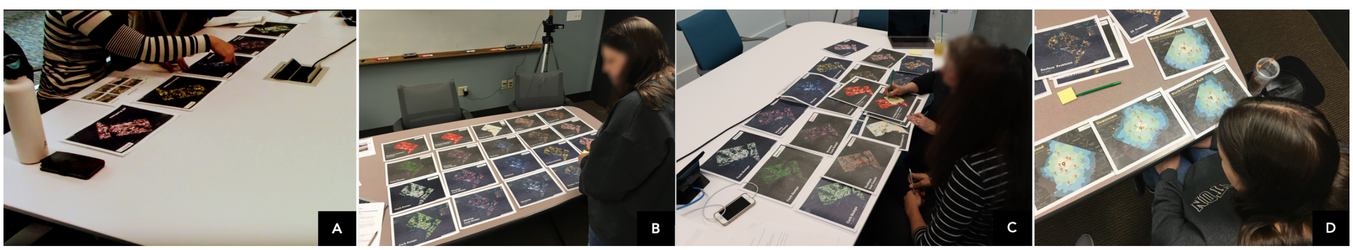

Figure 1: Interview setup and three-part study process. Part 1 presents visualization probes with seven map types. Row-by-row we gradually build a 5 x 5 map grid (A & B), where each row shows a different map type. Part 2 involves performing three sensemaking tasks. In (C), a participant completes a task using the map grid. (D) illustrates a task involving three ego-centric isochrone maps. Part 3 critiques map types and gathers opinions for future interactive visualization tools.

ABSTRACT

Urban accessibility assessments are challenging: they involve varied stakeholders across decision-making contexts while serving a diverse population of people with disabilities. To better support urban accessibility assessment using data visualizations, we conducted a three-part interview study with 25 participants across five stakeholder groups using map visualization probes. We present a multi-stakeholder analysis of visualization needs and sensemaking processes to explore how interactive visualizations can support stakeholder decision making. In particular, we elaborate how stakeholders' varying levels of familiarity with accessibility, geospatial analysis, and specific geographic locations influences their sensemaking needs. We then contribute 10 design considerations for geovisual analytic tools for urban accessibility communication, planning, policymaking, and advocacy.

CCS CONCEPTS

• **Human-centered computing** → *Geographic visualization*; *Accessibility systems and tools.*

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KEYWORDS

physical accessibility, visualization, sensemaking, decision-making, urban tech, geovisual analysis

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1 INTRODUCTION

A recent UN report notes a *"widespread lack of accessibility in built environments, from roads and housing to public buildings and spaces"* and this lack contributes to and further reinforces systemic inequalities in economic opportunity and access to basic services such as transportation, medicine, and education for people with disabilities [33]. While the open data movement has enabled new types of urban analytics and insights for transportation [55], climate change [6, 7], and public health [54], similar efforts in urban accessibility have been hampered by a lack of data [23]. Towards addressing this problem, new data collection tools such as *Project Sidewalk* [47, 61] and *WheelMap* [5] as well as open data initiatives such as *OpenSidewalks* [68] and *Accessibility Cloud* [1] have emerged, spurring new urban access visualization and mapping tools [5, 8, 12, 45]. While this progress is commendable, little work has characterized how best to visualize urban accessibility datasets across different stakeholders: what are the key visual analytic tasks and data needs (**RQ1**) and how might key stakeholders' sensemaking practices differ (**RQ2**).

To begin addressing these questions, we first developed 24 urban accessibility visualization design probes across seven map types using Project Sidewalk's Washington DC dataset [48, 61]: point visualizations, severity point visualizations, grid maps, heatmaps, choropleth, street visualizations, and ego-centric isochrones. Our designs were informed by prior work in urban accessibility visualizations [5, 12, 23, 32] and support a range of questions and tasks from *"Where are key (in)accessible hotspots in my city and why might this be?"* to *"How does neighborhood X compare to Y?"*. Using the probes to ground discussion and solicit feedback, we then conducted a three-part interview study (Figure 1) of five stakeholder groups (*N*=25): local transit officials, policymakers, accessibility advocates, caregivers, and people who use a mobility aid such as a cane or wheelchair (MI individuals). In Part 1, we observed how participants reacted to and made sense of the visualizations while in Part 2, they used the maps to complete specific sensemaking tasks. In Part 3, participants critiqued and reflected on their experience.

Through iterative coding and thematic analysis of the interview recordings, we present findings on urban accessibility tasks and data needs across stakeholders and share observations of the influence of professional role and/or life experience on their sensemaking process. Specifically, personal experience with accessibility, geographic location, and data analysis influenced their sensemaking processes. We find that participants analyzed maps based on personally relevant assessment factors and preferred maps that aligned with their mental model for assessing accessibility. For example, MI/Caregivers preferred localized views of the data (*e.g.*, street level), while policymakers and department officials preferred city-scale views. Participants built confidence when they could personally verify their assessments with other maps. Finally, establishing trust with the data was crucial to confidently interpret and draw insights from the visualizations.

Our contributions, which are situated at the intersection of the accessibility and visualization literature, are three-fold: (1) a multi-stakeholder data and task characterization within a multi-layered task model for urban accessibility visualizations, (2) elaborating the influence of individual differences on sensemaking processes, and (3) a set of 10 design considerations for implications and opportunities for future interactive geovisual analytic tools to support advocacy, policymaking, city planning, and daily living.

2 BACKGROUND AND RELATED WORK

We present background on urban accessibility assessments and stakeholders needs in accessibility decision-making followed by prior work in visual analytics and sensemaking.

2.1 Urban Accessibility Assessments

Urban accessibility seeks to enable access to opportunities and services while ensuring comfort and quality of experience to people of all abilities [19, 60, 70]. Physical access includes pedestrian infrastructure (*e.g.*, sidewalks), transit (*e.g.*, buses, trains), and Points of Interest or POIs (*e.g.*, buildings and facilities) [22, 30, 60, 66]. In this paper, we use sidewalk accessibility data to study visualization-based urban accessibility assessment needs. Physical access issues to sidewalks include the presence and absence of curb ramps, surface problems, sidewalk path obstacles, and the availability of sidewalks themselves. The Americans with Disabilities Act (ADA) [17, 18] together with US Access Board [10] provides standards for accessible sidewalks by specifying design requirements. For example, sidewalks must be a minimum 1.5m (5ft) passing width, a maximum 5% grade, and have curb ramps at intersections.

Maps are widely used for analyzing and communicating urban issues due to their spatial arrangement, visual impact, and perceived credibility [38]. Existing accessibility assessment tools are largely map-based [1, 5, 12, 13, 45, 52] with street- and sidewalk-level views. While these tools offer information on POI accessibility [1, 5] and customized views of sidewalk accessibility based on mobility needs [12, 45], these tools and visualization types have yet to be studied across different stakeholders. Closest to our work is a design probe-based study that envisioned future accessibility-aware location-based tools for MI individuals [32], where maps played a central role in the resultant designs. We extend that work [32] by studying sensemaking processes and visualization needs across five stakeholder groups using map-based paper prototype probes. We contribute to urban accessibility task and data characterization [53] by elaborating stakeholder goals, tasks, and needs for future geovisual decision support tools.

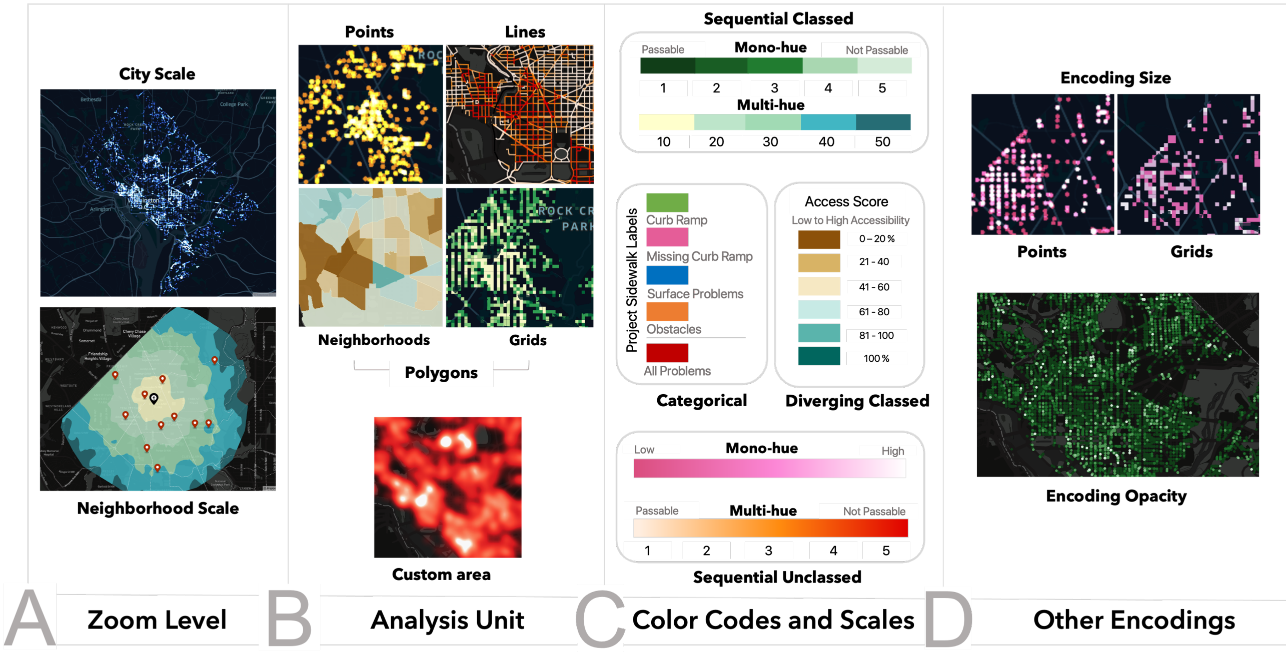

Figure 2: Design Dimensions of Map Probes. A. Zoom Level, B. Analysis Unit, C. Color Codes and Scales and D. Other Encodings (*e.g.*, size and opacity). For the accessibility label categories, we used Project Sidewalk's color palette [48, 49, 61] as color codes.

2.2 Stakeholders and their Decision Making Perspectives

Urban accessibility stakeholders include, people with disabilities, caregivers, occupational therapists, advocates and activists, policymakers, department officials, transit agency officials, and other professionals [41, 60, 69]. These groups, each with their own accessibility perspective, can be divided into two overlapping categories: people who are affected by accessibility issues and people who make or support infrastructure planning decisions and improvements. Saha *et al.* [60] studied the decision-making process and needs of five stakeholder groups: policymakers, department officials, accessibility advocates, MI individuals, and caregivers. They found that MI individuals and caregivers prioritize travel safety and quality, and therefore, have localized questions such as *"Is it doing to be a smooth ramp?"* or *"Is the entrance accessible?"*. Policymakers and department officials are concerned with more macro-scale questions related to planning and resource distribution: *"what are the highest priority sidewalks?"* or *"do we invest in new sidewalks or in repairing existing sidewalks?"*. Finally, advocates often act as an intermediate representative body between the government and the citizens to communicate needs and concerns to push for change. The nature of their questions are both investigative and exploratory to aid them in (a) understanding the extent and impact of the problem and (b) analyze effectiveness of remediation approaches to ensure accountability (*e.g.*, investigating a non-compliant curb ramp: *"When was this curb ramp installed? Was it part of this administration?"*). With these needs and perspectives in mind, we study these stakeholder groups' visualization needs for analyzing urban accessibility data.

2.3 Making Sense of Visualizations

Russell *et al.* [59] define sensemaking as the *"process of searching for a representation and encoding data in that representation to answer task-specific questions"*. Within geovisual analytics, sensemaking focuses on how people perceive information in geovisualizations and make sense of their inferences [58]. While past work in visual analysis research [57] typically focused on understanding analysts' sensemaking processes, a recent body of work has started studying how non-experts understand, process, and construct visualizations [44, 56]. With the proliferation and wide-scale consumption of visualizations in mass media, especially during the ongoing COVID crisis [43, 75], emerging research is examining visualization use in real world contexts, especially the social and political contexts of visualizations [21, 43, 56]. Our work fits within this growing body of work, where we study visualization use within the urban accessibility context, studying sensemaking processes of multiple stakeholders and the influence of stakeholder differences on their interpretation process of making accessibility assessments.

In this paper, we develop an understanding of the sensemaking processes of diverse non-expert stakeholders while performing geovisual analysis for urban accessibility. We specifically study people with little or no professional data analysis experience but have data questions for assessing accessibility. They have indirect interactions with such data-driven visual analyses. For example, policymakers are usually consumers of the visualizations (rather than an analyst) while advocates, who are not analysts by profession, are often involved in geovisual analysis as part of their job.

3 DESIGN OF MAP VISUALIZATION PROBES

To structure our visualization design work, we drew on common urban accessibility questions identified in the literature [32, 61]:

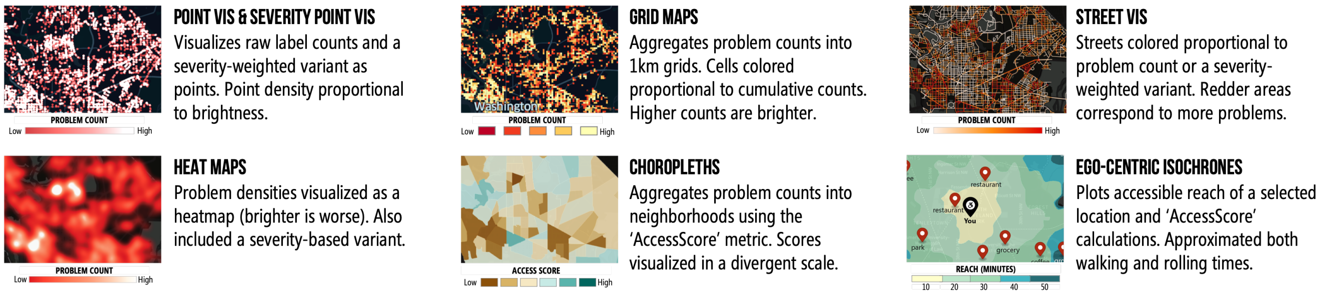

Figure 3: Design Probes. Seven map types used in the study. PointVis and SevPointVis are represented in one sub-figure.

"where are the most (in)accessible parts of the city?", *"which is the most accessible neighborhood to live?"*, and *"why is my neighborhood inaccessible?"*. We attempted to create a diverse visualization set that enabled both micro-assessments of urban accessibility such as via point- or street-level visualizations similar to AccessMap [12] as well as more holistic analyses via heatmaps and choropleths [45].

Dataset. All visualizations were created using Project Sidewalk's open sidewalk data from Washington DC [48, 49, 61]. Project Sidewalk is a web-based crowdsourcing tool for mapping and assessing sidewalks via remote annotations of Google Street View (GSV) imagery. The DC repository consists of 250,000+ geo-located sidewalk annotations identifying and assessing curb ramps, missing curb ramps, obstacles, and surface problems. Each label is annotated with a severity assessment on a 5-point Likert scale (5 – most severe) and optional open-ended descriptions.

3.1 Design Space Dimensions

Through iterative design amongst our cross-disciplinary team and informed by the geovisualization and cartography literature [11, 15, 20], we distilled a guiding set of design dimensions (Figure 2): *zoom level*, *analysis unit*, *color codes and scales*, and *other encodings*.

Zoom level describes map data at two different zoom levels: *city scale*, which are full maps of DC, and *neighborhood scale*, which visualize a zoomed-view of a specific neighborhood.

Analysis unit refers both to how the underlying sidewalk data is aggregated as well as how it is expressed on a map. For example, point visualizations render the frequency of a sidewalk label as small as 2px circles, grid maps and street visualizations render cumulative aggregated counts, and heatmaps visualize density clusters.

Color codes and scales. To visualize raw problem counts and severity-weighted variants, we used mono-hue gradients. Aggregated views such as grid maps and choropleths used discretized multi-hue color schemes denoting low-to-high problem areas. For some map types, we created multiple visualizations—one per sidewalk assessment type. Here, we used Project Sidewalk's color palette [48, 49, 61]: curb ramps (green), missing ramps (pink), surface problems (orange), and obstacles (blue). To emphasize problematic areas, we used a black background with bright problem clusters [51, 63].

Other Encodings. The size of map elements such as points or grids were chosen to facilitate comparison across map types. For point maps, where overplotting is common, we used opacity to convey point density.

3.2 Final Urban Accessibility Design Probes

For our interview study, we ultimately created 24 map-based visualizations across seven map types (Figure 3 and Figure 4): point (*PointVis*), severity point (*SevPointVis*), grid (*GridMaps*), heatmaps (*Heatmaps*), choropleth (*Choropleth*), street (*StreetVis*), and ego-centric isochrone (*Isochrones*). The maps are situated in different points in our design space utilizing unique aggregation models, visual encodings, and zoom levels and also reflect emerging prior work in urban accessibility visualizations [5, 12, 23, 32]. For *PointVis*, *SevPointVis*, and *GridMap* visualizations, we created five individual maps—one map for each label type (*e.g.*, obstacles, surface problems) as well as an aggregate map for all problems. To create the visualizations, we used Project Sidewalk's DC API [1] and geospatial mapping tools–Mapbox, kepler.gl, and QGIS [2–4]. To simplify technical map names, in the interviews, we used the terms "area map" for choropleth and "time plot" for Isochrones. While all designs were presented as paper prototypes, our findings are intended to inform the design of future interactive visualizations.

4 INTERVIEW STUDY

4.1 Study Methodology

To investigate our primary research questions on understanding visual analytic tasks and data needs (**RQ1**) and individual differences in sensemaking processes across stakeholder groups for urban accessibility (**RQ2**), we conducted a three-part interview study with the 24 paper-based map visualizations (Figure 1). In Part 1, we observed how participants reacted to and made sense of the visualization; in Part 2, they used the maps to complete specific sensemaking tasks; in Part 3, participants critiqued and reflected on their experience. Study sessions lasted 1.5–3 hours and were audio and video recorded. We provided compensation of US$25/hour and up to US$30 for transportation costs. Interviews were conducted by the first author, and the study was conducted as part of a larger interview study with the same participants. During all study parts, participants were asked to "*think aloud*."

Part 1: Initial Exploration of Visualizations. In Part 1, we studied cross-stakeholder similarities and differences in how participants initially reacted to and interpreted the map visualizations. Specifically, we studied *exploration*, *sensemaking*, *interpretation* practices, and solicited feedback on perceived *usefulness* and *desired features*. A secondary goal was to familiarize participants before the sensemaking tasks in Part 2. To begin, we first introduced Project

[1] dc.projectsidewalk.org/api

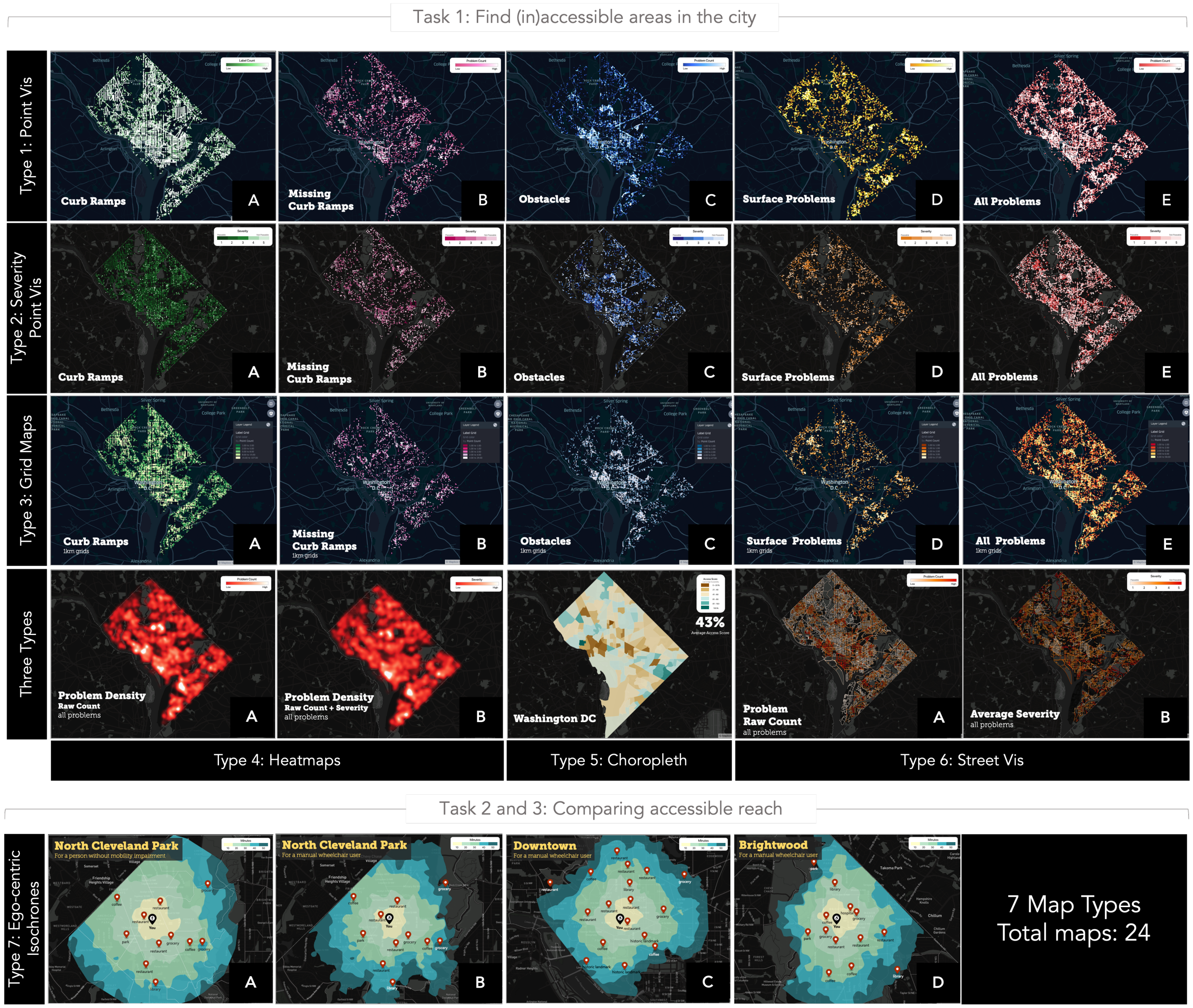

Figure 4: Illustration showing the 5x5 map grid of 24 prototypes across seven map types. High-resolution images are available as Supplementary Material.

Sidewalk and the collected data then sequentially introduced each map type by building a row-by-row visualization grid (Figure 4) on a large table surface. For each row, participants were asked: *"What do you learn from these visualizations?"*. While the order of the seven map types was kept the same across all participants, the rows closest to the participant (Figure 1) were randomly changed across participants.

Part 2: Visual Sensemaking Tasks. Next we sought to understand *sensemaking* processes with respect to a task: how do participants use the visualization(s) to answer task questions and why use specific visualizations? We asked participants to perform three sensemaking tasks: one *"find"* task and two *"compare"* tasks. These tasks, which were derived from the literature [32], require participants to assess overall city accessibility, compare accessibility of regions (such as neighborhood/locale), and compare the accessible reach of individuals. They represent common tasks for assessing and prioritizing infrastructure improvements and/or for informing travel decisions.

In Task 1, we asked participants to "find the *three most accessible* and *three most inaccessible* areas in the city" using any of the city-level maps (Figure 4: Types 1–6). Participants marked identified areas using Post-Its (Figure 1: sub-figure C) and were asked to explain their rationale. For Tasks 2 and 3, we used Isochrones (Type 7 in Figure 4). Here, participants compared the *accessible reach* of an individual [2]. In Task 2, participants compared the accessible reach of individuals with and without mobility impairments (Figure 6). In Task 3, participants compared selected neighborhoods (Figure 7)

[2]For tasks 2 and 3, *accessible reach* is defined as an area that can be covered by a person within the existing sidewalk barriers, specifically characterized as POIs that are within reach and how far are they from a given location

and were asked to select the most accessible neighborhood for a family member using a manual wheelchair. After each task, we asked: (1) What aspects of the selected visualization helped answer the question? (2) Was there any missing information? (3) How did they envision using these visualizations in their personal or professional lives?

Part 3: Critique and Reflections. Participants critiqued and reflected on their experience by discussing the perceived utility and limitations of the map types, rated the usefulness and trustworthiness of each, and stated their map preferences. We then solicited design recommendations for interactive visualization tools.

4.2 Participants

We recruited 25 people (11 female) aged 25–72 (*Mean*=48.3, *Median*=45, *SD*=14.5) across five stakeholder groups: six department officials (D), eight accessibility advocates (A), four policymakers (PM), seven people with mobility impairments (M), and five caregivers (C). Five participants identified with two stakeholder roles (*e.g.*, P4 and P20 both identified as advocates and caregivers) and were interviewed from both perspectives. Department officials included employees from city departments of transportation (DOTs) and other related government organizations. Policymakers were either elected officials or their legislative staff members. Advocates worked as active disability rights advocates either as paid employees or volunteers. MI participants used a mobility aid such as a wheelchair or a cane, and caregivers took care of an MI individual either as a professional, family member, or friend. During recruitment, we asked MI participants if they used a mobility aid and to describe their disability. We provide a description of all participants in the Supplementary Materials. Only one participant had a professional data analysis background. Participants were recruited from three cities: Washington DC (*N*=5), Seattle (*N*=19), and New York (*N*=1) via mailing lists, word-of-mouth, social media, and directed emails. All interviews were conducted in person in the participants' respective city. We refer to participants by 'P' suffixed by their participant number and stakeholder group [*D* | *A* | *PM* | *M* | *C*].

4.3 Analysis Method

We audio and video recorded the interviews and analyzed the data in two phases: (1) through iterative coding and thematic analysis [14] to identify common themes and (2) through video analysis to study how the five groups performed the sensemaking tasks.

For the first phase, four researchers independently open coded two participants' data—interview transcript and video—to generate initial codes. Next, we used affinity diagramming [42] on these codes to create a codebook followed by collaboratively coding the videos and transcripts of one participant using it. Codes covered the sensemaking practices used, insights learned, envisioned usage of those insights, confusions and challenges faced, map inspired new analysis questions, and desired features for future interactive tools. We coded nine participants across all coders to form the codebook before splitting the rest to code independently. During the process, new codes were added if required and all coders were updated.

For the second phase, the first author went through all the videos and conducted a part-by-part analysis of the study sections. The researcher made notes on the sensemaking processes and their responses to individual interview questions and conduced a stakeholder analysis analysing the similarities and differences between stakeholder groups. The sensemaking process analysis involved going over the study video to notice how they used the maps such as combining maps to answer questions, pointing at certain areas of the maps, and reasoning about them. For the analysis and reported findings, we combine MI individuals and caregivers (MI/Caregivers) into one group as their data/tool needs were similar.

5 RQ1: TASK AND DATA NEEDS

To address *what are the key visual analytic tasks and data needs* (RQ1), we summarize participants' comments across the study on desired data and map usage for different decision contexts. The analytic task and data needs are represented and combined in a multi-layer task model for urban accessibility analysis (Figure 5).

Across stakeholders, participants wanted to use interactive maps for planning travel, city planning and policymaking, supporting civic interactions, and advocacy. While MI/Caregivers primarily talked about *navigability*, policymakers, department officials, and advocates talked about sidewalk network *connectivity* and *livability* for investment decisions. To inform resource prioritization, stakeholders wanted to perform *impact analysis*—impact of (in)accessibility on quality of life such as healthcare, jobs, and housing and *equity analysis*—equitable access to resources and physical infrastructure across diverse populations and geographic regions. An example analysis question was *how does accessibility of low-income areas compare with high-income areas?*. Beyond prioritization of resources, department officials described using maps for communication and citizen engagement, while advocates envisioned them as a persuasion and accountability tool to visualize equity issues: *"You know that not all neighborhoods are created equal, so being able to show that view of the world is a useful tool, especially when places have goals that say they want to do the right thing"* (P11A). These analytic tasks are represented as macro goals, analysis strategies, and micro tasks in Figure 5: Analysis Task Needs.

Participants mentioned various assessment factors have to be balanced across these decision-making contexts: *"I feel like I understand the map. The question is what am I willing to compromise?"* (P4C, a caregiver). The assessment factors ranged from disaggregated sidewalk problems (*e.g.*, *"I want to know how many of these obstacles are parking signs? Utility poles?"*–P23PM) to destinations, transit, and routes (*e.g.*, *"What this isn't telling me is where I can and cannot get through"*–P21D) to experiential (*e.g.*, travel safety) and socioeconomic factors. For example, policymakers and advocates wanted to perform equity analysis and analyze correlations with socioeconomic factors such as demographics (*e.g.*, where people with disabilities lived), population, and business density: *"I want to be able to look at it by tract or zip code or some other defined district and probably in multiple ways. I want to look at population data. These [all maps] are fantastic for outreach with our programs and our advocacy. They also are suggestive of solutions."* (P24A). These factors are categorized across quantitative and qualitative measures (Figure 5: Data Needs).

We map the identified analytic tasks and data needs into a multi-layer task model to demonstrate the observed analysis workflow

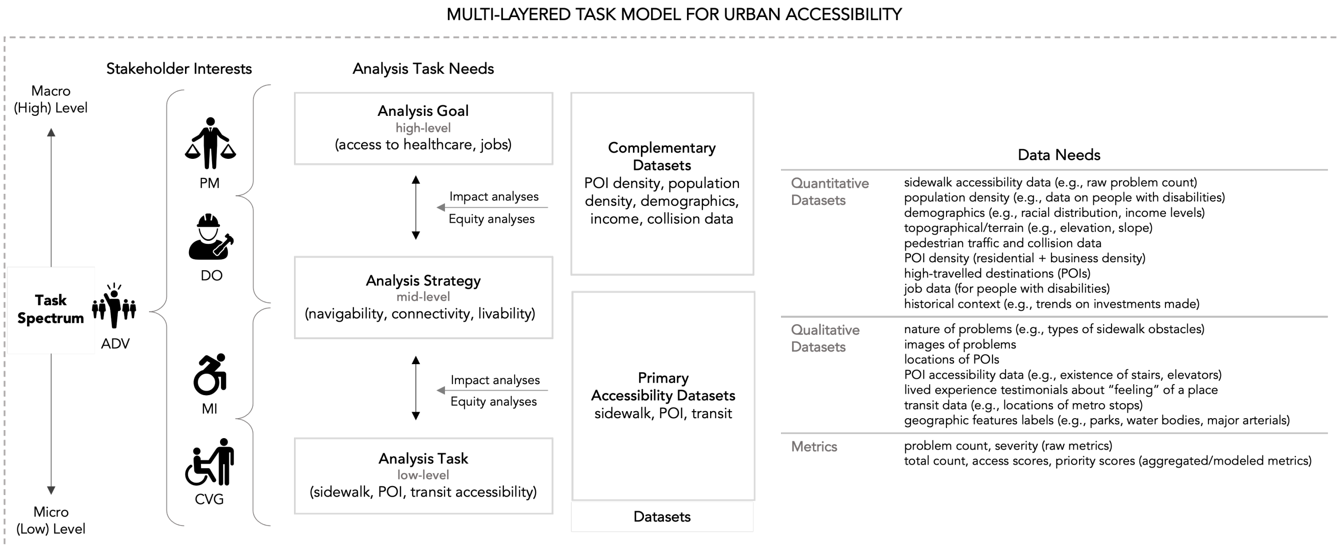

Figure 5: Mapping Stakeholders' Analysis Task and Data Needs into a Multi-layered Task Model for Urban Accessibility. The analysis needs are on a task spectrum, spanning from low-level micro tasks such as determining sidewalk (in)accessibility to high-level analysis tasks such as assessing healthcare access based on physical infrastructure conditions. The analyses occur at specific levels or across multiple levels (*e.g.*, equity analysis). 'Stakeholder Interests' represent stakeholders' primary focus and overlapping task needs: MI/Caregivers (MI/CVG) operate at low to mid levels, policymakers (PM) and department officials (DO) at mid to high, and advocates (ADV) across the spectrum. Note: The represented needs are not an exhaustive list, but reflect our participants' key tasks, strategies, and data needs. Icons from the Noun Project [24–28].

and how these needs overlap across stakeholders (Figure 5). Participant tasks are mapped on a spectrum as high-level (macro) analyses goals, mid-level strategies, and low-level (micro) tasks. Depending on the task, analyses occur at either a specific level such as the low level task of determining sidewalk (in)accessibility and associated causes or across levels such as equity analysis using mid-level assessment strategies such as connectivity analysis and complementary data such as regional income levels. For example, an advocate requested: *"I would want to look at home ownership income and education level by zip code, and see if those zip codes intersect with where the problem counts are high, and the severity is the least passable, or perhaps see if there is an intersection there"* (P15A). The stakeholder groups' primary tasks are at specific levels with some overlapping (shared) tasks (Figure 5: Stakeholder Interests). MI/Caregivers' primary tasks were between low to mid level, policymakers and department officials were usually at high-to-mid level, and advocates' were across the entire task spectrum. For example, policymakers and department officials talked about sidewalk network connectivity breakdowns as assessment strategies to perform impact analyses.

6 RQ2: SENSEMAKING PRACTICES

To examine *how sensemaking practices differ across stakeholders* (RQ2), we summarize observations across the open-ended map explorations (Part 1) and targeted visual analytic tasks (Part 2). We describe map use and present contributing factors for map preferences and trust in visualizations, supplemented with participants' Likert Scale ratings on each map type's utility and trustworthiness.

6.1 Task Analysis: Open and Targeted

Across both open exploration and targeted tasks, we report on participants' sensemaking processes for map understanding and usage for addressing the task prompt, challenges, and desired information.

Participants followed the sensemaking loop model. During open exploration, participants utilized the *bottom-up* processes of Pirolli *et al.*'s model [57] by building theory from data where sensemaking processes involved reading and extracting patterns and building a case for determining (in)accessibility. In contrast, participants employed *top-down* processes [57] for Task 1, namely searching for relevant information, relations across maps, and supporting evidence for self-evaluating assessments. Further, participants used 'tasks' as a sensemaking framework during Task 1: *"I'm trying to think of what my task is. Whether it's like to live there or to be there"* (P4C, a caregiver). Using a higher-level task as a "frame" to determine an area's (in)accessibility aligns with Klein *et al.*'s [39] data-frame theory of sensemaking, where the selected task is the mental frame within which sensemaking processes are performed. Policymakers and department officials adopted a prioritization of resources and investment decisions framing while MI/caregivers and advocates used navigability and livability. This layered approach is captured in the previously described task model (Figure 5).

In line with prior work [43, 56], personal experiences drove sensemaking. We identified three influential factors: (1) a participants' relationship with sidewalk accessibility as a function of their lived and/or professional experience (*Accessibility Familiarity*); (2) previous experience with analyzing map-based visualizations (*Map Familiarity*); and (3) familiarity with the city (*Location

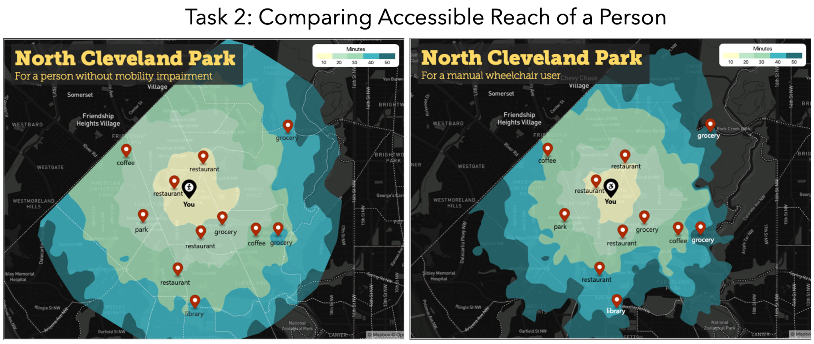

Figure 6: Isochrones used for Task 2: Comparing accessible reach of a person. The task is to compare the accessible reach of two individuals: one with a mobility disability (in this case, a manual wheelchair user) and an individual without mobility disability. Illustration shows the accessible reach for both individuals for a specific point in DC's North Cleveland Park neighborhood.

Familiarity)[3]. For example, those familiar with map types immediately started reasoning about the identified patterns (*e.g.*, causes of high inaccessibility) based off their prior knowledge: *"It looks like there's a high density of obstacles. I could imagine the sidewalks are really narrow in Georgetown, so I could imagine there being a utility pole or something in the middle of the sidewalk"* (P3GC, non-DC department official speaking based off prior visits to DC). Individuals with personal experience of disability analyzed maps based on their lived experience: *"From my perspective, even a severity of three, I can manage there. But once we get up to five, then that's a huge problem. So on this [PointVis], it looks really, really bad, and on this [SevPointVis], it still looks pretty bad"* (P1M, a motorized wheelchair user analyzing obstacle maps across both map types). Participants familiar with map-based analysis focused on searching for specific insights: *"what I'm looking for here [StreetVis] is not just redness, but the distribution of redness across a particular area as it connects to other red markings."* (P7AC, an advocate analyzing connectivity).

Contextualizing patterns was a core sub-task and need. All groups wanted to know the *"why"* behind the patterns seen: *"I don't feel like I can say anything about what is the cause of having it take the person longer"* (P4C, a caregiver during Task 2). Participants suggested contextualizing identified problem hotspots with quantitative data such as problem count, demographics as well as qualitative information (*e.g.*, problem images): *"There is a lot of problems highlighted in this area. It makes me wonder if that area has a lot of people of color who are disabled."* (P15AM, a black advocate interested in assessing racial inequities). Participants emphasized showing *personally* relevant information: problem locations (geo-context), problem types (identity context—*e.g.*, identifying utility pole from a water hydrant), reason for problems (root cause context), and what is harder to repair (remediation context): *"Adding a curb ramp is changeable. [...] [In contrast,] moving a telephone pole is really hard. [...] There are many, many agencies that have to approve that. So it would be interesting to find a way to assess the remediation possibility."* (P2M, an MI individual who assisted government agencies on accessible infrastructure). Unfamiliarity with the city's geography, makeup, and history with accessibility investments hindered analysis for policymakers as these external geo-contextual factors played key roles in drawing conclusions and making funding decisions. For Tasks 2 and 3, participants requested information on land topography (*e.g.*, elevation), underlying street grids, and important POIs.

Participants weighed metrics to determine *personally* relevant assessment factors. To pick (in)accessible areas in Task 1, participants weighed metrics such as problem count and severity based on what accessibility meant to them. An advocate explained her preferred quality of travel experience with her choice of low severe problem count over high problem count: *"I'd rather have the one big leech bite [high severity, low problem count] than the 100 mosquito bites [low severity, high problem count]"* (P15AM). Similarly, participants weighed label types against each other: missing ramps are a prime candidate for repairs (*e.g.*, for department officials) while obstacles are dealbreakers for navigation (*e.g.*, for MI/Caregivers). Depending on one's relation with accessibility, the metric combination varied.

Accounting for the diversity of accessibility needs across MI individuals was key. Accessibility assessments being a deeply personal problem manifested as participants found existing qualitative measures like severity useful but limited. While some participants expressed that severity added a nuanced information layer (*e.g.*, more problems does not always lead to an inaccessible path), others pointed out that severity is a subjective measure: *"Severity is in the eye of the beholder, or the eye of the traveler"* (P7AC, a caregiver) and *"people will have different ideas on what severity means to them"* (P10M, a cane user). During tasks 2 and 3, participants noted differences in accessible reach depending on a person's mobility profile, such as their pace and and functional status: *"I bet it's [accessible reach] even smaller than this when you consider functional status, meaning one uses a manual chair, but one is in excellent condition and doesn't have any other limitation in terms of upper body or fatigue. Because then what looks like 10 minutes is way longer because you've got to stop and rest."* (P24A, an advocate).

6.2 Map Types: Usefulness and Preferences

All groups wanted access to multiple map types to view the data from different perspectives and serve diverse audiences and decision contexts. Participants evaluated maps based on comprehensibility, comprehensiveness, and perceived utility for different contexts. In

[3]Six participants were Washington DC residents and three had visited or were otherwise familiar with DC.

Task 3: Comparing Accessibility of a Locale

Figure 7: Isochrones used for Task 3: Comparing accessibility of a locale. The task is choosing the neighborhood with the most accessible neighborhood in terms of accessible reach for a manual wheelchair user. Illustration shows the three neighborhood maps used for comparing accessible reach.

terms of self-reported usefulness, the top three map types were StreetVis (*Median*=5, *SD*=1.16), Isochrones (*Median*=4.5, *SD*=1.2), and SevPointVis (*Median*=4, *SD*=1.22). StreetVis and Isochrones were useful—especially preferred by MI/Caregivers and advocates—for their ability to inform travel decisions and equity advocacy. Below, we unpack contributing factors to a map's interpretability, utility, and preference.

Perceived utility aligned with how well a map supported existing mental models. Department officials preferred GridMaps and StreetVis because of the maps' close alignment with their mental model of sensemaking: GridMaps for its normalized data representation and StreetVis for streets as an analysis unit, both of which were commonly used in their jobs. MI/Caregivers focused on highly-localized problems such as the navigability of routes confined to specific areas (*e.g.*, neighborhoods, streets): *"I'm kind of wrapping my head around the fact that this is a global assessment versus usually my needs are very localized. And so from that perspective, this feels more like a data analysis task than really a problem assessment task. Because whenever I'm going someplace, it's highly context specific"* (P4C).

Stakeholder's decision context influenced map choices. A department official summarized a map's usefulness with respect to the ease of making individual decisions: *"What's most useful about the point maps, or the street map, or the zoomed in area map, is it allows me to begin to make individual choices about where I'm going to walk or route today. Or where I'm going to choose to make investments."* (P3DC). An advocate (P14A) preferred Heatmaps when acquiring investments and StreetVis when convincing MI/Caregivers with granular information like routes between A to B. Choropleth with access scores brought a sense of competitiveness that is useful as a persuasive political tool. Policymakers and advocates discussed Isochrones' wide utility from analysis to communication: understanding the impact of socioeconomic factors on MI individuals' navigability and neighborhood liveability, identifying points of change (*e.g.*, *"translating general feeling that we know to be true into [...] actual points of change"*—P23PM), and communicating with policymakers and civic groups. In contrast, all department officials acknowledged Isochrones' usefulness in guiding others while expressing limited personal utility due to insufficient specificity for city planning.

The analysis unit influenced map usefulness based on information granularity. Extending past work [32], the analysis unit (*e.g.*, points *vs.* grids *vs.* neighborhoods), referred as "location precision" in Hara *et al.* [32], influenced the information granularity and eventual usefulness towards decision-making tasks. For example, P3DC gave low ratings to Heatmaps, Choropleth, and GridMaps because of lower information granularity. Despite the ease of use, Choropleth was not preferred because of conflicting insights relative to other map types. The difference was due to the chosen analysis (aggregation) unit of neighborhoods *vs.* a much smaller area (*e.g.*, 1km grids) for PointVis, SevPointVis, HeatMap, GridMaps, also known as the Modifiable Areal Unit Problem (MAUP) [72, 73].

Participants preferred maps with experiential context. Policymakers preferred maps that conveyed the experiential context such as what an accessible path would look/feel like. For example, Isochrones to *"get a more dynamic change of what you're seeing [on the ground]"* (P17PM) and StreetVis as *"it is just more visceral because you can see the grid. [...] I want a presentation to be able to put someone in the mindset of someone who's in a wheelchair or blind or having a special mobility need"* (P18PM). A policymaker (P17PM) suggested showing PointVis coupled with the GSV problem image and associated severity as an effective way of visualizing experiential data.

6.3 Trustworthiness of Map Visualizations

Overall, *trust in the underlying data* and participants' *ability to interpret the metrics and maps* primarily drove trustworthiness. Participants who rated trustworthiness low ($\leq$ 3) or refused to rate it (*N*=2), wanted to know more about how the data was collected, how it was aggregated and modeled, and desired to personally confirm learned insights with on-the-ground reality (*e.g.*, field work). Some participants were skeptical about relying on crowdsourced data: *"I don't know who did this"*—P20AC who rated 1 for all maps. In contrast, participants rating high ($\geq$ 4) talked about having belief in the researcher, work, and the scientific methods used to generate the data and maps.

Information on the visualized data establishes trust. In line with the *disclosure* principle [21], participants suggested showing stronger ties to the underlying data to establish trust in the data, visualization, and gained insights. For example, algorithmic

Stakeholder Task	Primary Unit of Analysis	Low Level data		High level data	Context of Use (envisioned usage)
		Quantitative	Qualitative	Metrics / Trends	
Equity analysis	city neighborhood street	problem count income data past investments	demographics	temporal trends historical trends equity scores	Investment decisions Persuading public officials
Connectivity analysis	neighborhood street	problem count	severity POI locations issue images	priority scores distribution of "badness"	Informing policy Guiding MI individuals Persuading public officials Resource prioritization
Navigability of routes	street	problem count	severity issue images	temporal trends priority scores	Finding accessible routes Guiding MI individuals Persuading public officials Resource prioritization
Livability of neighborhoods	neighborhood street	pop. density business density	POI locations	historical trends	Guiding MI individuals Persuading public officials Resource prioritization

Policymakers   Department Officials   Advocates   MI/Caregivers

Table 1: Characterizing key stakeholder tasks. We adapt the design space dimensions of Schulz *et al.* [64]. Individual task cells are marked with stakeholder color markers to show tasks shared across groups. Note: This is not an exhaustive list; we represent a selected set of tasks mentioned by participants.

understanding of access scores, data collection method (*e.g.*, relative to ADA standards) and frequency, and impact of user bias on collected data: *"Did they annotate all the issues or just the ones they happen to care or know about, [...] but then didn't bother with other things?"* (P7AC). Underlying numbers and quantities such as sidewalk measurements (for ADA compliance) increase trust in the resultant analyses for decision-making and communication: *"As a district, state and local government, we need to be clear because the requirement by the law is to have the numbers. [...] Even though you can see it's wrong, you still need the numbers [sidewalk feature measurements] to confirm."* (P22D, a department official).

Ability to triangulate across map types and reaffirm inferred insights helped establish trust. Participants mentioned the ability to confirm their insights from other maps (*e.g.*, maps agreeing with each other) and prior knowledge: *"The areas that I am personally familiar with and I know to be problems in general showed up as problems here. So that makes me trust the areas that this highlights as problems that I'm maybe not so familiar with."* (P23PM). Corroborating prior work showing progressive disclosure via semantic zooming to assess data trust [16], participants suggested using interactivity to probe the raw data: *"If you have a heat map and you click in and it changes to, "Cool, I see streets." And you can click on a street segment and you can see what the problems are, maybe it shows you the three missing curb ramps and the obstacles and stuff. Something like that would allow me to trust it."* (P14A).

Influence of data/information granularity on trust varied based on relevance to the individual. For example, P24A trusted StreetVis because *"of how granular it is"* and PointVis for its strong association with the raw data: *"when you show a dot it's a specific problem. When you show a cluster of dots, it's very specific"*. In contrast, a policymaker P17PM did not trust PointVis because of lack of *desired* information granularity to understand the *"why"*: *"I just don't know what this is telling me. I feel more comfortable at this scale [city level] aggregating things"*. However, aggregation in GridMaps reduced trust for an advocate P7AC: *"amassing all of that[data] into some kind of generalized area, not score, but cumulative, is even more opaque. I'll reduce the trustworthiness for that reason"*.

7 DISCUSSION

Our interview study indicates that assessing urban accessibility requires multi-faceted analysis across diverse factors, ranging from quantitative measures (*e.g.*, problem count and severity) to qualitative concerns (*e.g.*, POI accessibility and lived experiences). We explored stakeholders' sensemaking processes through both open-ended and targeted exploration of map-based accessibility assessments. Through these tasks, we learned about individual differences in stakeholders' sensemaking processes and visualization needs. We reflect on these findings and present design implications for future interactive geovisual analytic tools for urban accessibility.

7.1 Assessing and Quantifying Accessibility

Q1: *How do we handle the diverse assessment factors needed across varied decision-making contexts for urban accessibility? Do we need separate tools for each context?*

Earlier, we mapped our participants' key analytic tasks into a multi-layered task model (Figure 5) where tasks ranged from low-level tasks such as assessing sidewalk accessibility to high-level tasks such as analysing access to healthcare. Table 1 breaks down these tasks at various levels into their individual data needs and envisioned use. Since these high level analyses can be performed in different ways, Table 1 represents one possible task analysis breakdown. For example, a policymaker's task of assessing the impact of sidewalk (in)accessibility on connectivity helps evaluate the impact on other aspects of life such as employment or healthcare. These interdependencies serve as a useful tool for policymaking, advocacy, daily living, and subsequently impact prioritization of resources by city departments. The task model (Figure 5) helps guide the design of tools to support complex analyses of urban accessibility: *"I think a lot of these visualization types as graphics are helpful, but then playing around with different overlays helps people*

to begin making decisions or understand what all this means." (P3DC, department official).

We also found that many mapped tasks are shared across stakeholders (Table 1). For example, an advocate and a policymaker both care about equity analysis. To support these shared tasks, we envision a single geoanalytic tool that can be personalized towards a particular stakeholder and a specific decision-making context while providing access to perform other shared multi-level tasks. This could prevent siloed analysis in existing task workflows of city governments and foster better cross-stakeholder interactions.

To complement these analysis tasks, we also need varied computational models to develop accessibility metrics (*e.g.*, access scores [45]) and account for the diversity of factors and analyses. A set of metrics supplemented by qualitative data such as lived experiences is needed to allow for comprehensive analyses. For example, an *Access Equity Score* to model the correlation of physical accessibility factors with socioeconomic factors, similar to the Tree Equity Score [9, 50] used by city governments to evaluate tree cover with respect to income and race. As one of the grand challenges in accessible visualizations, modeling accessibility is a rich open research problem for future work [23].

7.2 Stakeholders' Sensemaking Processes

Q2: *How did individual differences in stakeholders' needs and experiences impact sensemaking processes?*

Urban accessibility assessments are challenging because they are *deeply personal* and *deeply political* [60]. In our study, we saw how this dual nature manifests in the stakeholders' sensemaking and assessment processes of urban accessibility. We argue that engaging with the subjective nature of accessibility assessments, infused by the different stakeholders' analytical lenses and lived experiences, will be crucial for designing visualizations (and tools) for this application context.

Stakeholders' experiences with accessibility and disability (*Accessibility Familiarity*), either professionally and/or personally, introduced subjectivity in assessments. We saw differences in sensemaking processes in stakeholder's preferred information granularity, map types based on preferred unit of analysis (*e.g.*, streets or neighborhoods), and personally relevant assessment factors, metrics, and tasks. In line with prior work [56], we saw participants use 'personal relevance' to guide their process, from choosing a personally relevant task to weighing metrics based on the assessment factors that mattered the most (*e.g.*, severity more important than problem count). Further, a mismatch between a user's mental model of accessibility and the visualization made assessment challenging. For example, city-scale maps did not meet MI/Caregivers' localized needs. Similar to prior work [56], our findings suggest that an 'overview-first' model of visualization [67] is not suited for these participants, further suggesting a clear need to support varied accessibility tasks across stakeholders.

Relatedly, participants' personal experience with maps and geospatial analysis (*Map Familiarity*) influenced interpretation: maps that did not align with participant's mental model of map analysis were harder to use. Not all participants were familiar with these maps, imposing a learning curve. For example, a caregiver found PointVis overwhelming *vs.* a policymaker that found Heatmaps too abstract. These observations complement past work [43, 56] that finds personal ties with the data and visualization can supersede design dimensions for assessing usefulness based on *relatability*: if the user can relate to their own perspective or goal using the maps.

Finally, participants' personal experience with the city or location in question (*Location Familiarity*)—either lived, visited, or having prior knowledge—also influenced how they interpreted, used, and drew value from the maps. We found that a lack of geographic context hindered comprehensive analyses and participants requested more location-oriented information (*e.g.*, neighborhood name, street name, historical context). As we expect urban accessibility visualizations to be consumed by a variety of end-users, including those unfamiliar with the represented city (*e.g.*, when planning a trip), it is important to surface geographic contextual information to facilitate sensemaking.

In conclusion, our findings suggest the need to support stakeholders' personal differences and preferences, reaffirming Peck *et al.* [56]'s open question, *how can we design [visualization] systems that align with the personal experiences of our audience?*

7.3 Visualizing Urban Accessibility: Design Considerations

Q3: *Given these challenges, how might we utilize interactive visualizations to support communication and decision-making needs for urban accessibility?* Here, we discuss selected design implications for visualizing urban accessibility across diverse stakeholders and tasks. Table 2 lists ten corresponding design considerations.

7.3.1 Establishing Data Trust. We found that trust in the underlying data influences trust in the visualizations and insights. Hara *et al.* [32] emphasized the importance of *data quality* with five features: granularity, relevance, credibility, recency, and coverage. We extend this work by adding two data features for establishing trust: data and analytic provenance. Elaborating Hara *et al.*'s credibility feature, *data provenance* describes where the data is coming from and how was it collected. *Analytic provenance* refers to how models and metrics (*e.g.*, access scores [45]) are calculated. We suggest that future interactive urban accessibility visualizations should include features to provide both data and analytic/algorithmic provenance. While recent discussions around trust building in visual analytic systems has been in terms of describing and calibrating the trust continuum [31], *how we design these interactions to effectively support trust building* remains an area for future research.

7.3.2 Handling Diverse Assessment Factors. Diverse assessment factors require integration of numerous data sources, ranging from publicly available datasets from city governments to independently collected datasets by academic and advocacy organizations. The data formats vary and may be unstructured. Future visual analytic tools for urban accessibility could account for this diversity by making it easier to blend datasets and facilitate multivariate analysis. However, *how do we provide interactive visual support for these multivariate analysis tasks?* For example, assessing the impact of sidewalk inaccessibility on connectivity for MI individuals living in largely black neighborhoods requires multi-level analyses across four dimensions, namely—sidewalk accessibility, connectivity, population density for MI individuals, and race. Visualizing such

	Design Considerations (C)	Example Application of Design Considerations
Establishing Data Trust	C1: Make clear where the data comes from (Data Provenance)	Document data sources and collection information
	C2: Make clear how data is modeled (Analytic Provenance)	Provide explanation of the algorithms/models used
Handling Diverse Assessment Factors	C3: Support for adding diverse datasets	Advocates can add their personally collected data in their desired format (e.g., Excel, CSV)
	C4: Support multivariate analysis: both analyzing across accessibility assessment factors and visualizing diverse datasets	Policymakers assess the impact of inaccessible infrastructure on MI individuals to reveal inequities
Supporting Shared Stakeholder Tasks	C5: Support for varied, often conflicting, stakeholder group needs	MI/Caregivers assess navigability of a neighborhood Department officials assess equity in distribution and prioritization of resources and investments
	C6: Support for individual differences (e.g., familiarity with maps, accessibility, location)	MI/Caregivers' view tailored to localized data and neighborhood and street level maps (e.g., Isochrones)
	C7: Support for adjusting to visualization user needs as an analyst or target consumer	
Supporting Comparisons	C8: Make it easy to compare between multiple data, map, and geo-contextual views (e.g., providing historical context on accessibility investments across locations)	Department officials comparing accessibility of multiple locations within and across cities
Building Persuasive Stories	C9: Support for audience-driven message framing by adding relevant contextual data	Framing for policymakers: show impact of investments on citizen's quality of life
	C10: Support for exporting audience-driven stories in multiple visualization formats	Framing for MI/Caregivers: show impact of inaccessibility on their personal life

Table 2: Design Considerations for Interactive Visualization Tools in Urban Accessibility. The highlighted design considerations for 'Supporting Shared Stakeholder Tasks' play a central role across other design considerations.

multivariate geographic patterns effectively is a known challenge [29]. Current state-of-the-art geovisual analytic tools utilize linked views and layering to convey multivariate patterns, with a primary focus on univariate or bivariate patterns. Recent work for multivariate analysis [36] explored self-organizing maps [40] and parallel coordinate plots [34] to visualize high dimensional data. However, using such complex visualization techniques for non-expert users like our stakeholders seems ill-advised. We hope to explore the rich space of visualizing complex multivariate patterns for non-expert users in future research.

7.3.3 Supporting Shared Stakeholder Tasks. Previously, we characterized stakeholder tasks in a shared multi-layered task model (Figure 5), where tasks overlapped across stakeholder groups (Table 1). To account for group differences and support the rich shared task ecosystem for diverse stakeholders, future work is needed to explore tool designs that uses task characteristics as a configuration parameter. Do we design a full-featured analytic tool and have a derivative tool for MI/Caregivers? Is there a middle ground that serves all stakeholders? How easily could we customize such shared tasks based on stakeholder needs and differences?

7.3.4 Building Persuasive Stories. All groups envisioned using visualizations as a storytelling medium to spark engagement and dialogue with other stakeholders (*e.g.*, push agendas to decision makers) while driving awareness (*e.g.*, educating the general public). Crafting persuasive stories for cross-stakeholder interactions (*e.g.*, between policymakers and advocates for new policy/change [60]) requires tailored data stories for the target audience that consider their background while appropriately framing and contextualizing the data. Participants suggested adding and representing contextual information pictorially (*e.g.*, accessibility problem images, animations), textually (*e.g.*, lived experience stories), and quantitatively (*e.g.*, accessibility statistics). Future tool designs might explore a combination of visualization authoring techniques (*e.g.*, Lyra and others [62]), visualization recommenders (*e.g.*, Voyager 2 [35, 74]), and narrative visualization techniques [65] to provide interactive story-building support to produce artifacts such as story maps [71]. Handling existing biases by balancing maps with enough context such that false information is not percolated will be crucial [75]. An official said people came biased wanting to show their area in the worst light, corroborating an advocate's views on preferring maps showing problems in the worst way possible for a strong impact.

7.4 Limitations

We conducted our study in large US cities. While local government structures influence the decision-making processes, we argue that our findings would apply to most developed countries with similar structures and existing accessibility regulations. Second, we had very few participants from DC (*N*=6). Therefore, the map interpretation differences based on location familiarity may not hold as strongly in a dedicated local context. Future work could systematically study how location familiarity impacts one's interpretation process. Third, due to overlapping roles of some participants, both roles impacted their map interpretation and use, making it hard to identify the perspective they spoke from. Finally, the visualizations were not designed to support people with different visual abilities. Making accessible visualizations is an important and active area of research [37, 46], which we plan to draw upon in the future.

8 CONCLUSION

As an early work in understanding sensemaking processes using urban accessibility visualizations, this paper developed an understanding of how different stakeholders from different backgrounds and professions analysed urban accessibility. Through an interview study with 24 map visualizations as design probes, we studied the stakeholder groups' similarities and differences in map interpretation and urban accessibility assessment needs. We found that

personal ties to data, task, and maps played a primary role in driving sensemaking processes. Based on our findings, we mapped stakeholders' data and analysis needs into a multi-layered task model and proposed 10 design considerations for designing future geovisual analytic tools for urban accessibility. While we map the visualization task space based on our focused lab study, future longitudinal design studies with interactive tools are needed to closely engage with stakeholders and extend the visualization task space for urban accessibility.

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