Tangible Stats: An Embodied and Multimodal Platform for Teaching Data and Statistics to Blind and Low Vision Students

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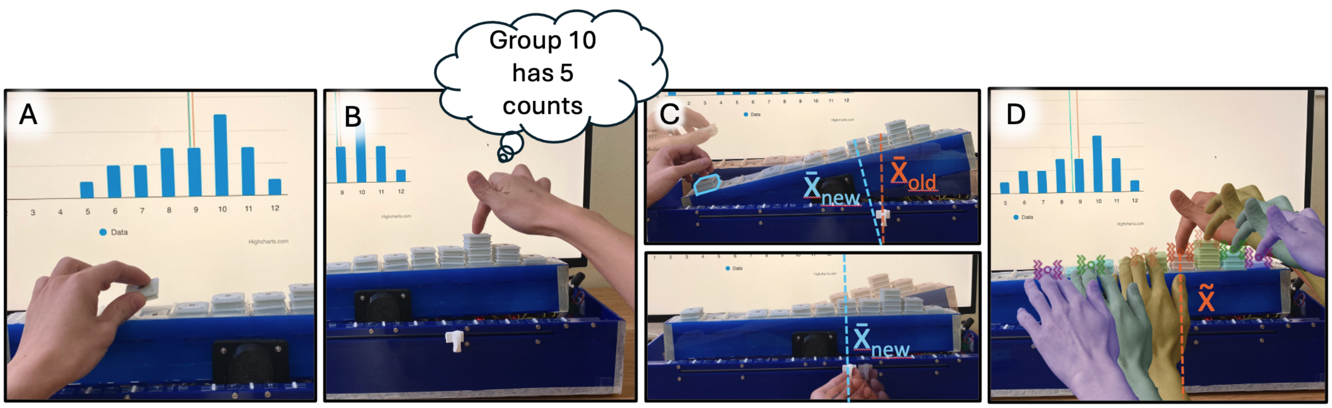

Figure 1: A statistical learning platform featuring a tilting interface where students can explore data physicalizations using tangible tokens. The platform enables students to: A) construct and manipulate data representations by stacking tokens, B) hear data and statistical parameters by pressing on specific regions of the representation, C) engage with the concept of mean by feeling the representation tilting off-balance when an emulated fulcrum deviates from the statistical mean (top), and practice sliding the fulcrum to the mean to restore balance (bottom), and D) explore the concepts of median and percentile by feeling symmetric values mirrored across the median through vibrations.

ABSTRACT

Interactive data learning tools provide explorable ways for students to build intuitions about data, data representations, and statistical parameters. However, these tools rely on visual consumption and are not accessible to blind and low vision (BLV) students. In this work, we investigate opportunities to leverage active exploration, enriched with multimodal feedback and embodied interaction, to foster an understanding of the relationships among individual data values, data representations, and statistical measures. We explore these opportunities in the form of an accessible learning platform that allows students to hear and feel how statistical measures are changing in real time as they construct and manipulate physicalized data representations. We introduced the platform to four teachers of students with visual impairments (TVIs) through a two-hour-long focus group. TVIs embraced the platform's exploratory nature and universality and recommended the consideration of additional auditory and texture-based interactions to enhance engagement.

CCS CONCEPTS

• **Human-centered computing → Visualization systems and tools**; **Interactive systems and tools**; **Accessibility systems and tools**.

CHI EA '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0331-7/24/05
https://doi.org/10.1145/3613905.3650793

KEYWORDS

Data, Statistics, Accessibility, Math, Embodied, Interactive Systems, Education

ACM Reference Format:

Danyang Fan, Gene S-H Kim, Olivia Tomassetti, Shloke N Patel, Sile O'Modhrain, Victor R Lee, and Sean Follmer. 2024. Tangible Stats: An Embodied and Multimodal Platform for Teaching Data and Statistics to Blind and Low Vision Students. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3613905.3650793

1 INTRODUCTION

The rapid growth of computing resources and data during the digital age has marked a paradigm shift in the way we perceive and consume information. As governments, industries, and individuals increasingly rely on data to communicate and make decisions, the ability to understand data and statistics is not only an applied skill but also a means to greater social inclusion [8]. Consequently, there is growing acknowledgment of the need to teach data and statistical concepts in ways that are more cohesive, [13, 67], participatory [71], and contextually-situated [71].

Several interactive data learning platforms have been developed to meet these needs [1, 3]. These platforms 1) provide closely coupled visualizations between the data, data representation, and statistical measures to surface relationships them, and 2) emphasize active exploration and participatory sense-making to reinforce a concept's underlying dynamics [47, 60]. However, blind and low-vision (BLV) students lack accessible non-visual or multimodal tools that benefit from similar types of interactivity [19]. Representation of BLV people in STEM-related fields is disproportionately low [44] and reports have found BLV students lagging in skills to efficiently and accurately interpret graphical information from as early as primary school [6].

To make spatial representations of information more accessible, researchers and practitioners often look towards other modalities, such as touch and sound [37]. Within these modalities, digital information is commonly described aurally, such as with screen readers [40], or rendered tactilely, such as using embossed graphics and multi-line displays [35, 52]. Multimodal interfaces use both tactile and auditory representations to teach early mathematical concepts in more interactive ways [39, 58]. However, the exploration of multimodal systems for teaching statistical concepts is relatively limited.

Additionally, there are opportunities to make use of qualities unique to non-visual modalities to help support a deeper understanding of data. Embodied cognition emphasizes the role of the body [20] and provides one avenue to leverage touch feedback. Prior work has shown how bodily movement [27, 49] and physical manipulation [5, 45, 53, 68, 77] help students learn when supported movements relate to target concepts [10, 64]. We hypothesize that the use of embodied analogies, which draw parallels between bodily experiences and abstract concepts, can enhance students' comprehension of statistics.

In this work, we explore: (RQ1) How might we leverage feedback and interactivity to help BLV students learn and build intuition for early statistical concepts and (RQ2) What additional factors should statistics learning platforms consider when designing for accessibility?

Our investigation into the use of feedback and interactivity for building statistical intuition (RQ1) began with early discussions among a multidisciplinary team of both blind and sighted researchers, educators, and students, who are the co-authors and contributors acknowledged in this paper. These conversations led to the development of a learning platform that uses physical manipulation and supports a series of multimodal and embodied interactions to bridge students' understandings of individual data points, physical representations, and statistical measures.

To gather feedback on the platform and insights on accessible learning practices (RQ2), we ran a focus group with four experienced teachers of students with visual impairments (TVIs) at the 2023 National Federation of the Blind (NFB) National Convention. The teachers embraced the exploratory nature and universality of the platform and recommended the consideration of additional auditory and texture-based interactions to make the experience more engaging.

Using these interactions as building blocks and drawing from learnings from the focus group, the next phase of our research encompasses a more extensive and structured co-design study with middle to high school BLV students and educators. By sharing our early findings with the research community, we hope to foster discussion around general needs in accessible data and statistical education, and surface opportunities to help BLV students learn and internalize statistical concepts in more interactive and engaging ways.

2 RELATED WORK

2.1 Data, Visualization, and Statistical Literacy

Data and visualization literacy encompass the capacity to transform questions into actionable queries and derive insights from data representations [12]. Prior research has examined the fundamental tasks individuals undertake to answer questions using data [79], how people establish connections between data and visual representations [33], and how these representations facilitate spatial reasoning tasks [30, 69]. With society's growing reliance on computing devices and the increasing quantification of information, proficiency in data and visualization literacy has become indispensable [16, 66].

Data and visualization literacy are often viewed as foundational skills in building statistical literacy [22, 63, 75], which Gal defines as the ability to interpret and critically evaluate statistical information [22]. Graphs are important tools for understanding and assessing how statistical measures represent the underlying data [4]. Given the relationship between data, data representations, and statistics, there has been an increasing emphasis on teaching data and statistics in more complementary ways [67].

Several tools have been developed to help users build data, visualization, and statistical literacy by enhancing the ease of data manipulation and interactive exploration [7, 11, 16, 28, 29, 48]. However, limited research has explored how audio and haptic interactivity can aid in the development of statistical literacy among BLV students. This work seeks to understand how we can leverage audio and haptic modalities to help BLV students engage with data, visualization, and statistical concepts in more interactive ways.

2.2 Accessible Data Education

Physical manipulatives, such as tokens and objects, are often first used to introduce data and graphical concepts to BLV students [61]. These manipulatives provide concrete experiences that can help students connect abstract concepts to realistic contexts [17, 26, 59]. As students gain more experience, they begin transitioning to more standardized representations of graphs and charts. These representations, called tactile graphics, consist of raised lines that BLV students can tactilely explore with their fingers. Effective use of tactile graphics often takes time to learn [62].

Due to the lower spatial density of information that can be reasonably understood tactilely compared to visually [52], and considering the time and effort required to produce tactile graphics [55], educators have increasingly turned toward auditory [72] and multimodal [21, 39] ways of teaching data. Interactive audio-tactile systems can improve the educational experience by monitoring student performance [46], offering immediate feedback [46], and fostering engagement through a variety of "fun" interactions [14].

Several studies have investigated the use of tangible user interfaces that support audio-tactile feedback in enhancing learning for BLV students. Pires et al. found that such systems can foster meaningful engagement, support hypothesis testing, encourage collaborative learning, and aid in the development of strategic thinking when used to teach programming [56] and counting [57]. Additionally, various studies have introduced new hardware systems capable of tracking location and orientation to teach STEM topics [42, 43]. However, the use of these systems in teaching data and statistical concepts, particularly through the use of embodied analogies, remains relatively unexplored. Building on insights gained from these multimodal systems, our work integrates embodied interactions to understand the role of these interactions on learning outcomes.

2.3 Embodied Cognition

Embodied cognition emphasizes the role of the body in our cognitive abilities [65]. In educational contexts, researchers have shown that engaging students' bodies can improve learning outcomes [41], such as directly feeling torques to learn angular momentum [38], or more abstractly, enacting data points to understand data representations [15].

Several theories propose when and how embodied cognition can improve learning outcomes. Conceptual salience theory posits that learning is enhanced when manipulation engages students in actions that draw attention to conceptually salient features [51]. Haptic encoding posits that parallel processing [51, 74] made available by haptic cues enhances learning. Embodied schema theory positions cognition as mental simulations of the body's actions in the world [24] and emphasizes learning through bodily experiences that align with concepts [34].

Several other learning paradigms also make use of embodied interactions to improve learning. Enactive cognition proposes that understanding is actively constructed through dynamic interactions between the body and its environment [23]. Constructive visualization encourages the physical construction of data representations and has been shown to encourage critical thinking of basic concepts [9, 18, 76]. With the lack of accessible statistical learning platforms, we see embodied learning approaches as opportunities to help students better internalize and reason about data and statistics.

3 SYSTEM INTRODUCTION

3.1 Learning Goals

We ground our system design in lessons on measures of central tendency and spread, which are core introductory statistical concepts [2]. We expand on the learning objectives defined by The Mathematics Framework for California Public Schools [50] to produce an initial set of learning goals, which are as follows:

- Represent univariate data with histograms.
- Understand the purpose of qualifying shapes of a distribution.
- Understand concepts of modality, symmetry, and skew.
- Understand the purpose of measures of central tendency.
- Calculate and interpret measures of central tendency for a set of data.
- Understand the sensitivity between measures of central tendency to different data points.
- Understand strengths and weaknesses of central tendency and when one might be used compared to another.
- Calculate and interpret the interquartile range and understand how it relates to the median of a distribution.
- Calculate and interpret standard deviation and how it relates to the mean of a distribution.

3.2 System Motivation and Interactions

To translate these learning goals into an interactive system, the authors first collaboratively shared insights on effective practices for inclusive learning. TVIs shared their experiences adapting materials to meet different needs and highlighted the critical role of building intuition through active exploration. They often employ physical objects and tokens to introduce data concepts to BLV students. Students underscored the significance of exploratory play in fostering engagement and intuition. Education researchers highlighted the pivotal role of analogies and metaphors in aiding students' comprehension and retention of complex concepts. Design and engineering researchers integrated established guidelines [31, 78] and drew from their own experiences in crafting and assessing accessible systems.

These perspectives informed several guiding principles motivating our design, which are: (DP1) encourage active exploration and play, (DP2) emphasize intuition-building through embodied and analogous interactions, (DP3) support customization, in addition to our objective of (DP4) providing non-visual access to all information.

Guided by these principles, we designed a data education platform to support data and statistical inquiry from representation construction to analysis. The platform supports the following data-driven interactions:

Construction and Manipulation (Figure 1A): When building data literacy, students need to consider the relationship between the data values and their corresponding data representation [9]. Tokens and physical manipulatives are often used to introduce complex and abstract math concepts across different abilities [25, 32, 61]. Constructive visualization provides a token-based framework that draws on Froebelian theories of play and encourages active exploration [32] (DP1). Following these approaches, our platform supports the use of tokens to construct and manipulate univariate datasets along 12 physical stacks (i.e. 12 bins of a histogram). The stacks are oriented vertically in close proximity, allowing students to enclose their hands over multiple stacks to gauge overall shape. A connected laptop allows educators to configure the value that each stack represents and monitor (visually or through a screen reader) the representation in real time.

Value and Statistical Retrieval (Figure 1B): Immediate feedback has been shown to improve learning [36]. In data contexts, auditory feedback is often used to provide details on demand non-visually [73, 78]. Using the platform, educators can configure the connected laptop to provide real-time auditory feedback on a set of data and statistical values (DP4). Data values include the value of a bin, the number of tokens in a bin, and the percentiles represented by each bin. Statistical values include the mean, median, mode, standard deviation, and interquartile range. The feedback can be configured to be triggered through two ways: 1) automatically whenever the student changes the physical representation, and 2) manually when the student presses on a token stack. For data values, only measures relating to where the change occurred or where the student pressed are spoken. With these options, educators have the flexibility to configure the spoken information and triggers to accommodate and scaffold a variety of learning activities (DP3).

Embodied Mean (Figure 1C): Stone et al. found center-of-balance to be a promising analogy to help students conceptualize the notion of mean in a univariate distribution [70]. We hypothesize that enabling active exploration through this notion draws upon students' prior schemas of balance to gain better intuition for the sensitivity of the mean to individual points and regions (DP2). We therefore situate the representation on a tilting board that is simulated to balance on a sliding fulcrum. As the students build and manipulate different distributions, they feel how the board tilts based on the relative position of the fulcrum to the distribution's center of balance. The further the fulcrum is from the mean, the more the entire physical representation tilts toward the direction of the mean. Students physically move the fulcrum to the balance point of the constructed representation to find the mean.

Embodied Median, Percentiles, and Interquartile Range (Figure 1D): We are exploring the use of the analogy of symmetry across the median to introduce concepts of median, percentiles, and interquartile range (DP2). As students press and hold one stack to retrieve percentile values, stacks representing the *1-p* percentiles vibrate. Students can narrow in on the median by feeling the percentiles converge using an outside-in approach and can follow a similar procedure for finding quartiles. We hypothesize that the exploration of percentiles and their mirrors across distributions of different skews will help build intuition for how these statistical measures are reflected by distribution shape.

3.3 Learning Activities

The interactions were designed to serve as building blocks from which students and educators can design learning activities in subsequent co-design sessions. In the meantime, we provide a sample scenario to convey one way the interactions might be used together in practice.

Customize Dataset: Suppose a student enjoys basketball and follows the Golden State Warriors. To integrate learning with the student's interests, the teacher uses the platform to anchor a data and statistics lesson around NBA All-Star Stephen Curry's 3-point shooting performance. They procure a dataset containing the number of 3-pointers Curry has made in the past fifty games. Using the connected laptop, they configure the x-axis range and interval to accommodate the dataset.

Representation Construction and Feedback: The student begins by plotting a histogram of Curry's performance by stacking the tokens, representing individual games, into the corresponding bin along the platform, denoting the number of 3-pointers made in a game. As they plot individual data points, they can enclose their hands over the resultant shape to perceive how each token contributes to the overall distribution. They track the number of games in which Curry has made six 3-pointers by gauging the height of the corresponding stack, counting the number of tokens in that stack, or pressing on the stack to hear the count, reinforcing the connection between shape, quantity, and context.

Embodied Exploration: The teacher now introduces the concept of statistical mean to the student. The platform provides a way for the student to conceptualize the mean by likening it to the distribution's geometric center of balance. As the student continues updating the distribution with data from additional games, they can sense, through the tilt of the board, the impact that each game has on Curry's mean 3-point performance. Modifying the fulcrum position as data is manipulated offers a tangible indication of the mean's responsiveness to these alterations. Similarly, students can investigate the sensitivity of data manipulations to other statistical measures through real-time haptic or auditory feedback of those measures.

Context-driven Inquiry: Moreover, the teacher can pose contextually situated questions to help students build intuition for these statistical measures, such as: how many 3-pointers does Curry need to make in next game to bring his average up by one, or how much might the mean and median go down if Curry only made two 3-pointers over the next three games. The teacher encourages the student to first form a hypothesis, then evaluate and reflect on that hypothesis by physically updating the distribution and locating the measure of interest. The student can also conduct their own inquiries by directly manipulating the data and perceiving how the measures change.

Scaffolding Feedback: As the student grows more adept with these statistical measures and no longer needs the embodied interactions for internalization, the teacher, via the interface, can deactivate the interaction and enable the interface to directly verbalize the measures whenever a token is updated. This allows students to more quickly explore the effect of many different distributions with respect to the measures.

Data Export: Finally, to bridge data inquiry using our tool with those commonly employed in practice, teachers can export the constructed dataset as a CSV file, which can be explored through a spreadsheet editor or translated into a tactile graphic. This allows students to establish connections between various methods for communicating the same data.

By the end of the activity, the student would have gained experience creating their own distribution based on a topic of interest; sensed how individual points, through their contributions to distribution shape, affect statistical measures of interest; reasoned about these measures in context with the data; and perceived how the distribution they created reflects other common representations of the same dataset. By enabling students to construct and explore their own data *"microworld"*— which Papert views as an exploratory incubator that enables learners to manipulate and perform activities through exploration and manipulation [54]— we hope that they learn the dynamics underlying the data and statics that govern it.

These activities represent one of many that we envision to be supported by the base interactions. Support for auditory feedback offers additional opportunities to guide students through various activities and enhance engagement with immersive sound effects. Token sensing enables the interface to gauge student understanding based on their response to prompts. Localized vibrotactile feedback can direct students' attention to different parts of the graph. These opportunities provide a rich design space for our follow-up co-design studies.

4 PLATFORM DESIGN

The current platform (shown in Figure 2A) consists of three key components: 1) tokens that represent individual data points, 2) a tilting board that the tokens are placed upon to construct data representations, and 3) a Chromium-supported computer that provides audio-visual and learning-related interactions.

Tokens: The tokens (Figure 2A, shaded green) are 2.8 cm x 2.8 cm x 0.725 cm. They are stackable and countable by the tilting board. To enable stacking, the outside of the tokens are 3D-printed with slots and plugs that vertically align (Figure 2B). Embedded neodymium magnets further assist with alignment stability. To be counted by the tilting board, enclosed in tokens are PCBs, each consisting of a resistor and two pogo pin connectors on both the top and bottom faces. When the top pogo pin connector of one token makes contact with the bottom connector of another token, the resistors connect in parallel causing a drop in equivalent resistance. This drop is measured by the tilting board to determine the number of tokens in a stack. Both the housing shape and pogo pin connectors are constructed in a way such that the tokens exhibit 90-degree rotational symmetry along the z-axis. A 0.15 cm lip at the top of each token allows students to count tokens in a stack by running their fingers up each stack.

Board: The tilting board consists of two subsystems. One subsystem consists of twelve base plates that sense the number of tokens along 12 individual stacks (Figure 2A, shaded purple). The other subsystem consists of a sliding fulcrum and tilt mechanism (Figure 2A, shaded red) that causes the entire representation to tilt based on the fulcrum.

Each base plate contains a token-sensing circuit, a coin vibration motor, and a switch (Figure 2B). The token-sensing circuit is a simple voltage divider in which the output voltage drops as additional tokens are added to the base plate. The coin vibration motor is controlled with an n-type mosfet and is used to draw students' attention to particular stacks. The switch allows for stack-specific feedback to be triggered whenever the stack is pressed upon.

The tilt mechanism is controlled by a single servo motor and a 3D-printed emulated fulcrum that slides along a 200 mm flexible membrane linear potentiometer. The physical position of the fulcrum is localized by its contact with the potentiometer. The tilt of the servo, which is coupled to the board, is computed based on the difference between the fulcrum and the token representation's center of mass. Although the location of the servo should follow the simulated fulcrum, we found through early pilot studies that a stationary motor was compelling enough to not warrant the additional complexities associated with creating such a system. The tilting board and fulcrum are lined with Braille lettered from "A" through "L" to aid in distinguishing the twelve bins.

An Arduino Mega is used to read the position of the emulated fulcrum and control the servo motor in the tilt mechanism. For all base plates, the Mega is also used to read the voltage divider output that senses the number of tokens in each stack, read the status of the switch, and control the vibration motors. A custom power distribution board is used to drive the servo motor (9V), vibration motors (3.3V), and circuit logic (5V).

Software: The microcontroller communicates sensed information to a Chromium-supported browser via web serial. The current browser interface supports a series of interactions. These include text fields that define the x-axis of the representation and toggles that select when and what types of auditory feedback are delivered. The constructed representation is also visualized through HighCharts in real time, which supports screen reader access.

5 PRELIMINARY FINDINGS

We conducted a focus group with four TVIs to introduce our prototype platform, gather their feedback, and surface key considerations for our forthcoming co-design study. This focus group received approval from Stanford's Institutional Review Board and NFB's research advisory council. Participants were selected through an NFB mailing list and screened based on their experience teaching BLV students and their self-reported frequency of developing or experimenting with new educational tools and activities. Participants (P1-P4) reported 5-20 years of experience teaching STEM to BLV students and often experimented with new educational tools and activities. Among the TVIs, three are blind, and one is sighted. The focus group was structured around semi-structured discussion questions divided into three sections: 1) reflections on current practices in teaching data concepts, 2) reflections on using educational tools, and 3) exploratory feedback on the platform. Participants were compensated $160 for their participation in the 2-hour-long focus group.

The entire focus group was audio-recorded, transcribed, and inductively coded by two members of the research team. Codes were categorized and synthesized into themes according to the four guiding principles, which are (DP1) encourage active exploration

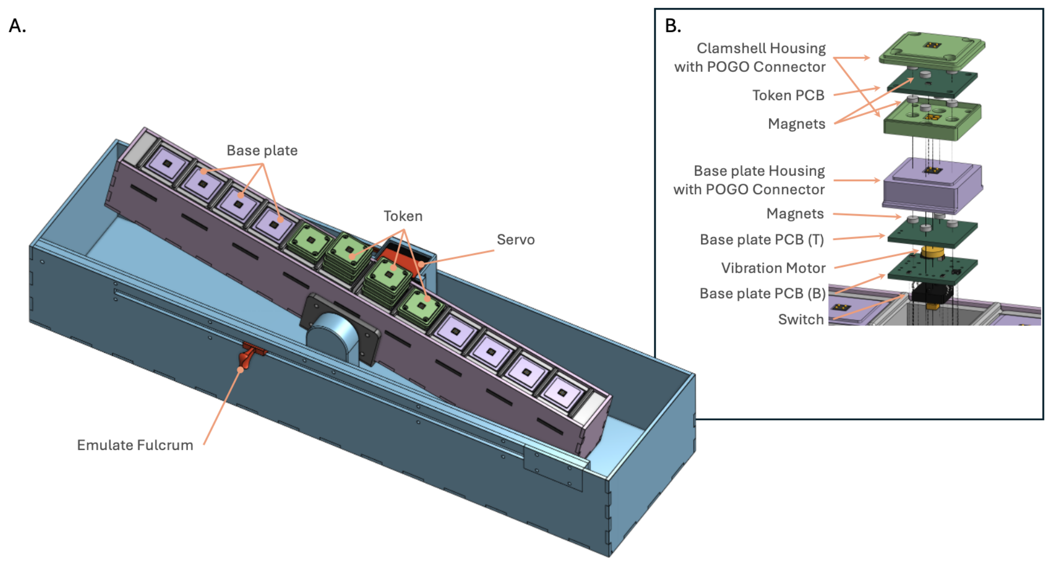

Figure 2: CAD Model of the Statistical Learning Platform

and play, (DP2) emphasize intuition-building through embodied and analogous interactions, (DP3) support customization, in addition to our objective of (DP4) providing non-visual access to all information. This classification was undertaken to scrutinize our underlying assumptions and offer deeper insights into these guiding principles, as well as to assess the extent to which the platform interactions aligned with or diverged from them.

5.1 Encourage Active Exploration and Play

Educational materials are often not motivated in contexts that are engaging for BLV students. P3 described how *"a lot of times for our blind kids, unfortunately, [is that] they feel isolated because they don't necessarily engage in all those same activities or feel a part of those activities. So if you can find a way to get them interested and involved and engage, that's a possible way to make them feel invested"*. Additionally, many students that they work with often do not get opportunities to actively explore their surroundings in a way that is conducive to learning. P1 shared that *"what happens a lot in the formative years of blind children's development, is that they are in a bubble. They're not experiencing any of the errors, so they can't detect them, so they can't correct them"*. There is a need for learning experiences that better engage learners in their interests and allow them to make and learn from their mistakes.

When interacting with our platform, participants found the use of physical tokens to be fun (P1), playful (P2), and encouraging of active exploration (P1, P4). P1 described how they *"like that [the platform] is exploratory. So [students] could just explore it and see how things are changing [to] figure these things out"*. Participants also recommended we explore other uses of sounds and token textures to make the experience more engaging (P1, P2, P3). Identifying the contexts that can ignite BLV students' interest in data and statistics, and investigating how platform features like sound and texture can engage students more deeply in these contexts are important next steps in our upcoming co-design sessions.

5.2 Emphasize Intuition Building

Because commonly used tools and practices for building intuition— such as diagrams, videos, and drawing boards— are not adapted to the needs of BLV students, participants shared how these students often find themselves resorting to memorization rather than achieving a conceptual understanding of STEM topics (P1, P2, P4). P4 described how *"a lot of kids can memorize step-by-step procedures, but they don't really understand what they're doing"*. To help BLV students understand and build intuition around data concepts, TVIs shared their experiences starting with more concrete representations that are easier to grasp to form bridges to more abstract representations (P1, P4). As an example, P1 shared how *"we would put pins in on [a] little rubberized graph board and then we could do our trend line across that...and then we yank our paper out and it makes a really satisfying tear. And now we have our line. And so we could kind of go from very concrete to more abstract because that graph that we were using already had the lines on it... So I'm not telling the child, this is what works [or] this is why it works. They're showing how it works by doing all the things that lead up to why we do it this way"*.

Furthermore, it's common for gaps in conceptual understanding to go unnoticed. P1 observed that *"a lot of teachers get really focused in on those scores. They want that right answer so they forget the process"*. Participants stressed the significance of being able to ask probing questions to assess understanding (P2, P4). P4 articulated that *"the best feedback is based on how [students] are answering the questions. Based on how they answer, you can evaluate what they're thinking and what their thoughts are and their understanding of the concepts that you're trying to teach"*.

When interacting with the platform, participants found that the embodied interactions hold promise for aiding students in cultivating an intuition for statistics through the lens of more familiar concepts (P1, P2, P4). P4 described how the haptic and audio feedback provides *"a great way to show how numbers can affect other numbers related to it"*. However, P1 cautioned that assessing these interactions with BLV children who are new to these concepts is essential to measure their effectiveness.

Taken together, participants' comments highlight several important areas and opportunities for future work. First, exploring effective scaffolding methods between concrete examples and abstract data and statistical concepts offers a promising approach to designing learning activities. Second, investigating strategies to systematically foster deeper conversations between students and teachers about the learning concepts through the platform and co-designed activities might assist teachers in monitoring students and ensuring their comprehension of taught materials. Similarly, maintaining opportunities for students to openly discuss and reflect on their reasoning will be essential for evaluating the effectiveness of our platform and activities.

5.3 Support Customization

Participants articulated a few reasons why being able to customize and adapt materials is important when working with BLV students in school settings (P1, P2, P3). One reason is the wide range of students' prior experiences and abilities, which requires TVIs to evaluate and develop educational materials tailored to their learning needs. P2 described how *"some children are going to need more support than others in order to be able to [get] access at the same level...even as a curriculum designer, I tell people I could give you the best curriculum possible, but that doesn't mean it's going to be the best curriculum ever for your specific student"*. Another is that TVIs often need to base their work on classroom lessons. As P1 shared, *"APH used to have a data collection and analysis kit... I took all the stuff out of it and used it and didn't use the curriculum that they came with it because I used the Gen ed materials to teach"*. Finally, systems that are too rigid do not leverage the expertise of experienced teachers. Where *"cookie cutter curriculum is only for an inexperienced teacher"* (P2), platforms that give level of flexibility allow TVIs to *"do things that you didn't even think of"* (P3).

When interacting with the platform, participants appreciated the ability to customize activities both internally (P1, P2) (such as through using the audio toggles) and externally (P1, P3) (such as in conjunction with tactile graphics or computing software). As P3 shared, *"I feel like there's more potential there for things like producing a tactile graph after interacting with your data...And then you take your computer home and analyze it at home and learn more about what you've collected or figured out separate from the activity"*.

Given the frequent need to adapt materials, all participants suggested developing a flexible activity guide rather than a rigid curriculum to accompany the platform. P1 further elaborated how *"what you want is an activity guide and a simple set of activities to get them started"*, such as *"[a guide], an extension [activity], and then give them a real-life application...for each of the types of skills you're trying to teach"*. These findings underscore the importance of viewing the platform not merely as an isolated system, but as a tool among many that teachers can integrate into their existing practices and tailor to the needs of their students. The co-design effort should extend beyond identifying learning activities that can be supported by the platform and aim to formalize processes and highlight interactions that empower teachers to modify or develop their own activities.

5.4 Provide Non-Visual Access to All Information

While our efforts primarily focused on supporting non-visual modes of access to the data, data representations, interactions, and statistical values, participants emphasized the need for sighted peers to engage collaboratively as well (P1, P3, P4). This need not only stems from blind students often feeling isolated (as quoted by P3 in Section 5.1), but also because, as described by P4, *"you're not going to be working individually as a scientist. And so I think when possible, having things that you can work on with three students together is better than having every individual student have something. When you can work as a group, I think you're teaching more life skills"*.

Several participants (P1, P3) appreciated the educational value that sighted students might also gain from interacting with the platform. P3 articulated how *"one thing I could say right now that I like about it is any student could use it. That's already a benefit"*. In P2's experience designing educational tools, providing ways that *"a sighted student can use it along with their blind peers helps avoid that 'I'm different' awkwardness"*. These results highlight the importance of social inclusion in learning practices and the need to co-design interactions that not only facilitate student-teacher interactions but peer interactions as well.

6 CONCLUSION AND FUTURE WORK

This work outlines a preliminary set of auditory and tactile interactions that were designed based on guiding principles co-developed by a multidisciplinary team of students, educators, and designers to support statistical learning (RQ1). By introducing these interactions to a focus group of experienced TVIs, we gained insight into important contexts and factors that learning platforms should consider and enriched our understanding of the guiding principals and interactions supporting them (RQ2).

Several of the guiding principles were reinforced by the observations shared by the TVIs in our focus group. These include our prioritization of active exploration (DP1) and intuition-building (DP2), especially as there is a reported lack of engaging opportunities for BLV students to gain intuition through active exploration and build understanding through accessible scaffolds. Positive feedback on the platform's playful nature, emphasis on exploration, and use of familiar analogies highlight its potential to effectively address these needs.

Insights from TVIs have also reshaped our perspective on the other principles. The importance of adapting materials to diverse student and curricular needs shifted our approach to customizability (DP3), from designing a standalone system and curriculum to conceptualizing the platform as one among many tools that TVIs can creatively integrate to meet the needs and interests of students. Additionally, TVIs' receptiveness to universal design has helped us recognize the importance of offering compelling visual in addition to non-visual access (DP4). Doing so fosters collaboration and shared experiences between BLV students and sighted peers and enables the platform to better support learning across the diverse visual abilities and experiences of BLV students.

Taken together, the focus group emphasized the importance of designing educational experiences that are engaging and not reductive, flexible and not prescriptive, universal and not alienating, as well as supportive of the valuable interpersonal interactions between TVIs, BLV students, and their peers.

The next stage of the project is to co-design learning activities that provide effective scaffolding between the concrete and abstract. To situate learning in the specific contexts of both TVIs and BLV students, we are planning a series of multi-week co-design sessions that focus on defining learning objectives, brainstorming motivating contexts, discussing engagement, and designing activities to support statistical learning through these multimodal and embodied paradigms. Following the co-design sessions, we hope to run user evaluations to more concretely understand how these paradigms contribute to the way students reason about data and statistics.

ACKNOWLEDGMENTS

This work was supported by NSF Award 2016789 and NSF GRFP grant No. DGE-1656518. We thank Pat Leader and Lucia Hasty for their valuable insights that informed the initial focus of our work. We thank our focus group participants for sharing their insights and experiences. We thank Savannah Cofer and Elizabeth Vazquez for their feedback on this work.

REFERENCES

[1] [n. d.]. Common Online Data Analysis Platform. https://codap.concord.org/. (Last accessed: Jan 24, 2024).
[2] [n. d.]. Grade 6 Statistics & Probability. https://www.thecorestandards.org/Math/Content/6/SP/. (Last accessed: Jan 24, 2024).
[3] [n. d.]. Tuva. https://tuvalabs.com/. (Last accessed: Jan 24, 2024).
[4] Francis J Anscombe. 1973. Graphs in statistical analysis. *The american statistician* 27, 1 (1973), 17–21.
[5] Saskia Bakker, Alissa N Antle, and Elise Van Den Hoven. 2012. Embodied metaphors in tangible interaction design. *Personal and Ubiquitous Computing* 16 (2012), 433–449.
[6] Carole R Beal and L Penny Rosenblum. 2018. Evaluation of the effectiveness of a tablet computer application (App) in helping students with visual impairments solve mathematics problems. *Journal of visual impairment & blindness* 112, 1 (2018), 5–19.
[7] Benjamin B Bederson and James D Hollan. 1994. Pad++ a zooming graphical interface for exploring alternate interface physics. In *Proceedings of the 7th annual ACM symposium on User interface software and technology*. 17–26.
[8] Rahul Bhargava, Erica Deahl, Emmanuel Letouzé, Amanda Noonan, David Sangokoya, and Natalie Shoup. 2015. Beyond data literacy: Reinventing community engagement and empowerment in the age of data. (2015).
[9] Fearn Bishop, Johannes Zagermann, Ulrike Pfeil, Gemma Sanderson, Harald Reiterer, and Uta Hinrichs. 2019. Construct-a-vis: Exploring the free-form visualization processes of children. *IEEE transactions on visualization and computer graphics* 26, 1 (2019), 451–460.
[10] John B Black, Ayelet Segal, Jonathan Vitale, and Cameron L Fadjo. 2012. Embodied cognition and learning environment design. *Theoretical foundations of learning environments* 2 (2012), 198–223.
[11] Michael Bostock and Jeffrey Heer. 2009. Protovis: A graphical toolkit for visualization. *IEEE transactions on visualization and computer graphics* 15, 6 (2009), 1121–1128.
[12] Jeremy Boy, Ronald A Rensink, Enrico Bertini, and Jean-Daniel Fekete. 2014. A principled way of assessing visualization literacy. *IEEE transactions on visualization and computer graphics* 20, 12 (2014), 1963–1972.
[13] Philipp Burckhardt, Rebecca Nugent, and Christopher R Genovese. 2021. Teaching statistical concepts and modern data analysis with a computing-integrated learning environment. *Journal of Statistics and Data Science Education* 29, sup1 (2021), S61–S73.
[14] Luis Cavazos Quero, Jorge Iranzo Bartolomé, and Jundong Cho. 2021. Accessible visual artworks for blind and visually impaired people: comparing a multimodal approach with tactile graphics. *Electronics* 10, 3 (2021), 297.
[15] Xin Chen, Jessica Zeitz Self, Leanna House, John Wenskovitch, Maoyuan Sun, Nathan Wycoff, Jane Robertson Evia, and Chris North. 2017. Be the data: Embodied visual analytics. *IEEE Transactions on Learning Technologies* 11, 1 (2017), 81–95.
[16] Fanny Chevalier, Nathalie Henry Riche, Basak Alper, Catherine Plaisant, Jeremy Boy, and Niklas Elmqvist. 2018. Observations and reflections on visualization literacy in elementary school. *IEEE computer graphics and applications* 38, 3 (2018), 21–29.
[17] Douglas H Clements. 2000. 'Concrete'manipulatives, concrete ideas. *Contemporary issues in early childhood* 1, 1 (2000), 45–60.
[18] Danyang Fan, Alexa Fay Siu, Sile O'Modhrain, and Sean Follmer. 2020. Constructive visualization to inform the design and exploration of tactile data representations. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. 1–4.
[19] Danyang Fan, Alexa Fay Siu, Hrishikesh Rao, Gene Sung-Ho Kim, Xavier Vazquez, Lucy Greco, Sile O'Modhrain, and Sean Follmer. 2023. The accessibility of data visualizations on the web for screen reader users: Practices and experiences during covid-19. *ACM Transactions on Accessible Computing* 16, 1 (2023), 1–29.
[20] Lucia Foglia and Robert A Wilson. 2013. Embodied cognition. *Wiley Interdisciplinary Reviews: Cognitive Science* 4, 3 (2013), 319–325.
[21] Giovanni Fusco and Valerie S Morash. 2015. The tactile graphics helper: providing audio clarification for tactile graphics using machine vision. In *Proceedings of the 17th international ACM SIGACCESS conference on computers & accessibility*. 97–106.
[22] Iddo Gal. 2002. Adults' statistical literacy: Meanings, components, responsibilities. *International statistical review* 70, 1 (2002), 1–25.
[23] Shaun Gallagher. 2018. Educating the right stuff: Lessons in enactivist learning. *Educational Theory* 68, 6 (2018), 625–641.
[24] Arthur M Glenberg, Jessica K Witt, and Janet Metcalfe. 2013. From the revolution to embodiment: 25 years of cognitive psychology. *Perspectives on psychological science* 8, 5 (2013), 573–585.
[25] Nahid Golafshani. 2013. Teachers' beliefs and teaching mathematics with manipulatives. *Canadian Journal of Education/Revue canadienne de l'éducation* 36, 3 (2013), 137–159.
[26] Robert L Goldstone and Ji Y Son. 2005. The transfer of scientific principles using concrete and idealized simulations. *The Journal of the learning sciences* 14, 1 (2005), 69–110.
[27] Justin C Hayes and David JM Kraemer. 2017. Grounded understanding of abstract concepts: The case of STEM learning. *Cognitive research: principles and implications* 2, 1 (2017), 1–15.
[28] Jeffrey Heer, Maneesh Agrawala, and Wesley Willett. 2008. Generalized selection via interactive query relaxation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 959–968.
[29] Jeffrey Heer, Stuart K Card, and James A Landay. 2005. Prefuse: a toolkit for interactive information visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 421–430.
[30] Mary Hegarty, Mike Stieff, and Bonnie Dixon. 2015. Reasoning with diagrams: Towards a broad ontology of spatial thinking strategies. *Space in mind: Concepts for spatial learning and education* (2015), 75–98.
[31] Juan Pablo Hourcade. 2015. Child-computer interaction. *Self, Iowa City, Iowa* (2015).
[32] Samuel Huron, Sheelagh Carpendale, Alice Thudt, Anthony Tang, and Michael Mauerer. 2014. Constructive visualization. In *Proceedings of the 2014 conference on Designing interactive systems*. 433–442.
[33] Samuel Huron, Yvonne Jansen, and Sheelagh Carpendale. 2014. Constructing visual representations: Investigating the use of tangible tokens. *IEEE transactions on visualization and computer graphics* 20, 12 (2014), 2102–2111.
[34] Mina C Johnson-Glenberg, David A Birchfield, Lisa Tolentino, and Tatyana Koziupa. 2014. Collaborative embodied learning in mixed reality motion-capture environments: Two science studies. *Journal of educational psychology* 106, 1 (2014), 86.
[35] Lynette A Jones and Nadine B Sarter. 2008. Tactile displays: Guidance for their design and application. *Human factors* 50, 1 (2008), 90–111.
[36] Paul Kehrer, Kim Kelly, and Neil Heffernan. 2013. Does Immediate Feedback While Doing Homework Improve Learning?. *Grantee Submission* (2013).
[37] NW Kim, SC Joyner, A Riegelhuth, and Y Kim. 2021. Accessible visualization: Design space, opportunities, and challenges. In *Computer Graphics Forum*, Vol. 40. Wiley Online Library, 173–188.
[38] Carly Kontra, Daniel J Lyons, Susan M Fischer, and Sian L Beilock. 2015. Physical experience enhances science learning. *Psychological science* 26, 6 (2015), 737–749.
[39] Steven Landau and Karen Gourgey. 2001. Development of a talking tactile tablet. *Information Technology and Disabilities* 7, 2 (2001).

[40] Jonathan Lazar, Aaron Allen, Jason Kleinman, and Chris Malarkey. 2007. What frustrates screen reader users on the web: A study of 100 blind users. *International Journal of human-computer interaction* 22, 3 (2007), 247–269.

[41] Manuela Macedonia. 2019. Embodied learning: Why at school the mind needs the body. *Frontiers in psychology* 10 (2019), 2098.

[42] Muhanad S Manshad, Enrico Pontelli, and Shakir J Manshad. 2011. MICOO (multimodal interactive cubes for object orientation) a tangible user interface for the blind and visually impaired. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility*. 261–262.

[43] Muhanad S Manshad, Enrico Pontelli, and Shakir J Manshad. 2013. Exploring tangible collaborative distance learning environments for the blind and visually impaired. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*. 55–60.

[44] Michele McDonnall, J Marty Geisen, and Brenda Cavenaugh. 2009. School climate, support and mathematics achievement for students with visual impairments. In *Poster presented at the annual Institute of Education Sciences Research Conference, Washington DC*, Vol. 8.

[45] Edward F Melcer, Victoria Hollis, and Katherine Isbister. 2017. Tangibles vs. mouse in educational programming games: Influences on enjoyment and self-beliefs. In *Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems*. 1901–1908.

[46] Giuseppe Melfi, Karin Müller, Thorsten Schwarz, Gerhard Jaworek, and Rainer Stiefelhagen. 2020. Understanding what you feel: A mobile audio-tactile system for graphics used at schools with students with visual impairment. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[47] Gemma F Mojica, Christina N Azmy, and Hollylynne S Lee. 2019. Exploring data with CODAP. *The Mathematics Teacher* 112, 6 (2019), 473–476.

[48] Scott Murray. 2017. *Interactive data visualization for the web: an introduction to designing with D3*. " O'Reilly Media, Inc.".

[49] Mitchell J Nathan and Candace Walkington. 2017. Grounded and embodied mathematical cognition: Promoting mathematical insight and proof using action and language. *Cognitive research: principles and implications* 2 (2017), 1–20.

[50] California. State Board of Education. 2013. *Mathematics framework for California public schools: Kindergarten through grade twelve*.

[51] Georgios Olympiou and Zacharias C Zacharia. 2012. Blending physical and virtual manipulatives: An effort to improve students' conceptual understanding through science laboratory experimentation. *Science Education* 96, 1 (2012), 21–47.

[52] Sile O'Modhrain, Nicholas A Giudice, John A Gardner, and Gordon E Legge. 2015. Designing media for visually-impaired users of refreshable touch displays: Possibilities and pitfalls. *IEEE transactions on haptics* 8, 3 (2015), 248–257.

[53] Edward A Pan. 2013. *The use of physical and virtual manipulatives in an undergraduate mechanical engineering (dynamics) course*. University of Virginia.

[54] Seymour Papert. 1980. Microworlds: Incubators for knowledge. *Mindstorms-Children, Computers and Powerful Ideas* (1980), 120–134.

[55] Jinseok Park and Sunggye Hong. 2023. Creating tactile graphics in school settings: A survey of training experience, competence, challenges, and future support needs. *British Journal of Visual Impairment* 41, 4 (2023), 864–875.

[56] Ana Cristina Pires, Lúcia Verónica Abreu, Filipa Rocha, Hugo Simão, João Guerreiro, Hugo Nicolau, and Tiago Guerreiro. 2023. TACTOPI: Exploring Play with an Inclusive Multisensory Environment for Children with Mixed-Visual Abilities. In *Proceedings of the 22nd Annual ACM Interaction Design and Children Conference*. 411–422.

[57] Ana Cristina Pires, Ewelina Bakala, Fernando González-Perilli, Gustavo Sansone, Bruno Fleischer, Sebastián Marichal, and Tiago Guerreiro. 2022. Learning maths with a tangible user interface: Lessons learned through participatory design with children with visual impairments and their educators. *International Journal of Child-Computer Interaction* 32 (2022), 100382.

[58] Hrishikesh Rao and Sile O'Modhrain. 2022. Designing Interactive Audio-Tactile Charts Grounded In Current Practices of Tactile Graphics Production. In *Designing Interactive Systems Conference*. 35–37.

[59] Martina A Rau and Tiffany Herder. 2021. Under which conditions are physical versus virtual representations effective? Contrasting conceptual and embodied mechanisms of learning. *Journal of educational psychology* 113, 8 (2021), 1565.

[60] Lindsay Reiten and Susanne Strachota. 2016. Promoting statistical literacy through tuva. *The Mathematics Teacher* 110, 3 (2016), 228–231.

[61] L Penny Rosenblum, Li Cheng, and Carole R Beal. 2018. Teachers of students with visual impairments share experiences and advice for supporting students in understanding graphics. *Journal of visual impairment & blindness* 112, 5 (2018), 475–487.

[62] L Penny Rosenblum, John Ristvey, and Laura Hospitál. 2019. Supporting elementary school students with visual impairments in science classes. *Journal of Visual Impairment & Blindness* 113, 1 (2019), 81–88.

[63] Richard L Scheaffer, Ann E Watkins, and James M Landwehr. 1998. What every high-school graduate should know about statistics. *Reflections on statistics: Learning, teaching, and assessment in grades K-12* (1998), 3–31.

[64] Ayelet Segal, Barbara Tversky, and John Black. 2014. Conceptually congruent actions can promote thought. *Journal of Applied Research in Memory and Cognition* 3, 3 (2014), 124–130.

[65] Lawrence Shapiro and Shannon Spaulding. 2021. Embodied Cognition. In *The Stanford Encyclopedia of Philosophy* (Winter 2021 ed.), Edward N. Zalta (Ed.). Metaphysics Research Lab, Stanford University.

[66] Sashi Sharma. 2017. Definitions and models of statistical literacy: a literature review. *Open Review of Educational Research* 4, 1 (2017), 118–133.

[67] Milo Shields. 2005. Information literacy, statistical literacy, data literacy. *IASSIST quarterly* 28, 2-3 (2005), 6–6.

[68] Alexander Skulmowski, Simon Pradel, Tom Kühnert, Guido Brunnett, and Günter Daniel Rey. 2016. Embodied learning using a tangible user interface: The effects of haptic perception and selective pointing on a spatial learning task. *Computers & Education* 92 (2016), 64–75.

[69] Mike Stieff, Mary Hegarty, and Bonnie Dixon. 2010. Alternative strategies for spatial reasoning with diagrams. In *International Conference on Theory and Application of Diagrams*. Springer, 115–127.

[70] Brian W Stone, Donovan Kay, and Anthony Reynolds. 2019. Teaching visually impaired college students in introductory statistics. *Journal of Statistics Education* 27, 3 (2019), 225–237.

[71] Svetlana Tishkovskaya and Gillian A Lancaster. 2012. Statistical education in the 21st century: A review of challenges, teaching innovations and strategies for reform. *Journal of Statistics Education* 20, 2 (2012).

[72] Karen Vines, Chris Hughes, Laura Alexander, Carol Calvert, Chetz Colwell, Hilary Holmes, Claire Kotecki, Kaela Parks, and Victoria Pearson. 2019. Sonification of numerical data for education. *Open Learning: The Journal of Open, Distance and e-Learning* 34, 1 (2019), 19–39.

[73] Steven Wall and Stephen Brewster. 2006. Feeling what you hear: tactile feedback for navigation of audio graphs. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*. 1123–1132.

[74] Tzu-Ling Wang and Yi-Kuan Tseng. 2018. The comparative effectiveness of physical, virtual, and virtual-physical manipulatives on third-grade students' science achievement and conceptual understanding of evaporation and condensation. *International Journal of Science and Mathematics Education* 16 (2018), 203–219.

[75] Jane M Watson. 2013. *Statistical literacy at school: Growth and goals*. Routledge.

[76] Wesley Willett and Samuel Huron. 2016. A constructive classroom exercise for teaching infovis. In *Pedagogy of Data Visualization Workshop at IEEE VIS 2016*.

[77] Nesra Yannier, Kenneth R Koedinger, and Scott E Hudson. 2015. Learning from mixed-reality games: Is shaking a tablet as effective as physical observation?. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1045–1054.

[78] Haixia Zhao, Catherine Plaisant, Ben Shneiderman, and Jonathan Lazar. 2008. Data sonification for users with visual impairment: a case study with georeferenced data. *ACM Transactions on Computer-Human Interaction (TOCHI)* 15, 1 (2008), 1–28.

[79] Michelle X Zhou and Steven K Feiner. 1998. Visual task characterization for automated visual discourse synthesis. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 392–399.