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ABSTRACT

Humans encounter a vast array of sensory stimuli in their everyday lives. However, many visualization techniques primarily utilize visual feedback, which may disregard certain intricate details. Relying on a single visual channel may overlook complex layouts. However, how haptic force feedback can be used to assist visualization remained under-explored. In this work, we initially conducted a literature review to identify potential problems in the visualization of large datasets and engaged in discussions with domain experts to explore the potential of haptic force feedback and visual collision representation. Subsequently, we designed an innovative haptic force feedback knob, which included 3 primary modules and 29 elements. To evaluate the clarity and usefulness of this design space, we conducted a workshop and devised "recommended solutions" for the identified visualization problems. Finally, we implemented a prototype of the haptic force feedback knob and assessed its performance on scatterplot and parallel coordinate plot tasks using large datasets. The results indicated that the knob prototype could reduce visual strain and enhance the efficiency of visualization tasks.

1. Introduction

Data utilized various visual channels aimed at presenting data in a way that enhanced human cognitive abilities. Visual channels played a crucial role in conveying feedback information, and variations in colors (Bu et al., 2020), shapes (Lu et al., 2020), and other visual cues helped people quickly and efficiently access valid information during visual search. For example, in scatter plots, overplotting was a common problem that arose when dealing with large numbers of data points. To address this challenge, researchers developed scaling techniques (Yuan et al., 2009) and sunspot maps (Trautner et al., 2020) to reduce visual clutter, although none of these methods could be examined for individual objects. As the number of attributes and items grew, parallel coordinate plots faced increased line overlap, leading to visual clutter (Mayorga & Gleicher, 2013; Perrot et al., 2015). Moreover, inferring attribute relationships from the visual patterns became more challenging when the axes were not adjacent.

Integrating perceptual channels could enhance user comprehension and reduce the visual burden, leading to a more comprehensive understanding of the data. Studying appropriate information channels for data comprehension was a popular research topic in the field of visual analytics. Previous studies explored the haptics (Brooks et al., 1990), auditory (Guerreiro et al., 2023), olfactory (Patnaik et al., 2018), and gustatory (Weidner et al., 2023) senses impact on data perception and understanding. For example, auditory

perception affected people's interpretation of visual information, as background music enhanced their emotional understanding of the images they saw. Similarly, the sense of smell affected people's attention to visual information, and the combination of taste and vision aided in the retention of visual information and improved memory. While senses such as hearing, smell and taste had potential advantages for data visualization, they also had limitations. For example, auditory perception was susceptible to environmental noise and had a limited range. Olfactory perception was limited in the amount of information it could convey, and its perceptual accuracy, while gustatory perception focused primarily on visualizing food and beverages and was challenging to accurately represent in other domains. Haptic perception, however, was effective in perceiving physical form and could help people understand information through the familiar sensations of touch and pressure. For example, Ipakchian et al. (2019) combined touch with morphologically consistent visual feedback, and their experimental results showed that this approach effectively enhanced the perceivability of touch and the realism of the experience. In the field of multisensory data visualization, Kruijff et al. (2016) outlined the current state of research on multisensory data visualization and proposed unidimensional multisensory data visualization and multidimensional multisensory data visualization. Breitschaft et al. (2022) proposed the Haptic Fidelity Framework for haptic feedback in virtual reality, but there was no systematic research on the extent to which haptic feedback could reduce visual burden and enhance visual

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perception. As a result, our understanding of the potential benefits of haptic feedback in reducing visual burden and enhancing visual perception remains limited.

Although recent work (Section 2) demonstrated the application of haptic force feedback in different scenarios, we were particularly interested in how haptic force feedback could assist in the visualization of large datasets, its role in enhancing visualization, and whether it could reduce the visual workload for individuals. To address these research questions, we conducted further literature research to identify eight types of visualizations and the potential problems they encountered in large datasets (Section 3). Then, we conducted several discussions with seven domain experts from hardware design, human-computer interaction, and other fields to understand the necessity of applying haptic force feedback to visualize and to determine which visualizations should be designed with haptic force feedback. Then, we collected a variety of force feedback knobs and analyzed their force feedback patterns. Based on these patterns, we proposed a design space based on haptic force feedback knobs, which was divided into three modules and 29 elements (Section 4). Last, we evaluated the design space with two studies. In study 1, to assess the clarity and usefulness of the design space, we conducted a workshop with 19 participants, who were asked to use the design space to propose a "recommended solution" to a problem that might arise in a large dataset (Section 5). We provided a series of animations as supporting materials that explain the meaning of each element in the design space, case examples, and can be found on our website.[1] The experimental results showed that haptic force feedback can effectively relieve users' visual burden and allow them to complete visualization tasks more efficiently. Meanwhile, the design space was found to be clear and useful, providing an effective framework for addressing visualization problems with large datasets, and the framework proved to be practical. In Study 2, to assess the effectiveness of the haptic force feedback knob in visualization applications, we designed and developed a haptic force feedback knob. We invited 20 participants to complete the task of scatter plot and parallel coordinate plot with a large dataset and to provide a subjective evaluation of using the haptic force feedback knob (Section 6). Our preprint and supplements are available at https://osf.io/5mrjn/. In summary, we made the following contributions to this work:

- **Design Space Exploration and Construction:** We proposed a design space based on haptic force feedback knobs, which was distilled from discussions with experts from various fields and an in-depth study of existing literature.
- **Workshop-Centric Validation and Utilization:** To validate the clarity and usefulness of the design space, we conducted a workshop with 19 participants and presented "recommended solutions" for problems in large datasets.
- **Knob Device Prototyping and Experimentation:** We developed a prototype of a haptic force feedback knob and assessed its effectiveness in both scatterplot and parallel coordinate plot tasks, as well as user feedback on the knob.

2. Related work

In this section, we revisited previous research on haptic force feedback technology, particularly focusing on its applications in visualization and knob controls.

2.1. Application of haptic force feedback

2.1.1. Human-computer interaction

Haptic force feedback was widely used in human-computer interaction environments to replicate human perception of the environment (Johansson & Linde, 1999). With haptic force feedback devices, users could experience a heightened sense of motion, leading to a more immersive experience. The first haptic force feedback device was developed in the 1960s, independent of the video game industry, and implemented in nuclear research laboratories, allowing scientists to understand the forces in potential industrial processes (Johansson & Linde, 1999). Early applications also originated from aviation, where manufacturers incorporated servo-mechanism systems to address adverse flight conditions, such as delivering haptic force feedback to pilots when an aircraft's pitch became too high, signaling an imminent stall (Ouhyoung et al., 1995). Haptic force feedback exploration was driven by various motivations, including enhancing accessibility for visually impaired individuals, developing more intuitive ways for information interaction, and refining interfaces for portable and small-scale devices. To address the challenge of navigating confined smartwatch displays, Gong et al. devised" Jetto," a hardware prototype that augmented the user experience by introducing lateral haptic feedback in response to visual collisions or overcrowding of virtual objects on the screen edge (Gong et al., 2018).

2.2. Haptic force feedback in visualization

In Wall and Brewster's research (2003), haptic attributes were subdivided into friction, stiffness, and texture. Integrating visual and tactile interactions held the promise of improving input accuracy, providing physical adaptability, or creating more natural and direct ways of interaction. This section focused on reviewing the applications of haptic force feedback in the field of visualization.

2.2.1. Scientific visualization

Haptic displays, as a complement to visual displays, enhanced the perception and understanding of world models composed of force fields and opaque objects (Brodlie et al., 2012). As early as the 1990s, researchers began applying haptic force feedback to molecular docking visualization (Brooks et al., 1990; Taylor, 2000). In the GROPE project, Brooks proposed a molecular docking case where users could observe molecular structures, interact with molecules, and feel the influence of various forces from individual

molecules (Brooks et al., 1990). Experimental results showed that in 6D rigid body docking operations, the use of haptic force feedback improved operation speed compared to relying solely on visual information. Similarly, Lundin et al. explored blood flow within the heart and used haptic feedback to determine the path of the blood. They concluded that "haptic feedback was considered beneficial, and the combination of haptic and visual feedback was superior to relying solely on visual feedback" (Lundin et al., 2007). Hogan et al. designed a 3D interactive visualization system with force feedback, providing users with haptic feedback, and demonstrating visual cases of liver models (Hogan & Hornecker, 2016).

2.2.2. Information visualization

Mapping information onto various sensory modalities potentially expanded the bandwidth for user comprehension of complex and varied data. Loftin et al. (2003) demonstrated that presenting data across multiple senses enhances user understanding. For example, Roberts and their team translated a month-long stock market dataset into a line graph, augmenting it with auditory elements. They represented different stocks with unique timbres, higher stock prices with higher pitches, and the dimensions of days and weeks through time, thus facilitating a more profound comprehension of the line graph (Roberts, 2004). Additionally, Feng et al. enhanced the coordination between visual and haptic to provide support for motor synchronization skills in stroke rehabilitation (Feng & Stockman, 2019). Visualization transformed data into visually digestible formats for swift spatial understanding, while haptic technology provided an accessible medium for the visually impaired to analyze and explore data (Paneels & Roberts, 2010; Swindells et al., 2006). Engel et al. analyzed 69 haptic feedback charts for the blind and established design guidelines for haptic charts (Engel & Weber, 2017). Fritz et al., developed a haptic visualization system that renders digital information into points, lines, and surfaces to represent vector fields, aiding visually impaired users in understanding datasets (Fritz & Barner, 1999). Additionally, Wall et al. employed the PHANToM haptic device to display graphical information, scaling data values by friction instead of traditional shape or size to make graphic data more accessible to visually impaired users (Wall and Brewster, 2003).

2.3. Haptic force feedback in knob

2.3.1. Application of knobs

Knobs played a crucial role in human-computer interaction. Compared to other forms of interaction, tangible knob interactions significantly reduce the demand for visual attention, enabling faster and more accurate operations. Haptic force feedback demonstrated significant utility in aiding users to complete specific tasks (Abbasimoshaei et al., 2023; Dennerlein et al., 2000; Kühner et al., 2011) and in task control (Bianchi et al., 2010). For example, Kim et al. (2010) designed a universal remote control that replaced complex

button layout with a force feedback knob. Similarly, MacLean et al. (Aranovskiy et al., 2016) integrated haptic force feedback with marked objects, achieving a seamless blend of discrete and continuous manual control. Moreover, Kirkegaard et al. designed a force feedback knob for digital musical instruments, where designers could map sensors to haptic effect parameters, achieving real-time dynamic modification of force feedback (Kirkegaard et al., 2020). Numerous studies illustrated that knobs effectively managed static and dynamic parameters (Michelitsch et al., 2004; van Oosterhout & Hoggan, 2020). With the rise of touchscreen technology, researchers explored combining haptic force feedback knobs with touchscreens, leveraging screen flexibility and knob interaction characteristics. For instance, the knob designed for Sony cameras (Yang & Newman, 2012) and the Apple Watch (Apple Inc, 2023) effectively alleviated interaction limitations due to smaller screen sizes (Visschedijk et al., 2022). Furthermore, researchers focused on the role of knob design and force feedback in user interaction. Anke et al. (Van Oosterhout et al., 2019) evaluated six widely used knob shapes and twelve different haptic stimuli to investigate how shape changes and haptic force feedback could improve usability, user experience, and performance (van Oosterhout & Hoggan, 2020). These studies indicated that altering the shape and haptic feedback of knobs could effectively change perceived functionality (van Oosterhout et al., 2018).

2.3.2. Design of knobs

In the realm of knob design, classic human-computer literature, such as (Woodson & Conover, 1964), provided fundamental principles for knob design, including size, shape, texture, and gripping methods. For instance, as indicated by (Sharp, 1962), serrated knobs could apply more torque compared to smooth-surfaced knobs. Furthermore, precision and operational speed were crucial considerations in knob design, aiding users in accomplishing tasks more accurately. For deeper insights, readers were recommended to consult Baumann's book (2001). Insights regarding detection thresholds for friction, inertia, and torque variations in knob control (Kühner et al., 2011; Peebles & Norris, 2003; Tan et al., 2015) guided the design space of haptic force feedback assistance in this study's visualization. We utilized perception-related parameters of knob control: relative inertia, damping amplitude, and damping spacing (Swindells et al., 2009) to design haptic force feedback patterns. For detailed information, please refer to Section 3.2, discussing the potential of dynamically providing haptic feedback through knobs to offer users more visual information and alleviate visual load.

Inspired by prior research on the detection thresholds of friction, inertia, and torque changes in knob controls (Kühner et al., 2011; Peebles & Norris, 2003; Tan et al., 2015), we delved into the design realm of haptic force feedback-assisted visualization. We focused on the perceptual parameters associated with knob control, such as relative inertia, damping amplitude, and damping spacing. In Section 4.2.4, we elaborated on how these parameters were

employed in designing haptic force feedback patterns and investigated the potential of dynamic haptic force feedback knobs to aid in visualization, thereby reducing visual strain.

3. Need-finding study

We conducted a comprehensive literature review to identify the challenges of visualizing large datasets and their current solutions. Furthermore, we collaborated with experts in human-computer interaction and visualization, carrying out a study that included in-depth interviews with seven experts to explore the potential application of haptic feedback in the visualization of large datasets.

3.1. Survey

We conducted a comprehensive literature review to answer the question: What problems does visualization encounter in the context of large datasets?

3.1.1. Research material

The survey of eight common visualizations identified potential problems associated with large datasets, helping better construct a design space for haptic feedback-assisted visualization. Visualizing large datasets presented perceptual and computational challenges: discerning what should be displayed was difficult, and once identified, efficiently presenting it also proved to be a significant hurdle.

Bar charts presented various challenges when displaying datasets with a large range (Cleveland & McGill, 1986; Hlawatsch et al., 2013). Disproportionate categories led to difficulties in comparing extreme values (Karduni et al., 2020). The separation between non-adjacent bars made comparing adjacent bars more accurate than comparing distant ones (Chen et al., 2021; Xiong et al., 2021), especially for short bars (Talbot et al., 2014). Accuracy decreased as the distance between bars increased (Cleveland & McGill, 1984; Lu et al., 2021). Bar charts also struggled to differentiate highly similar bars and indicate identical values (Lu et al., 2021). Researchers developed approaches such as cutoff bars, scale breaks, and logarithmic scaling to address these issues (Hlawatsch et al., 2013).

Line charts were considered optimal choice for visualizing time series data, representing changes over time through connected data points (Wang et al., 2017). However, when dealing with large datasets, excessive overlapping of lines could lead to visual clutter and misalignment, causing misinterpretations (Javed et al., 2010; Moritz & Fisher, 1808). Comparing lines with large, similar gaps was difficult (Moritz et al., 2023), creating false confidence in interpreting values between measurements (Cho et al., 2014; Xiong et al., 2019).

Pie charts encoded percentage values through angles, areas, and arc lengths (Cleveland & McGill, 1984). However, discerning small differences in values, such as distinguishing similar angles, was often difficult (Lu et al., 2021). Representing small areas was impractical, as their angles

tended to be significantly overestimated (Kosara, 2019). Despite the addition of labels for clarity, matching and comparing labels with corresponding slices in pie charts with many slices posed considerable challenges (Skau & Kosara, 2016).

Scatter plots were used for visualizing bivariate data (Trautner et al., 2020), representing relationships between two variables through discrete points. However, they encountered over-plotting issues with large, dense datasets (Tao et al., 2020; Trautner et al., 2020). Strategies to mitigate over-plotting included sampling (Chen et al., 2021), abstraction (Yang et al., 2020), modifying marker size (Chen et al., 2019) and opacity (Quadri & Rosen, 2020), and employing hybrid methods (Matejka et al., 2015; Yuan et al., 2020). Visual occlusion in scatter plots could lead to inaccurate display of point distribution (Shao et al., 2017) and difficulties in perceiving precise data values (Wall et al., 2019).

Heatmaps were a technique for visualizing continuous data, using color encoding to represent two-dimensional density distributions (Kraus et al., 2020). They effectively depicted variations among variables, allowing users to grasp overall trends. However, traditional heatmaps faced scaling challenges as X and Y axis dimensions increased (Dutta et al., 2016; Kraus et al., 2020). Pham et al. proposed ContiMap, using heuristic algorithms to group and sort data, reducing computational resource needs (Pham et al., 2020). Researchers identified inaccuracies in two-dimensional encoding (Palomo et al., 2015; Wu et al., 2015), and Kraus et al. introduced a third dimension, height, showing that three-dimensional heatmaps were more effective than traditional ones (Kraus et al., 2020). Additionally, heatmaps could lead to cognitive overload and high error rates when comparing highlighted values due to perceptual distortions.

Parallel coordinates, introduced by Inselberg (Inselberg, 1985), were a common method for visualizing high-dimensional geometry and analyzing multivariate data. Line crossings and over-plotting in parallel coordinate plots could create visual clutter, affecting the perception of visible patterns (Johansson & Johansson, 2009; Pomerenke et al., 2019). Solutions included using sampling and filtering techniques (Blumenschein et al., 2020; Bok et al., 2020), axis reordering and dimension reduction (Blumenschein et al., 2020; Johansson & Johansson, 2009), density-based and cluster-based rendering (Peng et al., 2004), edge bundling (Cui et al., 2023), and line modification (Nguyen & Rosen, 2017; Pomerenke et al., 2019). Researchers found that negative correlations were easily detected when lines crossed patterns between axes, but visualizing positive correlations was challenging (Zhou & Weiskopf, 2017).

Node-link diagrams suffered from dense regions of nodes and cluttering of edges (Zinsmaier et al., 2012) in large datasets, which severely affected readability due to visual confusion (Okoe et al., 2018). Researchers often encoded information using a combination of colors (Pan et al., 2020), opacity, stroke thickness (Saket et al., 2014), and stroke patterns to mitigate these issues. However, revealing complex interconnections remained a significant challenge (Reimann et al., 2023).

Word clouds served as a visual method for summarizing textual content (Lee et al., 2010; Viégas et al., 2009). Typically, word size corresponded to frequency, reflecting significance. While design could be varied through visual encodings, layouts, and interactive elements, challenges arose with large text volumes (Heimerl et al., 2015). Disproportionate word sizing could lead to imbalance, obscuring accurate perception of frequency (Wang et al., 2017, 2020). Word clouds often presented inexplicable local relationships between adjacent words, and small, vertically oriented words could hinder comprehension (Wang et al., 2019).

3.1.2. Results

In response to the contents identified above, we summarized four common challenges that arose in large datasets. It's important to note that these were not separate challenges, in visualizations of extensive datasets, multiple challenges might coexist.

Outlier detection in big data: Density variability and the struggle with quick detection. Identifying outliers posed significant challenges when dealing with large datasets (Nguyen & Rosen, 2017). The abundance of data points, highly overlapping categories, widely distributed outliers, and the uneven density of data points caused issues in the readability and scalability of existing methods (Li et al., 2022). In many applications, outliers might hold particular importance, making it crucial to tag them and link them with the actual semantics of corresponding entities (Mumtaz et al., 2019; Tao et al., 2020). However, in large datasets, overplotting and visual clutter made it even more difficult to quickly detect these anomalies.

Pattern identification in big data: Hindered by visual overload and overplotting. For large datasets, visual clutter and overplotting obscured the fundamental distribution of data and significantly hindered users' ability to discern patterns in visualizations (Cui et al., 2023; Xue et al., 2023). Many patterns, while present, were challenging to intuitively identify and comprehend through visual perception alone (Cui et al., 2019; Raidou et al., 2019). For instance, in parallel coordinate plots, the crisscrossing and overplotting of lines could conceal information within the data, complicating the identification of positively correlated patterns (Zhou & Weiskopf, 2017).

Cognitive strain in large dataset visualization: Comparing visual elements. A key challenge in visualization was the comparison of two or more visual elements. (Lu et al., 2021; Xiong et al., 2021). People faced the challenge of distinguishing minor variations in graphical elements, like slight differences in bar heights or pie chart angles (Cleveland & McGill, 1984; Talbot et al., 2014). Particularly in large datasets, engaging in visual comparison demanded significant cognitive effort and constituted a difficult and powerfully capacity-limited cognitive operation (Bäuerle et al., 2022; Kraus et al., 2020; Patil et al., 2022).

Displaying details in complex data: The challenge of visual "blind spots". In the visualization of complex data, there often existed a "blind spot" where displaying all data details was difficult (Lu et al., 2020; Rapp et al., 2019).

While many methods provided an overview pattern, the importance of detailed information in data analysis could not be overlooked (Nguyen et al., 2021). For instance, in parallel coordinate plots, when multiple lines overlapped or were close, distinguishing specific details of these line intersections became challenging (Zhou et al., 2014). Accurately identifying connected segments in the same polyline was crucial for users to track data paths and answer specific questions (Rapp et al., 2020; Yang et al., 2020).

3.2. Expert interviews

To clarify two issues, we conducted interviews with domain experts: (1) Why is haptic feedback necessary to assist visualization in large datasets? (2) In which scenarios can haptic feedback knobs be applied to enhance visualization?

3.2.1. Procedure

We invited seven domain experts via social media, including a hardware engineer (E1, with 4 years experience), a human-computer interaction engineer (E2, with 2 years experience), four data analysts (E3-E5, with 5 years experience in different visualization), and two professors (E6, E7, with 12 and 1 year of visualization research experience, respectively). We held three sessions with them: one interview and two brainstorming sessions, spaced 15 days apart.

In the initial interview, we briefed participants on essential concepts like haptic feedback and dynamic knobs, securing consent for recordings. We explored questions such as "Q1: What is the role of haptic feedback?", "Q2: Can haptic feedback aid in visualization?", "Q3: Have you faced issues during visual analysis?", "Q4: What challenges arise with large data visualization and solutions?", and "Q5: How can haptic feedback knobs enhance visualization?". During the interview, if we found the experts' answers unclear or wanted to delve deeper, we asked follow-up questions. This session lasted one hour and a half, followed by two one-hour brainstorming sessions focusing on Q4 and Q5.

3.2.2. Analysis and results

After interviewing, we transcribed the discussions and tasked two authors with independently analyzing the content, focusing on haptic feedback's necessity and applications in visualization. After reconciling differences in several meetings, we derived the following conclusions:

(1) Why is haptic feedback necessary to assist visualization in large datasets?

Regarding our first question, most participants (E1, E3-E7) confirmed its positive impact by enhancing engagement, reducing visual strain, and improving efficiency in tasks such as identifying discrete data points. However, E2 cautioned that adding haptic feedback might overload users cognitively in data-rich visual environments. E3 and E6 emphasized the need for careful haptic design to avoid

distraction, with E2 specifically noting that haptic feedback should aid, not detract from, visual perception.

(2) In which scenarios can haptic feedback knobs be applied to enhance visualization?

Regarding our second question, we found that domain experts with different backgrounds emphasized different aspects. E3, E4, and E6, with a focus on visualization, saw their potential use in adjusting visualization layouts, such as magnifying elements in a word cloud by rotating the knob. E3 also suggested their application in scaling force-directed nodes or adjusting color distributions based on chromatic criteria. E1, E2, and E6 proposed designing knobs with different damping levels to mirror data density sensitivities, enhancing interaction. E6 highlighted their effectiveness in anomaly analysis within scatter plots, where knob rotation could be adjusted to change the covered area size based on damping. E6 and E7 warned against "over-perception", where excessive haptic feedback might detract from the visualization's expressiveness. However, the specifics of effective haptic feedback design were uncertain, prompting expectations for a custom solution in visualization.

4. Designing haptic force feedback

In this section, we presented a design space which aimed at exploring the integration of haptic feedback knobs with visual collision.

4.1. Methods

Initially, we proposed four high-level principles to guide the design space. Subsequently, we gathered a variety of haptic force feedback knobs to serve as inspiration for our design. Ultimately, based on these principles, we finalized our design space.

4.1.1. Design principles

Synthesizing our discussions with experts in Section 3 and reviewing the literature on visualization design space and haptic force feedback knob design (Lan et al., 2021; Lee et al., 2022), we identified four design principles:

P1: Reducing Cognitive Load in Data Visualization. Force feedback should be used to improve the efficiency of visualization by reducing cognitive load and helping users quickly understand complex data (Rapp et al., 2019). Consideration should be given to users' cognitive limitations and perceptual characteristics in force feedback design, in order to reduce unnecessary cognitive burden and fatigue, while also improving their cognitive efficiency.

P2: Designing Intuitive Force Feedback for Data. Force feedback should convey information clearly so that users can easily comprehend data patterns without feeling confused or fatigued (Rapp et al., 2019; Yen et al., 2020). To achieve this, force feedback patterns should be designed in tandem with visual objectives to support data comprehension and analysis, rather than diverting users' attention.

P3: Adaptable Haptic Feedback for Diverse Data Analyses. Force feedback should be able to meet the diverse requirements of various analytical tasks and data features. In the course of design, it was imperative to consider the varying demands of analytical tasks to offer customized and adaptable feedback mechanisms (Liao et al., 2022). Similarly, the feedback pattern of the design must match with the data features to enable users to comprehend and analyze data.

P4: Transparent Force Feedback for Effective Monitoring. The designed force feedback mechanism should possess transparency, real-time capability, and feedback functionality so that users can promptly monitor the process and outcomes of data analysis. Moreover, it should be visible and interpretable for users to comprehend its underlying principles and mechanisms (Yen et al., 2020), and make essential adjustments and optimizations.

4.1.2. Design inspirations

To design haptic force feedback, we searched for common actuation patterns of haptic feedback knobs. To better stimulate our imagination for applying these knobs in visual displays, we gathered examples from multiple platforms, including YouTube[2] and Github.[3] Two authors then independently assessed the cases to ensure the feedback patterns effectively communicated perception (P2). If both authors agreed a case's pattern significantly aided visualization, it was added to our library; otherwise, it was excluded. The two lead authors, one specializing in visualization and the other in HCI, initially analyzed and coded the actuation patterns independently. We then compared codes and revised or removed them until reaching full consensus. In total, we identified nine distinct actuation patterns that can serve as effective force feedback patterns for enhancing visualization through haptic feedback.

4.1.3. Design process

Guided by design principles, the two designer co-authors balanced visualization, user interaction, and haptic force feedback patterns to achieve an effective integration. After three online discussions to refine the design space, we selected five visualization types based on previous works (Paneels & Roberts, 2010; Zhang et al., 2022). These types covered the eight visualizations researched in Section 3.2, namely bar charts, line charts, pie charts, scatter plots, heatmaps, parallel coordinate plots, node-link diagrams, and word clouds. Visualization interaction was crucial in combining haptic feedback patterns with visualization. Different interaction methods could energize the force feedback patterns, aiding users in completing tasks. To consider a broader range of possibilities, our design incorporated four interaction techniques (Zhang et al., 2022): selection and exploration, filtering and navigation, correlation and preservation, and encoding and reconfiguration. However, not every interaction technique has a positive effect on every visual chart.

A co-author specializing in force feedback research tested the haptic feedback patterns. After numerous experiments and assessing the feasibility of combining them with visualizations, we retained seven out of the nine actuation patterns. For example, the resistance of a haptic feedback knob changes with rotation, either increasing or decreasing, we merged this into a single pattern named "Mapping", signifying the resistance changes with the knob's rotation. We abandoned a constant resistance fixed displacement pattern, transforming the fixed displacement into "Restricted" under "Finiteness", allowing each haptic feedback actuation pattern to select its displacement to satisfy P1, offering users more flexible patterns to complete challenges. In the field of visualization, we evaluated the haptic feedback patterns by interviewing three experts and focusing on "force feedback overload". Each conversation lasted 40 minutes. Based on the collected opinions, we decided against combining all charts, force feedback patterns, and interaction techniques. For instance, we found it challenging to incorporate translational interactions with haptic feedback in pie charts. Conversely, rotational interactions in pie charts could enhance user efficiency and align with our P3.

Based on these insights, we further refined our design and focused on user interaction and visualization. In the user interaction module, we concentrated not only on visualization interaction techniques but also on the forms of interaction, i.e., how users implement exploration (more details in Section 4.2.3). When exploring visual charts, it's inevitable to involve visualizing haptic feedback content. Therefore, we discussed issues related to the projection of visualization. This inspiration can be traced back to previous work (Lee et al., 2022), which indicated the necessity of a comprehensive discussion of the design space. However, this design space was not prescriptive but served as a guideline to assist designers in considering various options and aspects of force feedback-aided visualization.

4.2. Design space

We followed the principles of design space analysis (MacLean et al., 1991; McKerlie & MacLean, 1994) and engaged in iterative discussions. In this section, we presented a design space for haptic force feedback knob-assisted visualization and explored the potential fusion of haptic and visual perception.

4.2.1. Design space overview
Design space followed the general process of visualization design space, which is shown in Figure 1, including visualization, user interaction and force feedback patterns. We roughly categorized them into four color-coded categories: initial visualization state (**pink**), interactive techniques (**green**), user interaction (**orange**), and force feedback patterns (**purple**). These design dimensions were not mutually exclusive but rather provided researchers with novel perspectives to explore the feedback-assisted potential of visualization techniques from multiple aspects. We described each

part of the design space and their design contents in order. We contemplated delineating the design space from the perspective of a data analyst using the haptic force feedback knob to analyze visualizations. When conducting visual analysis, the analyst needed to consider appropriate and effective interactive techniques and force feedback patterns.

4.2.2. Visualization
The initial visualization state and interaction techniques were integral components that constitute *visualization*.

Initial Visualization State referred to the state of the visualization prior to the application of haptic force feedback. This state was the first step in an analyst's attempt to apply force feedback through a knob-assisted visualization. Thus, the initial form of visualization was a visual representation of whatever data was provided. In the initial visualization state, we considered the visualization of complex datasets, which were the following five categories (Zhang et al., 2022): **Network Visualization**, **Text Visualization**, **Temporal Visualization**, **Geographic Visualization**, **Chart Visualization**.

Interactive Techniques played a vital role in visualization. They not only improved the user's understanding of the data and guided the user to discover patterns and regularities within the data, but also assisted the user in quickly locating and analyzing the data as needed. Interaction technologies were the process by which the user dialogued with the data, allowing the user to better utilize the force feedback knobs for exploration. To address these challenges, we categorized the interaction techniques into the following four categories (Zhang et al., 2022), which were: **Selection & Exploration**, **Filtering & Navigation**, **Connection & Saving**, **Encoding & Reconfiguration**.
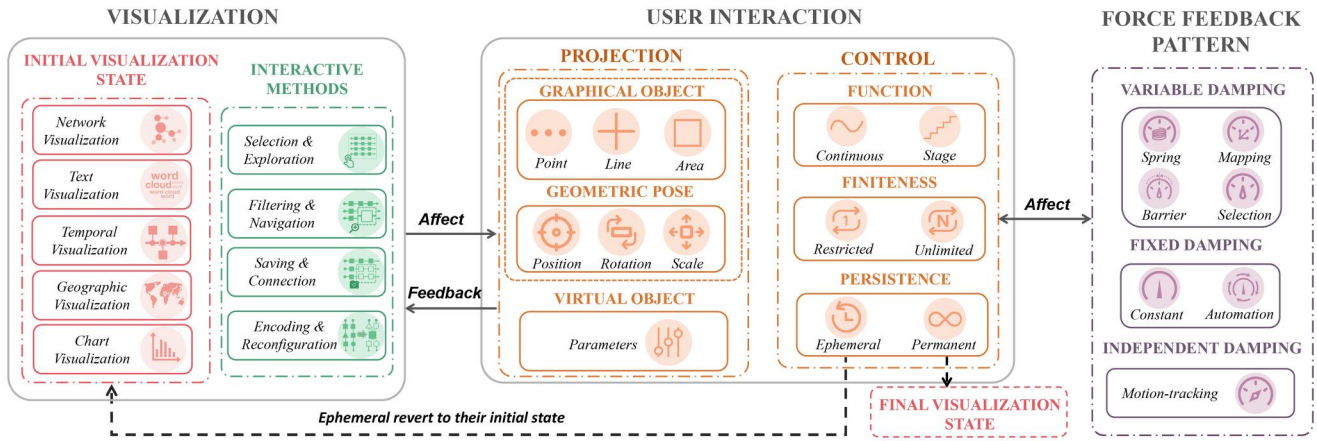
4.2.3. User interaction
The user interaction component focused on the interaction between users and the force feedback knob, aiming to assist in visual exploration. It's important to note that this interaction is distinct from the choice of interaction technologies, mainly focusing on the *projection* in which the user uses the haptic force feedback knob and the *control* of the force feedback knob. This approach helped to classify and understand different types of interactivities and their use in enhancing user experience and effective communication.

The choice of projections directly **fed back** into the visualization effects. Different visualizations also affected the choice of projection. For instance, pie charts were not suitable for area-based interactions but more appropriate for line-based ones. On the other hand, control and force feedback patterns mutually **affected** each other. Different force feedback patterns combined with various control produced different effects. For example, combining stage and selection made it easier for users to perceive the differences in gear selection.

4.2.3.1. Projection. referred to the process of projecting a haptic feedback knob to a visualization representation,

Figure 1. A design space for force feedback knob-assisted visualization. Visualization is necessary for the user to use the force feedback knob, user interaction is the interaction between the user and the force feedback knob, and the force feedback pattern is the form of force feedback during the exploration of the knob.

which involved two design dimensions. In the first dimension, the knob could be projected to different graphical object such as point, line, or area, with the knob's operations corresponding to geometric poses like *position, rotation, and scale*. This projection allowed users to intuitively manipulate the geometric pose of graphical objects using the knob. For example, projecting the knob to a point and controlling the point's position or scaling through rotation. The second dimension referred to the association of the knob with specific parameters in visualization, which might not have a direct physical representation. Therefore, the virtual object was independent of the geometric pose. For example, the rotation of the knob could be used to control the quantity of certain elements, such as adjusting the number of bars in a bar chart. In this manner, the operation of the knob aided users in better understanding and interpreting the dynamic changes in data distribution. This dimension offered a non-intuitive pattern of interaction, assisting users in conducting more in-depth analysis and comprehension of the data.

Graphical object. The Graphical Object was the physical projection entity of the haptic feedback knob in visualization representations. Choosing the right object was crucial for effective data representation, as different visualizations required various objects to display data's diversity and complexity (Few, 2004). For example, in pie charts, projecting the knob as a line could enhance user interaction efficiency and effectiveness, improving both data visualization and user experience. We listed three different possibilities.

Point was an interactive exploration of the visualization by projecting the haptic force feedback knob to a point where the horizontal and vertical lines intersect. Point was more flexible and detailed, allowing for more exploration of details and meeting the needs of P3.

Line represented objects that were projected for exploration in the horizontal or vertical directions. This was an interactive relation in a single direction, which facilitated the exploration of single-dimensional ambiguous views.

Area was a haptic force feedback knob that was bound to a custom-sized box for interactive exploration of a visualization. The *Area* could frame the graph within a certain range, facilitating quicker targeting of anomalies. For example, when the overlapping of graphical markers in a parallel coordinate plot significantly impaired the user's capacity to discern data patterns. Users explored along the axes using custom *Area* and highlighted the lines to effectively identify clusters in large and noisy datasets.

Geometric pose referred to the physical properties of the *graphical objects* and related to the **Position**, **Rotation** and **Scale** of the force feedback knobs in the visualization. For instance, when searching for outliers in a scatter plot, users can first select *points*, then manipulate their *positions*, and finally employ *scaling* to identify outliers within the target range. Generally, multiple *geometric poses* need to be used sequentially in order to accomplish the challenge. It was important to note that the scale here refers to the size of *graphical objects* and not the visualization.

Virtual object. *Parameters* signified the conjunction of haptic force feedback knob with a specific parameter within visualization. By rotating the haptic force feedback knob, users could fine-tune the parameter values, enabling a localized exploration of the data. For instance, associating the knob with the transparency parameter in a heatmap effectively mitigated the challenges of discerning excessively saturated (Pham et al., 2020).

4.2.3.2. Control. In order to fully describe the design of the haptic force feedback knob, we took a high-level generalization of the characteristics of the knob and called it *control*, which consists of three design dimensions.

Function referred to the way haptic force feedback was transmitted to the user when the knob was turned, and we distinguished between two rotations. Generally, *continuous rotation* was preferred when turning the knob quickly to get an overview of the data, and conversely, *stage rotation* was preferred when exploring the details.

Continuous Rotation had smooth haptic force feedback changes throughout the force feedback knob exploration. Figuratively speaking, continuous rotation was like riding an elevator.

Stage Rotation meant that the haptic force feedback received throughout the knob exploration process showed a staged force feedback, and this rotation experience could be analogous to the gear rotation of an electric fan. Figuratively speaking, stage rotation was like taking the stairs.

Finiteness referred to whether there was a limit to the displacement of the force feedback knob's rotation during exploration, and we set two possible states.

Restricted Rotation signified that a knob had a constrained rotational range, capable of rotating between 0 and 360 degrees. When the knob was rotated beyond its set maximum angle, it restarted interacting from the initial position. It was especially effective when exploring visualization charts that resemble circles, such as pie charts. Setting the knob's rotation range to 360 degrees helped users gain clearer insight into the variation and distribution of data in pie charts.

Unlimited Rotation meant that the knob can be rotated without limit until a given task was reached or an optimal end state was found. *Unlimited rotation* was more appropriate when dealing with complex temporal visualizations, as it allowed the user more flexibility in exploring the data without angular restrictions.

Persistence referred to the need to retain the visual effect produced by the interaction after the visual interaction with the knob, and there were two possibilities for this.

Ephemeral Interaction indicated that visualization returned to its initial state immediately after the knob stops rotating. This allowed the user to quickly navigate through the dataset while performing a pattern searching task (Zhou et al., 2014). Importantly, this was instantaneous and did not allow users to stop in the perceived optimal state.

Permanent Interaction meant that each turn of the knob updates the visualization state in real time, continuing until the next change. Users can reverse the rotation of the knob in order to precisely explore and find the pattern that was best suited to accomplish the task.

4.2.4. Force feedback pattern

The force feedback patterns designed in this study were inspired by previous research (Gellert et al., 2022; van Oosterhout et al., 2018; Van Oosterhout et al., 2019) on haptic force feedback knobs. We used key perceptual parameters of knobs, including inertia, damping amplitude, and damping pitch. As described in Section 4.1.3, we categorized the braking patterns of force feedback into three main categories, including seven different force feedback patterns, fulfilling P2. Force feedback was designed based on a combination of force angle and force intensity, where the force angle was related to the relative angle of the motor (Van Oosterhout et al., 2019). To better illustrate each haptic feedback pattern's knob and force effects, we added a figure following pattern description. The colors of the small boxes in these figures corresponded to the four challenges

mentioned in Section 3.1.2. Checkboxes indicated that the particular haptic feedback mode was especially suitable for addressing these visualization challenges.

4.2.4.1. Variable damping. It meant that when users rotated a knob for interaction, there were differences between the force angle and the relative angle of the knob based on the dataset, which created varying degrees of damping. This damping variation served to guide the user in exploring the visualization.

Spring Pattern design was based on the difference between the relative position and the force angle, which varied according to the distance between the start point of the effect and the relative position of the motor. In this pattern, by rotating the knob, users could intuitively see the changes after interacting with the visualization, providing a quick preview experience, and effectively returning to a default or center position. This pattern helped in discovering potential anomalies and patterns.
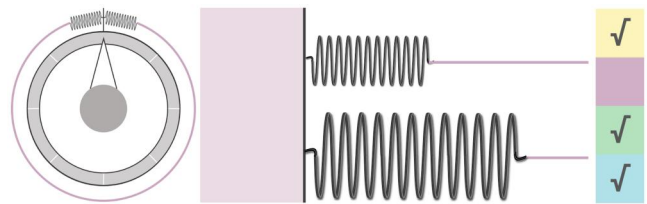
Example: When exploring node-link graphs, if users had set filters to display connections with weights below or above a certain value, the dispersed, tiny, or excessively drawn nodes would gradually become prominent as the knob was rotated.

Mapping Pattern referred to the force feedback knob acting as a variable damping knob, where the damping force adjusted automatically with changes in the current visualization chart information. Moreover, this pattern of altering force feedback magnitude helped users intuitively understand the current data, making it easier to identify anomalies and details within the data.
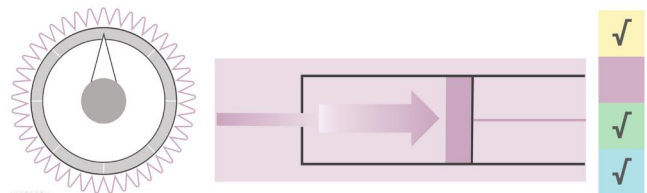
Examples: When exploring the bars of similar heights in a bar chart, the knob mapped the height of each bar to the magnitude of force feedback. When the current bar was shorter than the next one, continuing to rotate the knob increased the force feedback, thus alerting the user to compare. Similarly, while exploring a pie chart, the damping force increased when the current slice angle exceeded the previous slice angle, and decreased conversely, prompting further exploration.

Barrier Pattern was designed by simulating the sensation of hitting a hard obstacle when the relative motor angle

differed less from the force angle and remained constant while traversing the onset of the effect. This pattern was able to effectively highlight extreme situations, helping users identify anomalies. It reduced cognitive stress when comparing visual elements and facilitated a deeper exploration of the details in the visualization.
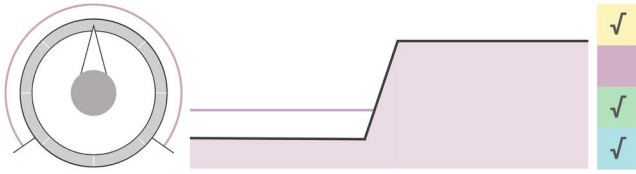
Example: During the exploration of the scatter plot, if the selected area by the user contained preset outliers or data points greater or lesser than a specific value, the control knob would lock, preventing further rotation. This design effectively emphasized the anomalies in the data by suddenly increasing the resistance of the knob.

Selection Pattern can be understood as a discrete step knob in which the force feedback knob acts like, similar to a switch on an electric fan. This pattern performed well in pattern recognition, as users could select different levels of data by rotating the knob to identify data patterns. Additionally, it also helped users quickly compare different visual elements in comparison tasks.
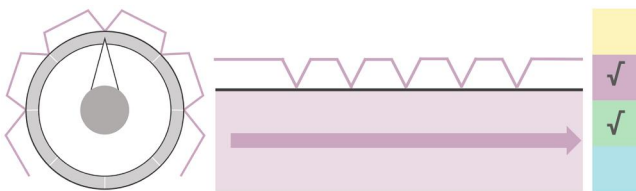
Examples: In exploring the scatter plot, rotating the knob mapped to moving a region, and each notch rotated moved the selected area in the scatter plot by a fixed distance. Similarly, users can set the steps so that they overlap when data values exceed one hundred, two hundred, or three hundred. When the current location of data points was between one hundred and two hundred, the damping increased as the knob rotates from the first step to the second step, which alerted the user to the current number of data points.

4.2.4.2. Fixed Damping.
It meant that the difference between the force angle and the relative angle of the knob was fixed during rotation, and the damping remains constant regardless of data changes. We developed two patterns for this characteristic.

Constant Pattern ensured that the force required to rotate the force feedback knob remained constant, regardless of its rotation. This pattern was ideal for employing various interaction techniques. For instance, turning the knob to the right reduced the current view, whereas turning it to the left enlarged it. Throughout this pattern, the constant force feedback enabled users to select different categories within the visualization and facilitated engagement in interaction.
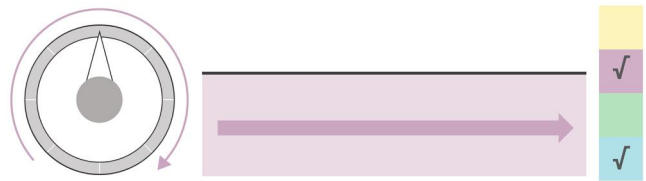
Example: In a pie chart with excessive segmentation, users could rotate the knob to align the slices with their corresponding labels. Additionally, the rotation of the knob corresponded to the horizontal movement of lines in the chart; rotating it to the right moved the lines to the right.

Auto Pattern meant that the knob rotates with a constant force, but when released it continued to rotate evenly to the edge of the graph at the same speed as before it was released. This pattern, which involved the automatic constant-speed rotation of the knob after the user applied basic force feedback, was particularly suitable for automatic viewing of large visualizations and typically combined with interactive techniques.
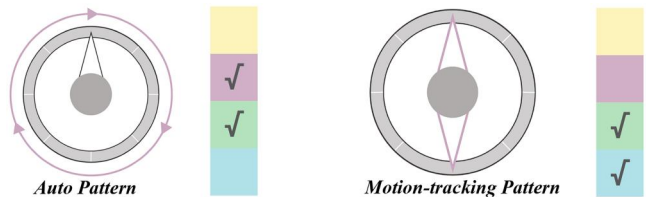
Example: In a heatmap, as the knob's rotation was mapped to color weights, the ongoing rotation altered the color distribution of the heatmap, thereby helping users uncover hidden patterns and details.

4.2.4.3. Independent Damping.
It indicated that the knob was an actively rotating motor that acts as a dynamic dashboard. During the interaction, the user did not need to overcome the knob's damping to achieve rotation. This helped users to track data in real-time, fulfilling P4.

Motion-tracking Pattern meant that the force feedback knob rotated as the information in the graph changes. In cases where it was difficult to distinguish between similar heights in a bar chart or similar angles in a pie chart, this pattern allowed the user to determine the size of the data by observing the rotation of the knob. It acted a dashboard in visualization exploration, effectively reflecting the current data values.

Example: In comparisons of size, the selected slices, points, or lines were represented by the rotation angle of the knob, facilitating the comparison of different visual elements. This pattern revealed information in visual blind spots, like overlapped points in scatter plot, which were detected through rotating the knob.

4.2.5. Final visualization state
The view formed after a series of interactions was known as the **final visualization state**, typically occurring after *permanent interaction*. For instance, when users rearranged axes in a

parallel coordinate, revealing new patterns, the resulting view of the reordered axes was the final visualization state.

5. Study 1: Applying and evaluating the design space

To comprehensively evaluate the recognizability and practicality of our innovative design, we conducted an extensive study focused on exploring and validating the overall effectiveness of our proposed design space.

5.1. Workshop

We held a workshop to investigate two key areas: (G1) Design Space Clarity and (G2) Design Space Usefulness. Moreover, we proposed "recommended solutions" for the challenges encountered in visualizing large datasets.

5.1.1. Participants

We recruited 19 participants (13 males), aged 20 to 36 years (M = 25.16, SD = 3.41), through open recruitment on social media. The participants included college students, researchers, and professionals from diverse educational backgrounds (Bachelor's degree or equivalent: 36.84%, Master's degree or equivalent: 26.31%, Ph.D. or equivalent: 36.84%). Their specializations varied, encompassing fields such as computer science, design, mechanical engineering, and cybersecurity. Their level of maturity in dealing with visualization varied greatly, from less than 1 year (31.58%), 1–2 years (26.32%), to 2–5 years (42.10%). Prior to the workshop, 36.84% of the participants had never heard of haptic force feedback knobs, 26.31% were aware of similar brake controllers, another 26.31% had heard of this, 5.27% were familiar with this technology, and 5.27% used it regularly.

5.1.2. Teaching materials

During the workshop, we provided a set of animations as teaching material for our design space. All animations can be found on our website at https://gopher943.github.io/F2vis-Design-space/. The animations inspired by Lan et al. (2021) on Kineticharts, were designed to help participants understand each element of our design space through animated presentations. In order to validate the effectiveness of the design space, we provided to provide a haptic force feedback knob "recommended solution" for the "possible problems in visualizing large datasets" mentioned in Section 3.1.1.

5.1.3. Procedure

To ensure ample space for movement and discussion, the workshop was held in a spacious conference room, covering an area of 75 square meters. The room was equipped with an 84-inch display, a large conference table that seated 20 people, and 20 chairs. To accommodate the schedules of all participants, the workshop was held on December 25, 2023, and lasted approximately 3 hours. Initially, we dedicated 40 minutes to discussing the challenges of visualizing large

datasets, the haptic force feedback knobs, and the significance of each element within the design space. After the introduction, we divided the participants into 6 groups of three to four individuals each. Each group was tasked with solving one or two sets of visualization problems using the design space. To thoroughly investigate our design space's ease of use and effectiveness, we allotted 30 minutes for each group to devise a "recommended solution". Following a 20-minute demonstration on utilizing our design space, participants were encouraged to freely refine their recommendations during a subsequent 20-minute phase. Once a group completed their recommendations, we instructed them to present these recommendations to groups that were visualizing the same visualization with different questions (All final recommended solutions were illustrated in Figure 2). Groups were allowed to present their recommended solutions to each other until at least two other groups agreed with them. The discussion phase lasted 1 hour, and the workshop was video recorded. At the end of the workshop, we asked each group to present their proposed solutions and share their experiences in using the design space. Subsequently, participants completed a 7-point Likert scale questionnaire to evaluate the clarity and usefulness of our design space. We also conducted semi-structured interviews with participants to further explore their feedback on the proposed design space and reviewed their design processes. The interview questions focused on: (1) evaluating the role of haptic force feedback in addressing data visualization complexities; (2) determining whether our proposed design space could offer solutions for mitigating visualization problems and assessing the overall evaluation of the design space.

5.2. Results

This section discussed the workshop and interview results.

5.2.1. Workshop

Participants successfully developed recommended solutions, which were endorsed and agreed upon by the other two groups, culminating in a credible solution as illustrated in Figure 2. It was important to note that these were recommended solutions, not the only solutions. In the figure, an asterisk (*) indicated that while the current design element was preferred, other elements within the same category were also viable options.

To better understand the recommended solutions proposed by the participants, we opted to utilize parallel coordinate plots, specifically focusing on *Problem 1: The crossing of lines and excessive drawing culminated in visual confusion.* Figure 3 demonstrated the actual problem encountered by our collaborators in their research. This parallel coordinate plot was enhanced with clustering sampling and edge bundling techniques. However, the problem of excessive line drawing still persisted. In light of this, we suggested employing **filtering & navigation** interaction techniques, along with designated **area** for more effective interaction within the

Figure 2. Using the design space. Visualization may reveal problems during the interaction process and our recommended solutions.

parallel coordinate plot, allowing for selections of **scale** and **position**. Given the extended length of the axes, we recommended the use of **unlimited rotation** for manipulating the force-feedback knobs. Additionally, to identify excessively drawn lines and better perceive force feedback, we recommended the **mapping pattern**, which, based on the magnitude of force feedback damping, could help in detecting areas of overdraw. At the same time, we recommended the use of the **barrier pattern**. When users selected areas and encountered overdrawn lines, this pattern increased the damping, making the knob difficult to turn and thereby allowing users to quickly realize the problem of line overdraw.

Figure 4 shows the participants' evaluation of clarity and usefulness for 20 elements of user interaction and force feedback patterns within the design space. The mean scores and the 95% confidence intervals for these ratings were reported. The questionnaire was conducted using a 7-point Likert scale, where a score of 7 indicates extremely clear or extremely useful. Across these two dimensions, participants generally gave high ratings, with the average score for each element exceeding 5. We noticed that the ratings for clarity were usually lower than those for usefulness, reflecting the participants' belief that mastering the design space requires a certain learning cost. After in-depth discussions in the workshop, participants gained a deeper understanding of the design space, resulting in higher ratings for usefulness.

5.2.2. Interview feedback

(1) *Evaluating the role of haptic force feedback in addressing data visualization complexities.* Given that most participants had experience with visualization but were not familiar with haptic force feedback knobs, 12 out of the 19 participants initially had a negative view of this issue, they believed that haptic force feedback was relatively limited in its usefulness. After the workshop presentations and discussions, the majority of participants shifted their views, beginning to recognize that including haptic force feedback could mitigate some of the challenges faced when visualizing large datasets. A participant observed that in numerous instances, haptic force feedback primarily aided in identifying anomalies rather than directly solving them. However, this capability was crucial as it immediately highlighted issues, serving as a critical point of intervention. Meanwhile, some participants pointed out that since the finger was exceptionally sensitive to touch, utilizing the sense of touch to convey data information was effective. Nonetheless, detailed case studies were essential to ascertain if haptic force feedback could directly address visualization challenges. Although incorporating haptic force feedback proved to ease some difficulties, comprehensive validation was still required to thoroughly address the issue. In particular, haptic force feedback knobs were beneficial in navigating comparative problems, like comparing similar angles in pie charts. However, when
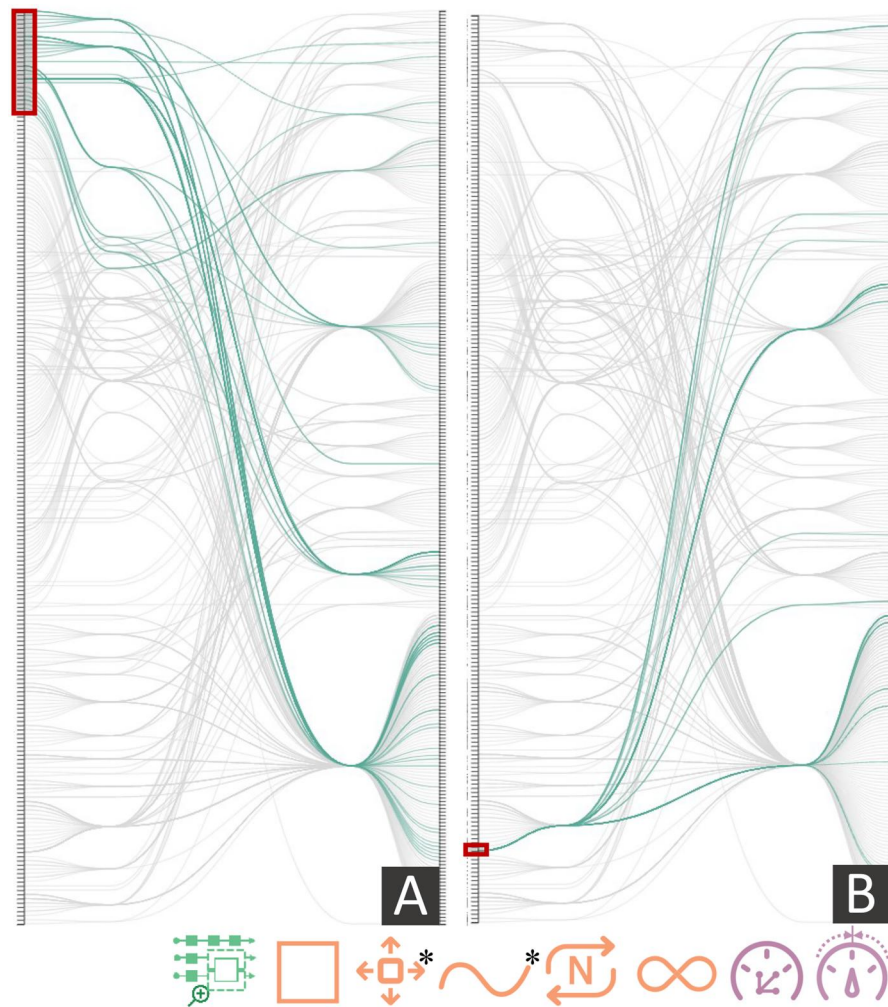
Figure 3. An example of the recommended solution in overdraw parallel coordinate.

dealing with visually confusing problems, difficulties persisted even with the assistance of haptic force feedback.

(2) *Determining whether our proposed design space could offer solutions for mitigating visualization problems and assessing the overall evaluation of the design space.* Fifteen out of nineteen participants believed that, through discussions, the design space could offer a "recommended solution" for mitigating visualization challenges. The remaining four participants felt they needed additional assistance to develop such a "recommended solution". Participants generally concurred that grasping the design space required some time. For instance, one participant mentioned that understanding the full potential of haptic force feedback was challenging for those unfamiliar with haptic force feedback knobs, especially in a brief period of time. Fortunately, through the process of discussing and formulating "recommended solutions" with their groups, many participants were able to grasp and comprehend the abstract concepts. The clarity and usefulness of each interaction element were evaluated by the participants, with the results displayed in Figure 4. Despite the overall positive feedback, participants rated the usefulness aspect highly, indicating the learning and mastery of the design space involved a considerable effort. In summary, participants indicated that our design

space inspired their designated recommended solutions (M = 1, SD = 2), and they were satisfied with the final recommended solution (M = 1, SD = 2).

6. Study 2: Enhancing interaction with haptic force feedback knob

To deeply explore the design space and fully understand the role of haptic force feedback in the context of assisted visualization, we carefully conducted Study 2. This study specifically aimed to assess the potential and effectiveness of the haptic force feedback knob in addressing the complexities of data visualization.

6.1. Methods

To further explore the usefulness and effectiveness of our design space, we designed and developed a haptic force feedback knob. The primary purpose of this knob was to assess how the physical control knob could enhance visualization applications. We organized two rounds of experiments and invited a total of 20 participants, aiming to further demonstrate the practical application potential of our design space. In the first round of experiments, participants were tasked

Figure 4. Participants' rating with 95% confidence of 20 elements.

with completing a series of tasks across various visualizations, such as discovering new patterns and identifying outliers in the data. In the second round of experiments, we used a 5-point Likert scale to allow users to subjectively rate their experience with the knobs (Brooke, 1996). Through these two rounds of experiments, we aimed to gain insights into how the knobs performed in practice, as well as users' feelings and feedback about this physical interaction.

6.1.1. Stimuli
In designing the haptic force feedback knob, we used a three-phase brushless DC motor (Model 2208BLDCH) as the haptic actuator. The research revealed a strong correlation between pointer-style knob designs and haptic force feedback. Based on this finding, we utilized 3D printing technology to create a knob in the shape of a pointer, which was then mounted on the top of the motor. Figure 5 showed the main prototype of our haptic force feedback knob device.
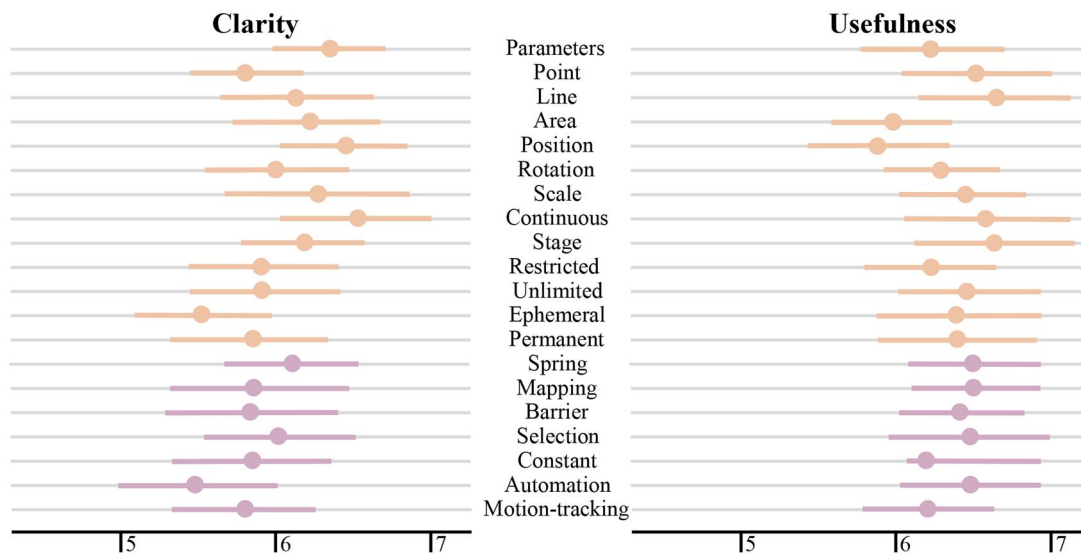
6.1.2. Participants
We recruited 20 participants (13 males) between the ages of 22 and 30 (M = 24.85, SD = 2.50), including 14 right-handed and 6 left-handed, from diverse professional backgrounds, such as computer science, design, and mechanical engineering, via open recruitment on social media. Notably, these participants lacked professional experience with physical control knobs. However, we sought to derive valuable insights from their everyday experiences using physical knobs. Prior to the start of the experiment, all participants signed an informed consent form. We highlighted that their involvement was entirely voluntary, and they received no compensation for their participation.

6.1.3. Study procedure
To ensure that participants could focus on exploring the haptic force feedback knob, the experiment was conducted in a quiet, 30-square-meters conference room to eliminate external distractions. To maintain the participants' concentration and accuracy, we received only one participant at a time. The space was equipped with a table capable of accommodating five people side by side and five corresponding chairs. Additionally, a 14-inch MacBook Pro was prepared by us for the participants' use. To accommodate the schedules of all participants, the scatter plot exploration experiment took place from December 26 to 28, 2023, with each participant spending an average of 40 minutes completing the experiment. The exploration experiment using parallel coordinate plots was conducted from April 15 to 18, 2024, with each participant taking an average of 30 minutes to finish. In the experiment, participants were arranged to sit on one side of the table while the knobs were placed horizontally directly in front of them. The interface used to visualize the exploration in the experiment was displayed on a MacBook Pro display that was located behind the knobs. The online questionnaire to be filled in by the participants was displayed in a separate window, as shown in Figure 6.

We chose to apply haptic force feedback knobs on scatterplots and parallel coordinates, and based on the three questions about scatterplots and parallel coordinates mentioned in Figure 2, we designed two tasks for each of these questions. To eliminate the potential influence of color on task completion, we decided to standardize the color scheme in all charts to green. Additionally, to ensure visual consistency, we employed the same visual elements across all charts, such as chart axes, labels, and legends. At the beginning of the experiment, the knobs were automatically adjusted to their initial position, which was pointing at 12 o'clock, and participants were asked to use their dominant hand to rotate the knob in a clockwise or counterclockwise manner. No specific guidelines were set for how to hold the knobs, allowing participants to operate them according to their comfort level. After completing each question, participants were required to submit their answers and continue to complete the remaining questions until all questions had been answered. To further demonstrate the effectiveness of
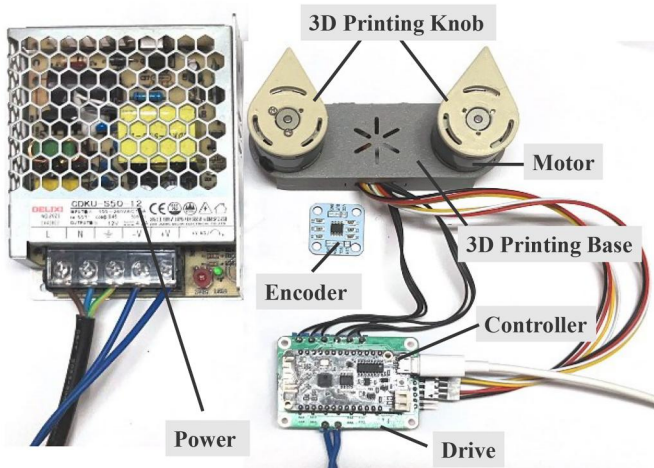
Figure 5. Physical representation of the haptic force feedback knob device prototype.

Figure 6. Study setup with haptic force feedback knob.

haptic feedback compared to the use of visual feedback alone, we proposed the following hypothesis:

- *Null hypothesis (H0)*: Using the force feedback knob performs worse compared to using visual feedback in corresponding tasks.
- *Alternative hypothesis (H1)*: Using the force feedback knob outperforms using visual feedback in corresponding tasks.

After completing all tasks associated with a specific condition, participants proceeded to respond to the System Usability Scale (SUS) questionnaire (Brooke, 1996), shown in Table 1. This involved evaluating their experience based on 10 statements about the system's usability, with their level of agreement being indicated on a 5-point Likert scale. In both rounds of the experiment, no time limit was shown, and participants were allowed to experience haptic force feedback and submit their answers multiple times, with the last submitted answer ultimately taking precedence. Overall, each participant was involved in this study for approximately 60 minutes.

6.2. Analysis and results

6.2.1. Accuracy in scatter plot

User accuracy results were summarized in Figure 7. When interacting with the haptic force feedback knob, users generally achieved an accuracy rate of over 50%, particularly notable in responses to questions *Q2* and *Q3*. This indicated that users were able to precisely perceive the changes in values within the scatter plot through the knob. Moreover, the results showed that as users progressively completed the questions, the accuracy of their task completion also correspondingly increased. Due to the small sample size, we decided not to use the Chi-square test. Instead, we employed Barnard's test (Barnard, 1947), a method used for odds ratio testing in contingency tables, to analyze the results of accuracy performance. Our hypothesis **(H1)** on accuracy was validated for *Q2 and Q3 (p<.05)*. However, the addition of
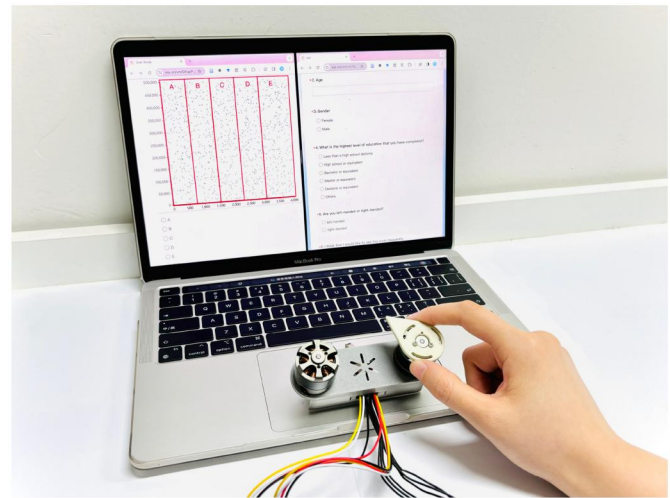
haptic force feedback did not have a significant effect on accuracy in *Q1*. Therefore, we speculated that users needed some time to adapt to the force feedback, as it involved using a force feedback knob in the first two questions for *Q1*, which might impact task accuracy. Overall, we rejected the null hypothesis and accepted the alternative hypothesis that the intervention of haptic force feedback knob was superior to using visual feedback alone.

6.2.2. Accuracy in parallel coordinate

User accuracy results were summarized in Figure 7. When interacting with the haptic force feedback knob, users generally achieved an accuracy rate of over 50%, particularly notable in responses to questions *Q2*. This indicated that users were able to effectively identify anomalies and data patterns by using the haptic feedback knob. Similarly, we utilized Barnard's Test (Barnard, 1947), an odds ratio test approach for contingency tables, to analyze accuracy performance results. Our hypothesis **(H1)** on accuracy was validated for *Q1, Q2 and Q3(p<.05)*. We observed that after completing the scatter plot tests, users became better adapted to the tactile feedback knobs, which also improved their accuracy in using parallel coordinate plots. During the use of parallel coordinate plots, users explored the data with two knobs: one knob was used to adjust the size of the selection box, while the other controlled the position of the selection box. This dual-knob setup allowed users to make more effective adjustments based on the data distribution within the box. A participant reported that while using the parallel coordinate plot, by adjusting the size of the selection box with one knob and controlling its displacement with another, they were able to quickly locate areas of data overplotting and effectively identify specific anomalies by reducing the size of the selection box. This effect, which had not been achieved during earlier explorations of scatter plots, was only applied to parallel coordinate plots, and it sparked strong anticipation among participants for further enhancements to the knob functions. Overall, we rejected the null hypothesis and accepted the alternative hypothesis that the intervention of
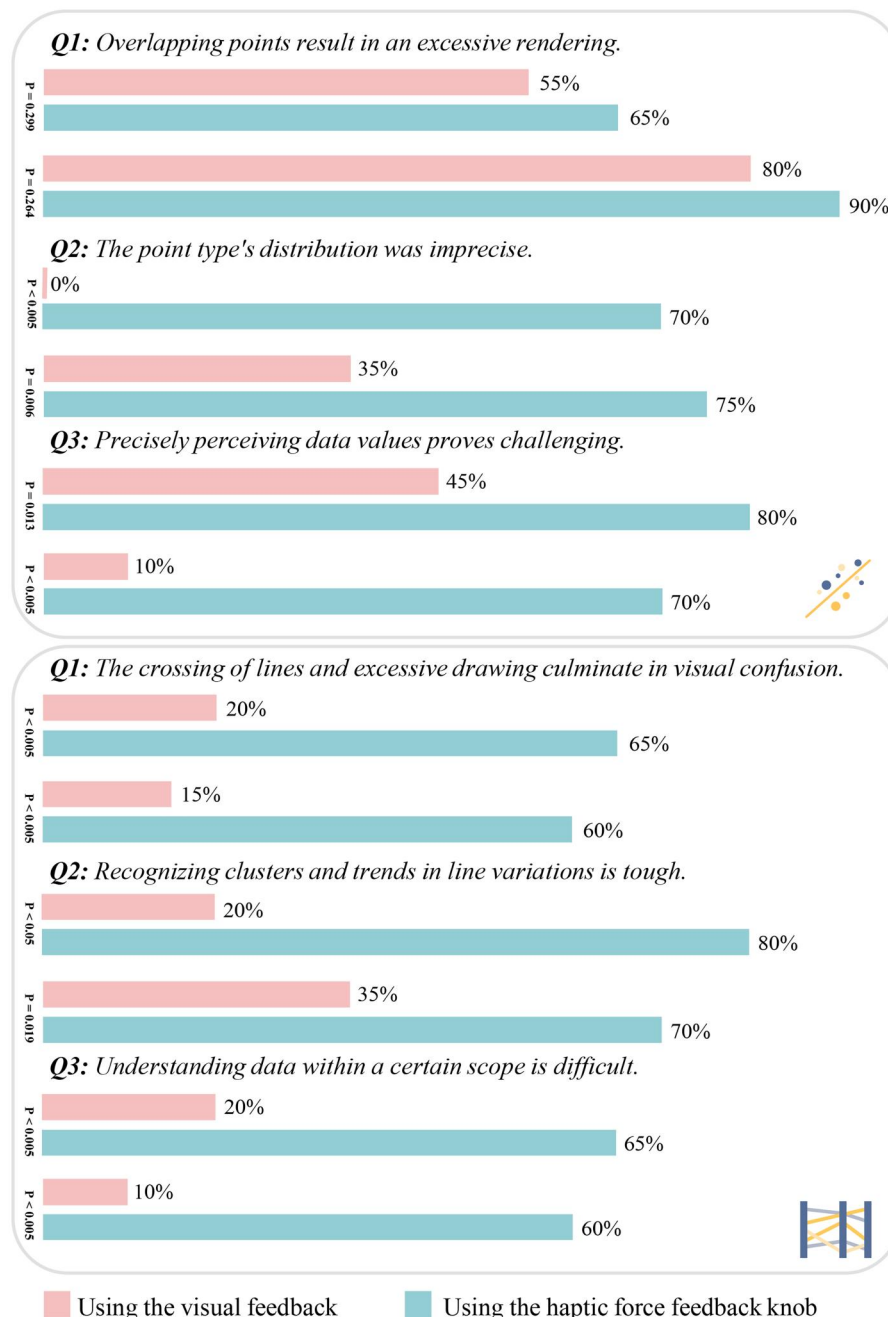
Figure 7. The accuracy of the participants' controlled experiment, *p*-value.

Table 1. SUS Evaluation results. Scores (mean ± std) for each question were reported.

	Question	Score
Q1	I think that I would like to use this knob frequently.	3.80 ± 0.46
Q2	I found the knob unnecessarily complex.	2.35 ± 0.43
Q3	I thought the knob was easy to use.	4.45 ± 0.29
Q4	I think that I would need the support of a technical person to be able to use this knob.	4.05 ± 0.40
Q5	I found the various functions in this knob were well integrated.	3.80 ± 0.46
Q6	I thought there was too much inconsistency in this knob.	2.80 ± 0.49
Q7	I would imagine that most people would learn to use this knob very quickly.	4.15 ± 0.45
Q8	I found the knob very cumbersome to use.	2.30 ± 0.39
Q9	I felt very confident using the knob.	4.45 ± 0.37
Q10	I needed to learn a lot of things before I could get going with this knob.	3.95 ± 0.43

haptic force feedback knob was superior to using visual feedback alone.

Regarding the usefulness rating of the force feedback knob, Table 1 presented the assessment results of the SUS (System Usability Scale) questionnaire, detailing each question and its corresponding score. Notably, most positive aspects, such as Q1, Q3, Q5, Q7, and Q9, received high scores. This reflected the excellent performance of our designed force-feedback knob in assisting users to understand data distributions more deeply. Moreover, the operation of the force-feedback knob was both convenient and easy to master. A participant with experience in visualization expressed great surprise at the effectiveness of the haptic force feedback knob. He struggled with the problem of

overplotting in scatter plots. He stated, "In complex data visualization, it's difficult to accurately pinpoint areas using vision alone. However, initially intervening with haptic force feedback allows for more effective targeting of the desired area. Subsequently integrating visual inspection with the view leads to a more precise identification of anomalies. This is a highly efficient method!"

However, we noticed some "contradictions" in our results, especially regarding questions Q2, Q4, and Q10 of the questionnaire. A participant mentioned that although the operation of the knob is simple and user-friendly, it required prior knowledge before use, including understanding changes in damping and the professional background of scatter plots. He pointed out that this could be a challenge for those without any prior knowledge. Moreover, some participants raised another issue that caught our attention: when exploring visualizations using the haptic force feedback knob, the factor of time could affect the perception of haptic force feedback. They pointed out that as time passed, users might gradually forget the sensation of previous force feedback, making it difficult to effectively quantify and compare different levels of force.

7. Discussion

We believed that our design space provided a rich framework for the integration of visual and haptic perception. Here we discussed the lessons as well as the limitations that emerged from this work.

7.1. Lessons learned for design space

In our review of devising solutions, we uncovered some interesting experiences in Figure 8. Furthermore, we investigated the frequency with which participants used elements of the design space. In Figure 8, the data preceding each element indicated the frequency with which that element was used as a "recommended solution". It was important to note that since we employed eight different visualizations, these initial visualization states and interaction methods were not included in our statistics. In terms of graphical elements, *line* and *area* were the most frequently chosen, while in the category of geometric postures, *position* was the most common. Regarding the control of knobs, *stage rotation* was favored over continuous rotation for knob functions, and *unlimited rotation* was chosen more often than restricted rotation. This might be because most people perceive traditional knobs as being associated with stage rotation and having the characteristic of unlimited rotation. Participants showed a preference for *ephemeral interactions*, suggesting that they might find it challenging to directly find the desired results when exploring complex datasets, thus necessitating frequent returns to the initial visualization state for further exploration. In the choice of force feedback patterns, *barrier*, *mapping*, and *spring patterns* were the most popular, all of which were types of variable damping. Among these, the *barrier pattern* was particularly prominent, differing from our expectations.

1 The exploration of *Point* was enhanced, allowing users to scale and reposition to delve deeper into visualization details, a method especially common in scatter plots.

8 *Lines*, commonly used in axis-based visualizations, allowed exploration through rotations and positional shifts, horizontally or vertically.

8 *Areas* were interacted with through scaling and positional changes. Scales were commonly used to quickly pinpoint target patterns during area exploration.

9 *Position* was the most commonly used method of interaction, exploring hidden patterns and details in visualizations by changing positions.

3 *Rotation* was commonly used in explorations involving lines and was also applicable to circular-like visualizations.

7 *Scaling* was recommended when exploring areas, using scales to quickly locate target patterns.

4 *Parameters* were often used to adjust the overall changes in the visualization rather than local adjustments, such as changing the color distribution in a heatmap.

11 *Continuous Rotation* aligned more with users' habits of using knobs and was often used in conjunction with unrestricted rotation.

10 *Stage Rotation* was typically used in conjunction with **mapping pattern** or **selected pattern**, sensitively detecting changes in tactile feedback damping.

3 *Restricted Rotation* was suitable for circular charts like pie charts, aligning with people's understanding of knobs, and was often paired with stage rotation.

17 *Unlimited Rotation* aligned more with users' habits of using standard knobs, allowing for infinite rotations.

14 *Ephemeral Interaction* was commonly used in preview tasks and worked best when paired with the spring pattern.

7 *Permanent Interaction* was the state after most task interactions, retaining the visual content explored.

Most visualization tasks, especially comparison tasks, were accomplished by adjusting the damping size.

9 *Spring Pattern* excelled in locating discrete values and details, with its strong tactile feedback quickly drawing attention to anomalies.

8 *Mapping Pattern* was highly effective in comparing visual elements and displaying details, particularly excelling in data comparison.

9 *Barrier Pattern* performed well in identifying outliers, for example, it was used to detect overlapping outliers in scatter plots.

5 *Selection Pattern* combined with stage rotation, allowing for sensitive perception of changes in damping within tactile feedback.

In data labeling matching tasks, the use of non-damped modes was more common. For example, for a pie chart containing many small slices and numerous categories, matching these slices accurately with the legend presented a challenge.

1 *Constant Pattern* helped users match more effectively and also performed well in pattern recognition tasks.

1 *Auto Pattern* enabled automatic matching, helping users comprehensively view visualization content.

2 The applicability of *Motion-tracking Pattern* was limited to some extent.

Figure 8. Lessons learned for design space.
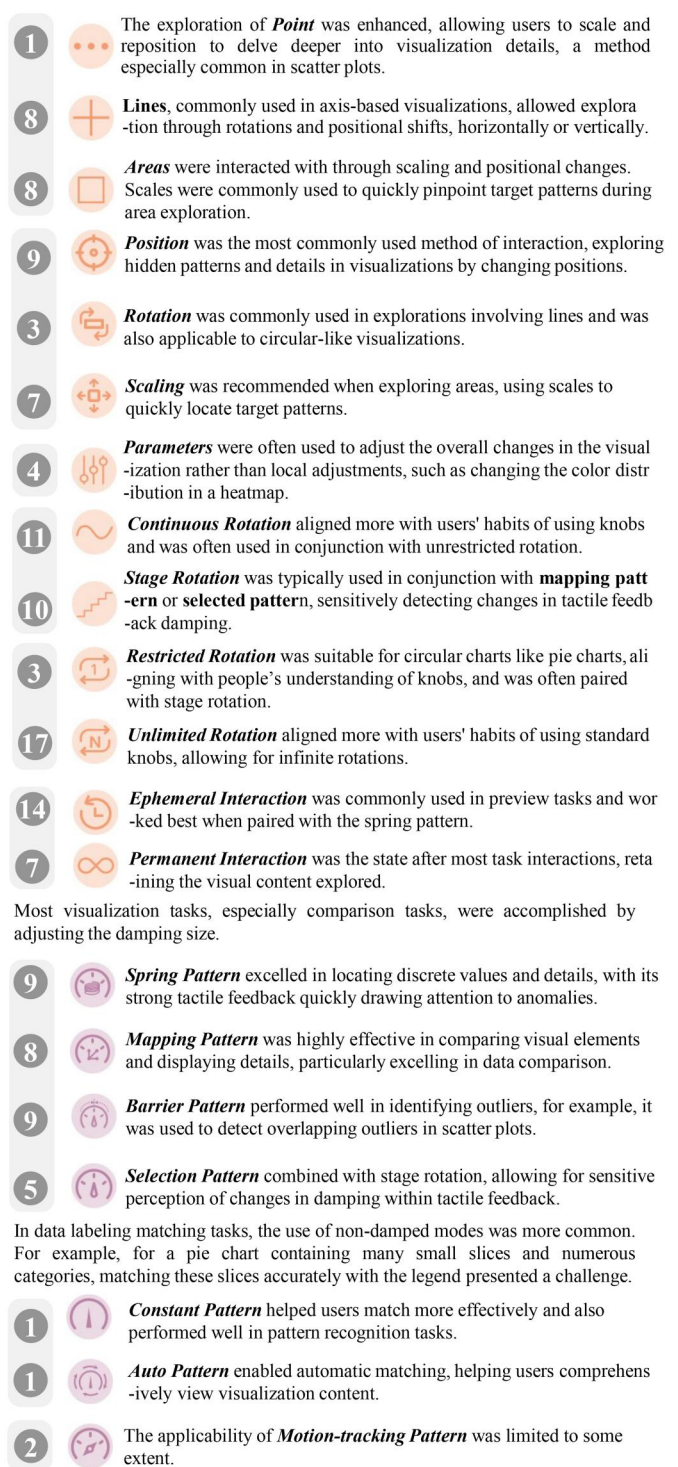
Participants believed that strong damping haptic feedback was helpful in discovering outliers and patterns.

7.2. Future work and limitations

Numerous potential pathways for further investigation remain. Up to this point, our research has been limited to examining the role of haptic feedback knobs in enhancing visualizations. Clearly, this constitutes merely one point

within a vast design space composed of visualization, sensory modalities, and physical hardware. However, continuing to explore this vast design space point-by-point requires more time and technology costs.

This indicates that in future research, continuing to explore multi-channel and multi-sensory methods to enhance visualizations still holds significant potential. For instance, while our study primarily focuses on using haptic force feedback knobs to improve visualization exploration, we could also consider employing haptic temperature or textures along with different hardware prototypes to enhance users' understanding and exploration of visualization. Moreover, the scope of research utilizing olfactory, gustatory, and auditory senses to augment visualizations is broader. These explorations require additional experiments, which are beyond the scope of our current research. More comprehensive research outcomes will further enhance users' understanding of visualizations, making them more interpretable and credible.

At the same time, as Chen et al., (2023). have pointed out, using the design space as a roadmap can enhance our abstract understanding of various phenomena and help comprehensively explain some phenomena. Therefore, we must also understand the relationship between the design space and the haptic force feedback knob prototypes. In other words, although there are certain commonalities among different visualizations and tasks, haptic force feedback knob prototype is unlikely to be directly applicable to every visualization scenario within the design space. More likely, each visualization scenario requires the development of a specific" program" (or proxy) to meet its unique needs.

Our main contribution lies in completing the entire development process from the design space to physical controls, enabling the practical application of design space. This demonstrates that our design space is not based on subjective design creation by designers, but rather validates the viability of design space. Therefore, although our haptic force feedback knob prototypes have currently been evaluated only in scatter plots and parallel coordinate plots, this has not diminished participants' high regard for the design space; instead, it has increased their anticipation for the haptic knobs. Consequently, our future work will focus on more effectively developing haptic force feedback knobs that can be recognized and utilized across various visualizations and tasks.

Additionally, our study still faces several limitations. Firstly, in our exploration of needs, we attempted to reduce visual strain by introducing additional sensory channels. However, our focus was overly concentrated on the design space centered around haptic force feedback knobs, which limited the scope of haptic feedback application and may not have fully demonstrated its potential to alleviate visual fatigue. Secondly, our force feedback design primarily focused on changes in damping, without thoroughly investigating how changes in motion speed and position affect the effectiveness of haptic feedback. Thirdly, our study predominantly recruited participants with higher education, suggesting that future research should broaden the participant pool to better represent a wider user demographic.

8. Conclusion

In this paper, we studied the design of visualization assisted by haptic force feedback knobs, exploring how haptic perception through force feedback could alleviate the visual burden. We first conducted a literature review to discuss potential problems in visualizing large datasets as well as existing methods and technologies. Then, we engaged in in-depth interviews with domain experts to discuss the necessity of applying haptic force feedback technology to visualization and its potential application scenarios. Based on these discussions, we designed a design space centered around haptic force feedback knobs, defining the concept and principles of each design element in detail. We demonstrated the application of these elements in real-world scenarios through examples, helping users to identify and resolve problems during the visualization process.

Further, we validated the effectiveness and practicality of the proposed design space through two studies. In the study 1, we organized a workshop with 19 participants. The results indicated that the participants were able to understand our design space well and apply it to offer "recommended solutions" for problems encountered in visualizing large datasets. In study 2, we designed and developed a prototype device featuring a haptic force feedback knob, which we applied to the visualization of scatter plots and parallel coordinate plots. The results showed that using the haptic force feedback knob resulted in a higher accuracy rate compared to relying solely on visual feedback, demonstrating its effectiveness in enhancing the user experience with data visualization tasks. In conclusion, our research highlighted the significant potential of haptic force feedback in enhancing data visualization, especially for large datasets. We believed that the developed design space and the prototype of the haptic force feedback knob provided a robust framework and hardware prototype for future research.

Notes

1. https://gopher943.github.io/F2vis-Design-space/
2. https://www.youtube.com/watch?v=Q76dMggUH1M
3. https://github.com/scottbez1/smartknob

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