Accounting for Visual Bias in Tangible Data Design

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Abstract

Data engagement has become an important facet of engaged citizenship. While this is celebrated by those who advocate for expanding participatory channels in civic experience, others have rightfully expressed concern about the complicated dimensions of balancing access with data literacy. If engaged citizenship increasingly requires the ability to interpret civic data through city dashboards and open data portals, then there is a concomitant requirement for diverse populations to develop critical perspectives on data representation (what is commonly referred to as data visualisation, information graphics, etc.). Effective data representations are used to ground conversations, communicate policy ideas and substantiate arguments about important civic issues, but they are also frequently used to deceive and mislead. Expanding statistical, graphical, digital and media literacy is a necessary component of fostering a critical data culture, but who are the beneficiaries of expanded models of literacy and modes of civic engagement? Which communities are invalidated in the design of civic data interfaces?

In this article, I summarise the results of a design study undertaken to inform the development of accessible data representation techniques. In this study, I conducted fourteen 2-h participatory design-inspired interview sessions with blind and visually impaired citizens. These sessions, in which I iteratively developed new physical data objects and assessed their interpretability, leveraged a public transit dataset made available by the City of Toronto through its open data portal. While ostensibly "open," this dataset was initially published in a format that was exclusively visual, excluding blind and visually impaired citizens from engaging with it. What I discovered through the study was that the process of translating 2D, screen-based civic dashboards and data visualisations into tangible objects has the capacity to reintroduce visual biases in ways that data designers may not generally be aware of.

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Introduction

For many of us, especially those who live in cities and communities where data-driven logic carries a kind of religious fervour, interaction with data has become a commonplace aspect of engaged citizenship. Voting in a civic election, for example, often entails familiarising oneself with housing and demographic statistics through interactive websites. Selecting a school for one's children can require interpreting complex metrics built from standardised test results, STEM funding and infrastructure investment figures. Even choosing whether to get a flu vaccination, a decision that is no longer really personal, might mean having to engage with maps and charts that would once have been the domain of professional epidemiologists. While active, data-engaged citizenship is frequently celebrated by the many among us who advocate for expanding participatory channels in civic experience (D'Ignazio & Bhargava 2015), others have rightfully expressed concerns about the complicated dimensions of balancing increased access to civic data with comprehensive digital literacy initiatives (Farina et al. 2014). Visual and graphical literacy are essential aspects of this knotty calculus. If engaged citizenship increasingly necessitates being able to interpret civic data through interfaces such as city dashboards and open data portals, then data literacy programs should support diverse populations to both interpret and develop critical perspectives on data representation.

Effective data representations (what are commonly referred to as data visualisation, information graphics, etc.) are not only used to assist decision-making, support querying or reduce cognitive load. They also ground conversations, communicate policy ideas and substantiate arguments about important civic issues. At the same time, they can be (and often are) used to persuade or mislead. From truncated axes to scale manipulation to cherry-picked data, the practice of graphical deception is regularly employed by politicians, activists and professionals of various stripes. The stakes for being unable to *read* a chart can be incredibly high. Imagine basing a life decision, such as a the purchase of a home, on misleading data, or making an everyday decision, like choosing a traffic route, without having developed the capacity to understand the UI of dynamic digital mapping platforms. Expanding statistical, graphical, digital and media literacy is a necessary foundation for any kind of critical data culture and, as such, has become an important site of research, development and scholarship.

Data literacy initiatives, ranging from enhanced after-school digital literacy programs to new research funding mechanisms, have grown exponentially over the past decade. Most purport to promote the growth of crucial data literacy skills without exception, and the distribution of these skills across income, racial and gender divides has become a key topic of research in fields like information science, critical data studies and science and technology studies (STS). Who are the participants in these expanded models of literacy and modes of civic engagement, though? Inclusion often starts and ends with questions around social equality, but data literacy has rarely intersected with accessibility and inclusive design research. Truly inclusive data literacy initiatives must not only include marginalised ethnic, linguistic, racial and gender communities, but should seek to promote greater access for disabled citizens as well. By asking which communities are invalidated in the design of civic data interfaces, we are able to surface a persistent problem: nearly all civic data interfaces are almost exclusively visual and ocularcentric.

In this article, I describe ongoing research on accessible visualisation and summarise the results of a design study undertaken to develop novel and alternative data representation techniques. In the study that is described, I conducted 14 participatory design-informed interview sessions with blind and visually impaired citizens. A goal of these sessions was to assess the level of engagement with civic data that blind and visually impaired citizens typically have. Throughout the sessions, I iteratively developed new physical data models and evaluated their interpretability, leveraging a public transportation dataset made available by the City of Toronto through its open data portal. While ostensibly free and open, this dataset was published in an almost exclusively visual format, excluding blind and visually impaired citizens from fully engaging with it. Through extensive experimentation with creating tangible representations from this dataset, I have found that the process of translating 2D, screen-based civic dashboards and data visualisations into 3D tactile models has a tendency to reinscribe visual biases – in the process, generating entirely new and unexpected barriers to access. These additional barriers are rooted in naturalised assumptions about the epistemic validity of visual media, as well as an inherent ocularcentrism in data interpretation, that many designers are unlikely to reflect on.

InclusiVis

Big data has been variously described as an opportunity (Lohr 2012), a harbinger for the death of politics (Morozov 2014) and a disruptor that waits for no one (Maycotte 2014). The ability to understand algorithmic manipulation of large datasets and the capacity to weigh the ethical impacts of data-driven decisions are crucial data literacy skills that increasingly challenge active, engaged citizenship. While the long-term effects of data-driven citizenship have yet to be realised, the role of data visualisation in its sensemaking apparatus is already apparent. Data-literate citizens must be able to read visualisations, which include both static and dynamic graphical representations of abstract data, frequently rely on visual metaphors and are commonly rendered as screen-based media. Most contemporary visualisation technologies, however, are insufficient for users with visual restrictions. In late 2017, I initiated InclusiVis, an ongoing research project to explore alternative data visualisation modalities, particularly tactile and auditory forms that afford greater accessibility for people with visual impairments. The project was hosted out of the Semaphore Research Cluster for Inclusive Design in Mobile and Pervasive Computing at the University of Toronto. The long-term goal of this research project is to inform the generation of novel accessible interfaces for interpretation of large datasets. Throughout its various stages, I have engaged directly with blind and visually impaired citizens, using participatory action research methods, in order to generate and evaluate physical "data objects" that employ 3D-printed tactile features and embedded responsive electronics. I have purposefully focused on topical civic data and leveraged our laboratory's extensive 3D-printing capacity.

In the sections that follow, I present selected insights from the design process and evaluation sessions in which blind and visually impaired research participants assessed and discussed physical data objects I had prepared for the study. Throughout these sessions, participants provided rich feedback that extends well beyond usability criteria. They described what data experience has been like in their lives, communicating, among other things, an almost universal resignation in the face of data engagement – that it's something completely alien to their lived experience. That data visualisation is not media "designed for them" was a refrain expressed by nearly every person who participated in the study. They also expressed thoughtful consideration around what might be appropriate forms of data engagement for the visually impaired. One particularly valuable insight, which was discovered through both a study of the literature and a survey of existing examples, as well as my iterative design process, is that it is difficult to prevent ocularcentric biases from influencing physical representations when converting screen-based visualisations into tangible objects. The study illuminated multiple instances where this happened. The tendency to incorporate and, in effect, naturalise visual biases results in two related phenomena: (1) decreased usability for blind and visually impaired users and (2) a prevailing sense that visualisation and, in effect, numerical data is a medium that is not accessible to the blind and visually impaired community. By iteratively building on participants' feedback, I had an opportunity to reveal and correct for these visualist biases by denaturalising them and producing alternatives.

In general, naturalisation of biases occurs when a group knowingly or unknowingly takes for granted how prevailing conditions come to be – in effect, assuming that they are perfectly natural. Naturalisation makes opaque the various social and structural influences that shape epistemic phenomena. To counteract this pervasive force, various programs in STS (and cognate disciplines) have advocated diverse techniques to make the "familiar strange" by approaching phenomena as if "through the eyes of visitors from other worlds" (Jasanoff 2012: 6–7). This is denaturalisation. By invoking denaturalisation in the context of visualisation design, we are able to illuminate visual biases that inadvertently (and sometimes deliberately) proliferate in the process of translation from screen to tactile. Following this, we can correct for them. Friedman and Nissenbaum (1996: 343) suggest that in order to remedy bias in design, we first "need to be able to identify or 'diagnose' bias in any given system. Second, we need to develop methods of avoiding bias in systems and correcting it when it is identified." Towards this end, designers must develop "a good understanding of relevant biases out in the world." Building this contextual knowledge in a space where blind citizens have to engage with a medium that was effectively *never designed for them* is a significant challenge. A starting point for denaturalising visual biases in the development of tangible representations, however, is to recognise that many of the conventions for inclusive design that are used to guide accessible graphics development still primarily rely on visual experience (e. g. correcting colour scales for colour-blind users).

Project Background and Research Design

Over the past 5 years, I have experimented with a number of novel data representation methods that incorporate 3D-printing technology, a core research specialisation of the laboratory and research cluster I work in. Substantial infrastructure grants for projects involving prosthetic design have outfitted our laboratory with over 20 3D printers, ranging from sub-$1000 desktop hobbyist printers to high-resolution commercial machines. Members of our laboratory have carried out extensive work on design software for prosthetic technicians, object reproduction for museums and the use of 3D printing for children's STEM literacy initiatives. My own work in the domain of tangible data representation has included capturing and making physical data sculptures of inconspicuous biometric processes, developing processes for creating modular 3D printed data maps and building scale experiments in virtual reality environments that incorporate tangible objects.[1]

Relying on the technical foundation of these projects, the InclusiVis project was initially motivated by a goal of promoting new modes of accessibility for datasets associated with civic experience. Additionally, it was guided by a desire to develop alternatives to the typically ocularcentric tools found in contemporary data visualisation practice. This specific goal requires that we first surface the epistemic biases produced by ocularcentric practices before attempting to denaturalise and create alternatives to them. The project has been inspired by the following question: as the ability to interpret and analyse data becomes an increasingly significant aspect of informed citizenship, how can physical "data objects" assist blind and partially sighted citizens? As I hope the following sections will make clear, this is not an easy question to answer. These sections describe the four main aspects of the InclusiVis research project: filtering and selection of appropriate civic datasets, exploratory design of 3D-printed tactile models, design-based evaluation with blind citizens and dissemination and engagement outside of the academy.

1 See http://semaphore.utoronto.ca/ and http://losingtime.ca/portfolio.html for more information about specific projects.

Civic Data Context

After some initial design strategising, datasets related to civic experience in my home city, Toronto, became the core focus of the InclusiVis project. Examples of this included Toronto subway station capacity and layout; granular population density and demographic data drawn from the most recent Canadian census and neighbourhood-specific violent crime statistics available through the Toronto Police Service's Public Safety Data Portal. Through informal consultations with blind peers, I gained insight into the kinds of data-based questions and concerns that blind citizens might have. After weighing various options that would be of potential interest to blind citizens, I made a strategic decision to focus on datasets that are purportedly open and accessible but, for one reason or another, are available through exclusively visual channels, thereby creating a barrier of access for blind users who might wish to query them. As a consequence, the focus of the project gravitated towards data that were of topical interest in advance of the October 2018 mayoral and city council election. In other words, I began to work with issues that were in the public conversation – issues about which data-based claims were being made. This enabled a consideration of how specific policy decisions and public communiques were being made through exclusively visual media, eventually pointing towards an interesting new dataset related to a contentious traffic management project.

In November of 2017, the City of Toronto initiated a pilot project on King Street, a major downtown thoroughfare, to remove nearly all vehicle traffic and provide unimpeded access for streetcars. Toronto's streetcar system is the second busiest light-rail network in North America, and King Street is its heart. Recent densification and persistent traffic gridlock have made transit reliability a key civic issue in Toronto, and the foundational aim of the King Street pilot project was to "improve transit reliability, speed, and capacity." At the time the pilot project commenced, a firestorm of media controversy ensued as business owners along King Street claimed the project had resulted in an immediate and significant decrease in pedestrian traffic. One vocal restaurant owner suggested that King had become a ghost town. The city (and various councillors) countered these claims by relying on data, made publicly available through monthly reports, related to reduced headway for streetcars and growing pedestrian traffic.

Notably, these monthly reports were provided through the city's open data portal as .pdf formatted "dashboards."[2] While ostensibly open through the reports, the underlying data were not released until October 2018. Instead, they were published in exclusively visual infographics embedded in the .pdf reports, thereby excluding blind and visually impaired citizens from engaging with them. Moreover, the visual graphics contained in the monthly dashboards provided

2 https://www.toronto.ca/city-government/planning-development/planning-studies-initiatives/king-street-pilot/data-reports-background-materials/

very little accompanying descriptive text. While the decision to work with this dataset was hindered by the fact that the data were new and by no means complete, it provided a unique opportunity to engage with a dataset that would be consequential in an upcoming election. Because the data had not been released in a format that would make it easy to work with in contemporary analysis tools, I wrote a scraper in the Python programming language and used the Python-based Jupyter notebook format, along with libraries including pandas and matplotlib that are essential components of the Python data science ecosystem, to create visual prototypes of the data story that could be presented to blind and visually impaired study participants. These prototypes formed the backbone of later 3D-printed designs, as well as the more public-facing communication objects that I would later share with digital literacy specialists employed by the Toronto Public Library.

Tactile Graphics

Drawing inspiration from a number of projects[3] – including previous ones I had worked on – that make use of 3D design and printing to reimagine visualisation and object interaction, my initial design goal was to prototype new methods for preparing and 3D printing data graphics inspired by visual analogues. Tangible data representations have existed for at least a century in formats that resemble data visualisation tropes common today. These include 3D bar charts, tactile maps, physical Sankey diagrams, and layered area charts. (Numerous examples predate these, including Polynesian "stick-chart" navigational aids and Inca *quipus* that operated as a kind of data storage device.)[4] Recent developments in 3D modelling and digital fabrication technology have inspired various projects and approaches that seek to make the field of data visualisation more accessible for blind and visually impaired users.

Tangible data design for the blind and visually impaired should not be taken as a concern or sub-field of data visualisation (which is commonly referred to as *infovis*). It is its own rich design space that poses challenges for researchers working on interactive alternatives to screen-based visualisation. It also presents a range of new problems and concerns that the standard perceptual usability methods used in infovis research cannot fully account for. In this novel design context, 2D, screen-based visualisation objects that are meant to serve as cognitive supports in the process of data analysis are typically reinterpreted as 3D, tangible, immersive and multisensory physical objects. The problem of ocularcentric bias in what is considered a "translation" process, however, serves as a crucial design challenge.

3 Examples include work by Kane and Bigham (2014), Jafri and Ali (2015) and Shi et al. (2016).

4 The most extensive project to document the history of such objects can be found here: http://dataphys.org/list/

In my work, overcoming this bias has meant doing away with the translation metaphor in favour of a transductive approach that William Turkel (2011) has used to describe a necessary reframing of digitisation as *materialisation*.

While the term materialisation has come into vogue in some infovis quarters, its use in these contexts typically belies the fact that the transductive processes required to produce these media are never unidirectional. Proper transductive materialisation focuses on the seams between materials, presenting new possibilities for creative expression within them. It is not merely about giving shape to supposedly ephemeral digital processes or objects. And, importantly, it does not obscure the materiality of digital media – it calls attention to it. This kind of materialisation entails acknowledging that the pipeline of data visualisation does not begin in the digital realm at all. It invariably begins in the material world. It is never a linear process. There is a real-world material context for every tangible graph in both its origins and its output. Paolo Magaudda (2013) argues for a similar use of this term in digital consumption of music, where he suggests considering materiality as a kind of bidirectional circuit. This method of transductive materialisation, as a way of producing tangible data objects, entails accounting for the entire chain of materiality, as well as pushing back against the reductive, simplistic notion of linear translation.

My approach to rendering 3D-printable objects from 2D visualisations includes both automated script-based processes and custom artistic computer-aided design. Throughout the InclusiVis project, I prepared, among other things, physical bar graphs, maps, line and area charts, suspended 3D scatter plots, donut charts and star plots/radar charts. Each of these techniques has required custom de novo designs, despite the fact that I would typically start with visual inspirations with long and storied histories.[5] Furthermore, each prototype I built has taken on a new life in physical form, as I have had to accommodate interactive features that one might encounter on a screen, or scale and perception issues that conventional screen-based visualisation perception studies might call attention to (e. g. cylinder volume when creating 3D donuts). As a consequence, the methodological choice to use iterative participatory design techniques to inform future design work was backdropped by a lack of appropriate precedents to draw on when attempting to assess the interpretability of custom data objects.

Design Study

The direction of the InclusiVis project has been strongly informed by feedback from 14 interviews with blind and visually impaired citizens, each of who expressed an interest in accessing civic data or finding out about accessible data representation techniques. Averaging 2 h in duration, interviews included questions about

5 See Friendly (2008) for an overview of various visualization tropes and their histories.

each participant's experience and familiarity with statistics and data visualisation techniques, about the kinds of civic data they might find useful and about their interest in using new digital tools to access data related to their civic experience (e. g. audio-based mobile navigational apps such as BlindSquare). The open conversational flow of the interviews was guided by the use of tactile prompts, which participants were asked to reflect on in the context of specific data stories. Participants split evenly along gender expression lines and ranged in age from university students to retirees. All were legally blind, with nearly all experiencing almost total blindness (only four had any ability to read a screen, and only with the assistance of digital accessibility tools). Nine participants read braille. Roughly a third of participants had experienced degenerative vision loss later in life (within the past 15 years) and, as a consequence, had some degree of previous visual experience that influences their sensemaking capabilities. All research sessions were video recorded to capture both the audio conversation and tactile gestures. I analysed these conversations using inductive thematic analysis, coding for variables that were unanticipated at the start of the interviewing process (e. g. "embodied data experience").

Dissemination of Code and Processes

A final component of the InclusiVis project is worth describing, as it includes the "action" part associated with project mandate. The goal from the start was to develop new techniques and inform future design work in the context of accessible data analysis tools. Over the course of the project, I developed various prototypes for tactile civic data dashboards. Many of these were included as prompts in interview sessions, but I had a larger goal of encouraging the development of these objects throughout the city. Similar tactile interfaces, while rare, exist as maps at museums and public parks in Toronto, and my motivation has been to develop tangible dashboards for dynamic contexts in which they may be of use to both the blind and sighted community. Towards this end, I initiated a collaboration with employees of the Toronto Reference Library's (TRL) *Digital Innovation Hub*. TRL is the centrepiece of the world's busiest urban library system. With its non-circulating collection, TRL operates as more of a community centre, and its Digital Innovation Hub has been at the forefront of library-based digital literacy initiatives in Canada. Located close to the city's major subway intersection, thousands of people visit the library daily, including many people with disabilities.

In September 2018, I conducted a half-day instructional workshop for employees of the TRL Digital Innovation Hub, along with other digital literacy specialists working in the library system's network of new digital innovation hubs and popup learning laboratories. For this workshop, I walked participants through a handful of user-friendly methods for rendering 3D-printable data representations from City of Toronto open data. I made instructions, data and a Python-based workflow available online through a code repository on GitHub and shared an open-source Jupyter notebook to communicate the workflow.[6] The mandate of the workshop was to seed these hubs, each of which is outfitted with 3D printers, with the tools and capacity to print custom data graphics for blind citizens who might request them. In addition to this, my long-term goal of creating an *in situ* tactile dashboard at TRL will only be possible if library employees have the ability to update or reconfigure data representations. In an age of dynamic, interactive data visualisation, it would be a shame to promote static graphs that would soon be obsolete.

Findings and Design Considerations

The sequential nature of the interview process allowed for iterative construction and examination of new designs and approaches, as well as a prolonged consideration of possible design flaws that were revealed in initial prototypes (e.g. illegible braille caused by "stringing," a common problem faced with desktop 3D printers). However, I was largely unaware of how prominent my own embedded visual design biases were, even as I attempted to move away from visual tropes altogether. This problem – the epistemic biases of designers – constitutes a core pillar of *exclusion by design*, and yet it is criminally under-recognised outside of the small context of reflexive/reflective design research in human–computer interaction.[7] It is a fundamentally different kind of exclusion by design than has been traditionally discussed in the STS and design literature (e.g. the bridges of Robert Moses). Through a reflexive process that entailed interviewing blind citizens, iteratively prototyping based on their feedback and preparing public-facing output with a goal of influencing the design of future accessible data interfaces, I was forced to account for my own epistemic biases early in the process. Let us examine how this came about.

Abstract and Embodied Mental Models

The very first research participant, Ron[8], has been almost completely blind since childhood. Having had encountered tactile maps at some point in his life, he could not recall making much use of them, or even being able to really interpret them. The very first data interaction I presented him with involved evaluating the efficacy of 3D-printed data tiles. These separate tiles were derived from bar charts depicting traffic volume at major intersections during morning and evening rush hours throughout the King Street pilot project. While Ron has years of experience advocating for accessible interfaces under his belt, and has deeply-held beliefs

6 The code repository is here: https://github.com/CriticalMaking/TPL and the notebook is accessible here: http://nbviewer.jupyter.org/github/CriticalMaking/TPL/blob/master/tpl.ipynb

7 See, for example, Dourish et al. (2004) for more on this theme.

8 Pseudonyms are used throughout this text.

about what tools are effective in this kind of context, he was quite open to experiencing traffic volume in a new way. Having laid out the tiles along an impromptu city grid that matched the general location of each intersection in the actual Toronto city grid, I assumed that Ron, who walks downtown regularly and has a high degree of familiarity with the transit system and its subway locations, would be able to easily imagine the big picture and each individual tile's place within it. What I had taken for granted, however, was that he would not find meaning in the *orientation* of the tiles. I assumed that he would naturally wish to encounter them as one would on a screen – facing upward, in a vertical orientation. Almost immediately, Ron asked why the tiles depicting eastbound traffic were not laid out horizontally, with their data peaks pointing right to indicate cardinal direction. The direction of traffic flow was crucial to his embodied understanding of the city, as he walks against traffic on King Street regularly, using auditory signals to guide himself, and had noticed a significant decrease in (literal) traffic volume.

Ron had a very personal, idiosyncratic mental "map" of the parts of the city he had been forced to navigate without vision. His description of it related to the groundbreaking work of Kevin Lynch (1960), who has described how we build mental models through embodied experience, accumulating traces of paths, boundaries, distinct districts, nodes and landmarks. Sighted people interpret a geospatial data landscape from an omniscient map-view perspective, while blind people, depending on their familiarity with maps, often see themselves in the map and situate themselves relationally according to specific landmarks. In designing geospatial representations, visual bias towards a map-view perspective needs to be avoided.

An additional problem surfaced as I tried to logically direct Ron through a navigational path that moved across the grid's tiles from SW to NE. In doing so, I had presented him with a layout that resembled a map as one would encounter it on a screen or paper, assuming that this base template would be familiar. Because he lives at the NE corner of the presented grid, however, and regularly walks downtown against the grain that had been placed in front of him, my assistance was counter-intuitive. Ron described his mental model of the city not as an ordered grid over which he has a kind of God's-eye perspective, but as similar to "a big ball of cooked spaghetti" that one can turn around in one's hand. His home orientation, he described, is somewhere in the middle of the spaghetti. "It would make no sense to a visual person," he said. The model I presented had attempted to translate, as directly as possible, the visual experience of encountering geolocative data, as one might on a civic data dashboard. This was a completely alien perspective to him, though. For Ron, his own embodied map unfolds as he moves through space, like a procedurally generated game environment. As I presented the same data tiles to other participants, with adjustments to the base orientation and initial tactile experience, I found that there were two major differences in how they preferred to receive the tangible data objects.

Those who had either never had vision or had lost it at an early age found it confusing when the graphs were placed vertically, as one would typically encounter them in a 2D screen or paper-based context. Those who had previous vision and lost it later in life, or were partially sighted and had relied on "visual" tools in the past, generally preferred the vertical orientation because, in most cases, they were familiar with what bar graphs were and how they functioned. Many of them had internalised the standards of graphic representation from a sighted perspective. Furthermore, these participants, who maintained some sort of visually oriented information model, relied in many cases on a detached, God's-eye perspective to facilitate navigation. For them, relating to tactile objects as translations from their familiar visual analogues was perfectly acceptable.

Those who had never had sight or lost their vision early in childhood did not typically share this view. Participants who had no experience with visual models like maps or grids situated themselves through memory or personal embodied experience, a number of them constructing abstract mental models that, to a sighted person, would be wholly incomplete. Reena, for example, relies on her father to drive her between her home and the university where she works. She has little sense of the city's grid, and can only place key landmarks relative to her experience passing them on her route. According to her, they have little geospatial relation to each other in her mental model. These specific insights related to embodied experience caused me, the sighted designer, to reconsider how my own ocularcentric biases about the efficacy and validity of statistical graphics were shaping my design of tactile objects for users who may have no reason to consider these graphical tools at all. For me, bar graphs were the most common and best understood graphical trope to tell the story of grouped categorical data. Whether they had the same epistemological currency to the users I was claiming to design for was something I had not fully considered.

Scale Shifts

An aspect of visualisation that makes it a core piece of the data analysis pipeline is that it offers the chance to discern patterns at different scales of interpretation. The distal sense of vision offers the possibility of quickly scanning an entire image, getting, in effect, a bird's eye perspective. This macro read on a graph's overall shape and meaning relies on various perceptual conventions, depending on the type of graph one is dealing with. "Drilling down" to discover granular detail – moving to what is effectively a worm's eye or microperspective – can produce additional insights. Outside of immersive visualisation, these scale shifts rarely take on an embodied character in screen-based visualisation. The data analyst or interpreter is effectively disembodied. Their body is not to be inscribed in the interface for fear of interrupting the God's eye of objectivity. Communicating an information overview in order to discover broad trends, then, without losing granular detail, is a significant challenge when preparing tactile data graphics as the body is effectively reinscribed into the site of interpretation.

Finding the right scale for a tangible data object so that a user could get an overview using their hand, and then explore with their fingertips key features, commonalities and disjunctures, braille text and even the materiality of the object factored into my design process. I observed that a number of participants would feel the entire object, tracing its outlines and asking questions about the scale and meaning of different pieces, many ambidextrously. Mark, for example, was a participant with a background in accessible technology assessment. His considerable experience testing braille displays gave him a keen sense of whether the 3D-printed braille text and other semiotic features were placed appropriately. I presented him with a number of small dashboard prototypes that were meant to test the side-by-side layout of multiple graphs (designed similarly to what is known in the visualisation world as "small multiples") placed alongside larger context views of specific graphs along with crucial braille descriptive text. Because these dashboard prototypes were, for the most part, modelled on screen-based UI templates, I failed to consider whether the vertical placement of braille along the sides of certain graphs – a technique designed to accommodate 3D-printing space constraints – would be easy to read or would interfere with the user's ability to interpret what was going on in the graph itself.

Although most of the participants could jump between a "zoomed-out" big picture view and a granular focus using their fingertips, I found that this problem was compounded when I would hand singular data objects removed from their context and ask research participants to interpret them. This sort of separation can be an important part of dynamic interaction, but it can also place an undue cognitive burden on the user who is forced to remember the spacing, placement and orientation of the tactile graphic if they wish to place it in relation to other objects in order to "zoom back out." In the context of a tactile dashboard, what might be needed is not multimodal placement, but multidepth representation, in which exploded views of different scales can be stacked on top of each other or nested like a matryoshka doll.

This problem of scale dissonance was additionally compounded when I tested prototypes that were wired with conductive tape to produce seamless capacitive touch buttons that would trigger audio descriptions of the data using familiar text-to-speech voices. In the visual graphical design world, seamlessness and minimalism are often considered virtues. In the space of tactile interaction, they were major design flaws, as participant users were generally unable to determine the boundaries of the inputs, often triggering audio to play inadvertently. While this mixing of sensory modalities – tangible object with specific tactile features embedded with auditory feedback – was an interesting design experiment, the rapid fire of numerical data proved only to confuse participants while they were attempting to interpret the data at differing tactile scales. Almost unequivocally, participants requested prominent buttons for interaction, stating that seamless interfaces, even if they provoked a serendipitous interaction, were counter to the goal of providing information and designing a usable interface. My own bias towards minimalist seamless design caused me to be completely oblivious to the fact that blind users might find this move towards the seamless even more alien than the digital interfaces they already encounter regularly. Despite this, the idea of audio-based feedback proved to be a promising area of future research, as even the participants with considerable braille and tactile experience held great hope for audio tools that would resemble the navigational apps and screen readers they had become accustomed to in the smartphone era.

The Real-World Effects of Translation

3D-printed tactile data visualisation is an emerging research topic, and scant work has been done to determine the efficacy of innovative applications of it. Like the emerging research areas of immersive and multisensory visualisation, data "physicalisation"[9] suffers from a critique that what it makes up for in aesthetics and novelty, it lacks in truthfulness. Regardless, researchers, data designers and infovis practitioners are beginning to produce innovative work. Getting this into the hands of the general public – and the vision-impaired community in particular – remains challenging. Even if we disseminate code, build tutorials and design engaging examples, there is still a risk that the same visual tropes inherent in flat visualisation practices will get ported into this new space, in the process limiting the usability and interaction possibilities that might exist unless they are surfaced and denaturalised early in the design process. My findings suggest that the process of translating 2D, screen-based civic dashboards and data visualisations into 3D tactile models has the capacity to reinscribe visual biases that produce entirely new and unexpected barriers to access. These additional barriers are rooted in naturalised assumptions about the inherent ocularcentric character of data interpretation that many designers are unlikely to be aware of. What happens when epistemic biases like ocularcentrism are not denaturalised? People like the engaged citizens who have taken part in this study are effectively erased from participating in an aspect of the public sphere that is gaining greater importance. In a data-driven society, where data representation helps determine the weight of political arguments, this is a consequence worth rooting out before it has a chance to produce the kind of data inequality that already exists in other marginalised communities.

9 This is a term proposed by Jansen et al. (2015) who describe physical "artifacts whose geometry or material properties encode data."

Conclusions

When we reflexively examine and act on our own visual biases, it becomes easy to see how persistent they are. Attempts to reimagine data visualisation – to make it more accessible and inclusive – frequently replicate inherent visual biases. Tangible data representations, from 3D maps to materialised bar charts, typically resemble the visual charts from which they take inspiration. Even if visual features are withdrawn, these epistemic objects reside on a substrate of ocularcentric design tropes. When visual biases are allowed to infiltrate tangible data design processes, they both reproduce their ocularcentrism and produce additional barriers to data access. As data interpretation increasingly becomes a factor in civic experience, we must consider how normative assumptions (e.g. that dashboards should resemble the user interface of screens) make it possible to exclude entire groups of people from engagement. If data literacy initiatives are to be taken seriously, each time a new interface, data portal, app or hackathon is proposed, it will be of crucial importance to weigh whose agency is being reduced by design choices.

Focusing on specific datasets that have ocularcentric characteristics, I was forced to address the question: are there datasets that do not? Could I have reframed the question to InclusiVis study participants from "what data/datasets do you think might be valuable or appropriate for blind citizens" to "are there data/datasets that are particularly suited to blind citizens and the blind experience?" Sheila Jasanoff, in making a case for a method of surfacing naturalisations and then denaturalising them, advocates studying phenomena as if "through the eyes of visitors from other worlds." Maybe, if my starting point had been to adopt this strategy – to adopt the blind perspective, rather than the perspective of an inclusive designer – I might not have had as many challenges translating between media. I might not have had to denaturalise through an exhaustive process of reflexive self-critique. Today's inclusive design movement envisions wholly new modes of interaction enabled by technologies that encourage multisensory and multiple-user experiences. And, yet, effective tangible visualisation design for visually impaired users still needs to decentre the eye.

This research suggests that it is imperative for technology designers and engineers who are working on tangible objects for blind and visually impaired users – in fact, all designers and engineers who are interested in working against *inequality by design* – to be aware of and address the epistemic biases that are naturalised in their design processes, software tools, etc. Paramount among these biases, in the space of data interaction at least, is a persistent ocularcentric bias that can be traced to the Cartesian revolution. This is a story of inequality of access, but it is also a story of inequality by design. Any time evidence of inequality by design emerges, designers interested in denaturalising their own biases are forced to ask which groups get excluded. There is an important flipside to this. Exclusion means some other group will be included – some other group is privileged in the design process. In the case of accessibility to civic data experience, we must ask who makes up this group. Is it an active process of exclusion that they either create or participate in? I suspect that the City of Toronto's graphic designer who prepared the King Street pilot documents was not trying to actively exclude blind citizens. Given the resources to produce multimodal data experiences, I'm sure they would do their best to accommodate as wide a public as possible. My own tendency is to support this, rather than simply critique them. To this end, I have sought pathways to make my processes and findings accessible by sharing them with the City of Toronto's open data team, as well as the Toronto Public Library's digital innovation network.

Despite claims that it will make inclusive technologies more prevalent, data-driven society continues to present an ominous vision of unequal access. From smart city infrastructure built for those who can afford it, to data mining in communities that lack the literacy to challenge privacy incursion, to inaccessible interfaces that assume blind users will never encounter them, the technologies of this momentous shift in social arrangement are a long way from being equality driven. Naturalised assumptions about appropriate knowledge practices are too often taken for granted, even by those of us who profess to engage in inclusive design. In telling this story, I want to emphasise a specific methodological and design orientation. Revealing exclusion (i.e. which citizens or users are denied civic agency due to intentional and unintentional design choices, as well as which ones are granted greater agency) is only one half of the equation. The other half is about placing inclusion at the foundation of a data design practice by considering the needs and concerns of excluded communities first and foremost.

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