Exploring Vibrotactile Cues for Interactive Guidance in Data Visualization

Wenkai Han
wenkaihan@cs.au.dk
Department of Computer Science, Aarhus University
Aarhus, Denmark

Hans-Jörg Schulz
hjschulz@cs.au.dk
Department of Computer Science, Aarhus University
Aarhus, Denmark

ABSTRACT

In visualization, user guidance has become an essential concept to aid users in making informed decisions ranging from what subsets to focus on in the data space to which regions to explore in the view space. To guide users, predominantly visual cues like colors or arrows are used to indicate particular targets or directions. In this paper, we explore the possibility of another sensory channel for guidance cues: vibrotactile feedback. To that end, we explore different properties of the vibrotactile channel (e.g., amplitude and duration) and discuss their potential use as guidance cues. We then report on an experiment (N=14) in which we investigate possible vibrotactile cues in comparison to visual cues and to a combination of visual and vibrotactile cues for a guided selection scenario and a guided navigation scenario. Although none of the vibrotactile cues significantly outperformed the visual cues, our study results shed light on a number of practical issues when using vibration for user guidance – including differences between various types of vibrotactile feedback, as well as diverging performance for different guidance scenarios.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; **Visualization design and evaluation methods**.

KEYWORDS

visual exploration, interactive guidance, vibrotactile feedback

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1 INTRODUCTION

Over the last years, guidance has emerged as an important tool to facilitate user interaction and decision making in visual data analysis. Ceneda et al. define guidance in the context of visual analytics as *"a computer-assisted process that aims to actively resolve a knowledge gap encountered by users during an interactive visual analytics session"* [11]. Guidance can be provided in a variety of ways, depending on the type of the knowledge gap between the users and their goal and the desired level of computer assistance [8, 10, 12]. While the variety of guidance explicitly includes non-visual means of guidance, subsequent research has so far exclusively focused on visual guidance cues and left out any other type of cues (e.g. haptic and sonic ones) [9, 11].

This stands in contrast to a growing interest in using non-visual forms to represent data: data physicalization approaches explore haptics to make data tangible [24], data sonification uses sound to make data audible [28], and data olfactation applies scents to make data perceivable through smell [35].

These non-visual forms of data presentation not only solve problems in traditional visual presentation but also provide additional benefits to the existing visualization systems. In visual analytics tasks where users are already visually overloaded, alternative forms of data presentation can help to solve visual conflicts and ease the visual load. Additionally, using non-visual forms in data visualization can also aid visually impaired users and provide an immersive experience for others [15, 21].

Among non-visual presentation forms, vibrotactile approaches have proven as only second to visual ones with respect to sensory bandwidth [13, 29, 30]. In the light of input devices with vibrotactile feedback now being readily and commercially available (e.g., gaming mice, Microsoft Surface Dial), we explore the use of vibrotactile means for guidance in data visualization. Among the different options like amplitude or frequency of a vibration, we identify possible vibrotactile cues that seem to be good candidates for guiding users in interactive visualizations. We put these cues to a test in a user experiment that compares performance and experience between visual cues, vibrotactile cues, and a combination of both using an off-the-shelf vibrating mouse.

As a result of these experiments, our work not only proposes and validates a new vibrotactile channel for guidance in data visualization, but also opens up a new design space of different vibrotactile patterns for interaction design in data visualization. The analysis of the gathered user performance and experience data from different vibrotactile patterns provides further insights in how such guidance should be designed.

In the following, we present the related work on vibrotactile data presentation. Thereafter, we present the setup of our experiment on two data visualization scenarios and report the results of the experiment. From our findings, we present open research questions for vibrotactile guidance in visual analytics.

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2 VIBROTACTILE DATA PRESENTATION

Although nearly untouched in the area of guidance, vibrotactile cues have been well studied for presenting data in the existing literature. In general, vibrotactile data visualization has been proven useful in presenting ordinal [40] and categorical data such as discrete directions and locations [25, 31]. But, as detailed in the following, different vibration parameters lend themselves to the presentation of data to different degrees. For example, frequency and amplitude have been shown to represent relative values better than absolute ones [18, 40].

2.1 Amplitude

Amplitude refers to the intensity of vibration. It can be described in G as acceleration or dB as acceleration level. The recommended range of amplitude has been discussed with regard to the acceleration level. Craig and Sherrick [14] found that 28 dB would be a practical maximum of vibration, as human perception deteriorates above this threshold. Gunther [20] reported that vibration of more than 55 dB might invoke pain and should be avoided.

Even though a vibration's amplitude is continuous, it is not well suited for representing continuous data. This is because it can be rather hard for human beings to differentiate between different intensities of vibrations. Gill [18] states that no more than four different intensities should be used.

Early studies [25–27] on using vibrotactile and auditory cues to present bivariate and trivariate maps of categorical data suggested that the vibrotactile cues with different amplitudes can increase the recall rate of the information, while the completion time is similar to visual cues. However, they also pointed out that the vibrotactile cues might interfere with other forms of cues for presenting information.

2.2 Frequency

The frequency of a vibration refers to the number of times that the vibration unit goes back and forth between the amplitude per unit of time. The range of frequencies that human beings are most sensitive to is between 20 Hz and 1000 Hz, with the optimal point lying at around 250 Hz [20].

The change of frequency can usually be used to encode numerical changes similar to amplitude. However, a lower frequency of vibration would provide a more loose and rough feeling to the users, while a higher frequency would invoke a tighter and finer sensation. Like amplitude, the number of different frequencies that can be differentiated is limited. No more than 9 different levels of frequency should be used, and the difference between the levels should be no less than 20% [18]. For representing ordinal information haptically through different frequencies, a study with a force-feedback rotary device found that the response time for using vibrotactile cues is significantly better than for positional cues, but the accuracy can be 10% to 20% lower [40]. However, the frequency of vibration might interfere with other parameters like amplitude. Enriquez and MacLean [32] suggest that the frequency range of 5 Hz to 20 Hz would reduce this interference and increase the expressive capability of the vibrations.

Different rates of the change in amplitude and frequency can also carry more intricate meanings. Participants in a study by Gunther [19] describe an abrupt change in these parameters as similar to a tap against the skin, while a gradual change feels like something rising up or out of the skin. In addition, the profiles of these changes (e.g. linear, Gaussian, or polynomial profiles) can have an influence on user performance and experience. A study on haptic feedback found that linear patterns might lead to lower performance and are less preferred by users than non-linear ones [4].

2.3 Waveform

Sine, square, triangle and sawtooth waveforms are the most commonly used waveforms of vibrations. Although people are relatively good at discerning between two different waveforms [19], studies on discriminating between more than three waveforms have been lacking. Rovan and Hayward [37] explain that the sine waveform is commonly used as it provides a sense of smoothness, while other waveforms like square and sawtooth would be rougher.

Different from amplitude and frequency, the change of waveform can be used to imply a change between ordinal or categorical data values. As the different waveforms have different degrees of smoothness, it would be possible to use it for representing discrete data. However, we should also be aware that human beings' ability to differentiate between more than three waveforms has not been proven. Therefore, caution is needed when using waveforms to encode data values.

2.4 Duration

Different duration of vibrotactile cues can encode information by changing the length of vibration. Stimuli less than 100 ms are usually perceived as a tap [19], while longer stimuli combined with different patterns can deliver a wide range of physical perceptions.

The change of duration and intervals of vibrations can be used to combine individual vibrations into sequential patterns. These patterns can be used to encode data similar to Morse code, but with the potential of adding in other properties. For example, a sequence of a shorter interval with strong vibrations can suggest a more intense feeling, and vice versa. Compared to encoding such information only with the intensity, we argue that the metaphor for a value or the severity of a situation might be more easily understood by users through such sequences.

2.5 Pattern

The pattern of a vibration refers to the change in amplitude, frequency, waveform, and duration. These patterns can encode information using metaphorical vibrations (the single tap, multiple knocks, a faint buzz, etc.) or not.

Tactons, a design structure for vibrotactile patterns, in particular, are used in various studies to represent different information [5–7, 36]. Tactons are constructed with different vibrotactile patterns to non-visually communicate complex concepts by compounding different parameters such as frequency, amplitude and duration [5]. For example, a gradual increase in amplitude can represent the process of user actions, and a click vibration at the end can indicate the action has been successfully executed. Studies on different tactons all suggested that vibrotactile cues have a rather good identification rate [2, 6, 7].

Table 1: A List of Widely Available Devices with Input Capability and Vibrotactile Output

Parameter & Device	Amplitude	Frequency	Waveform	Duration	Pattern	Source
SteelSeries RIVAL mouse	5 variations	No	No	Yes	Limited Selection	[39]
Microsoft Surface Dial	Yes	No	No	Yes	Limited Selection	[33]
Apple Magic Trackpad 2	Yes	Yes	No	Yes	Yes	[22, 23]
MacBook Pro Trackpad (2016 or later)	Yes	Yes	No	Yes	Yes	[22, 23]
iPhone (iOS 13 or later)	Yes	Yes	No	Yes	Yes	[22, 23]
Apple Watch	Yes	Yes	No	Yes	Yes	[22, 23]
Mi Band 4/5	3 variations	No	No	Yes	Limited Selection	[42]

3 A USER STUDY ON VIBRATION AS A GUIDANCE CUE

In the real world, vibration is frequently used to guide humans. Examples range from laser pointers that signal through vibration that the presentation time is almost up, to rumble strips being used as road markings to draw drivers' attention to potential dangers. Hence, it is only reasonable to adapt this tried and true idea for visual exploration, so as to see if it works for this domain as well. This makes particular sense, as vibrotactile feedback has been made available in several commercial input devices. In Table 1, we present how different commercially available devices support the different customized parameters for vibrotactile cues. Note that in this table, the degree of support is defined by their application programming interfaces (APIs) as of October 2020. To adapt vibration for visual exploration, we went through internal discussions and pilot testing to build a software prototype and to plan a user experiment to observe vibration-guided visual data exploration.

3.1 Participants

14 participants (6 female and 8 male) were invited to a one-hour experiment session. Participants were students and researchers across different faculties from Aarhus University. The age of the participants ranged from 22 to 40. Among them, two were left-handed but used their right hands for computer mice in daily life. Two of the male participants were red-green colorblind. Two female participants had myopia, but their eyesight was corrected by their glasses. None of the participants had prior experience with haptic feedback in data visualization or was familiar with our prototype.

3.2 Apparatus

The experiment was conducted on a 14-inch laptop (HP Elitebook 840 G5) with Intel Core i7-8550U at 1920 pixels × 1080 pixels resolution. The mouse was a SteelSeries RIVAL 710 with embedded vibrotactile feedback. Participants interacted with the prototype through the mouse with their right hand. A Logitech G240 cloth mouse pad was used to provide a consistent surface for the mouse movement and vibrotactile feedback.

The choice for a vibrating computer mouse was made based on several reasons. First, as most current interactions with data visualization are still performed through computer mice, using a commercially available mouse makes our design more accessible for different users without the need to learn how to interact with an unusual device. Second, as the mouse has embedded vibrotactile feedback, users do not need to change between two different devices during the experiment (e.g., a mouse and a vibrotactile device). Finally, an off-the-shelf computer mouse makes it simpler to reproduce and extend our work.

The tactile motor in the mouse was an ELV1030A Linear Resonant Actuator (LRA) from AAC Technologies. The maximum vibration acceleration level was at 1.7G, and the resonant frequency was set to 205 Hz. The waveforms we used were predefined in the SDK. We chose the "ti predefined buzz" group of vibrotactile cues, as they had more constant waveforms and more varieties of amplitudes. The selection of vibrotactile cues can be found on the SDK's webpage [39].

3.3 Tasks and Visual Cues

There are two types of guidance in visual analytics based on the types of the knowledge gap [9–11]. For situations in which the *target is unknown*, a user knows how to reach a certain target, but does not know what that target is. Whereas for situations in which the *path is unknown*, a user knows the target, but does not know how to reach it. We aim to cover both of the two types in our study by matching them with two of the most prominent visualization tasks: selection and navigation.

3.3.1 Selection Task. Selecting data items in a plot is one of the most common actions in visual data exploration [43], with the rectangular brush being probably the most popular interactive tool to do so. Yet, how many items should one select? This question stands at the heart of visual analytics approaches, such as the one presented by Angelini et al. [1], where too large a selection renders the resulting computation intractable due to combinatorial explosion, while too small a selection renders the result of that computation statistically insignificant. And even if one knew the optimal number to select, how could one judge if one was close to that number – in particular in the presence of overplotting and visual clutter? This scenario presents a case of an *unknown target*, where users are unaware of the specific target, but guidance can direct users. Following this idea, we built a prototype where the desired number of selected items would be hinted at by the background color of the brush (see Figure 1). When the number of selected items is closer to the desired number, the intensity of the background color would increase, and vice versa.

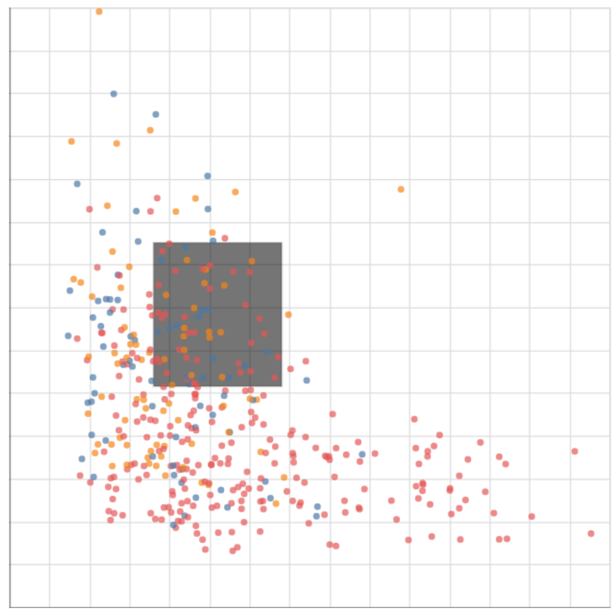

Figure 1: Example of the Prototype in the Selection Task

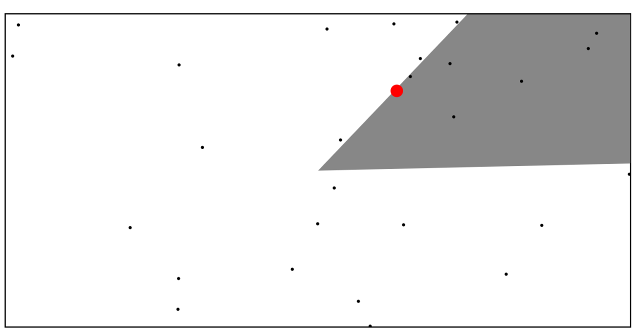

Figure 2: Example of the Prototype in the Navigation Task

3.3.2 Navigation Task. The most universal form of navigation is panning. Whether one peers over a map or scrolls through a document, panning is embedded in many routine tasks. Hence, we use panning for testing navigational guidance cues that are inspired by the look-ahead radar view [41]. In the look-ahead radar view, an arc will appear when users are panning a graph visualization in the direction in which off-screen items of interest lie. Similar to the design in the selection task, we are also using the color opacity of the arc to indicate the speed with which the current panning movement is closing in on the target (see Figure 2). The highest speed is achieved by moving directly towards the target, lower speeds result from moving in its general direction, and "negative speed" occurs when moving away from it. With increasing speed, the opacity of the background color also increases, and vice versa. The navigation task corresponds to the *path unknown* type of guidance where users know the target they are searching for – in our case a red dot – but as the target is out of sight, the users are unaware of the path to that red dot.

3.3.3 Measures against Learning Effect. To reduce the influence of potential learning effects, in both of the tasks, the visualizations and the type of cue were randomly generated for each trial. The data in the selection task were based on the cars dataset by J. C. Schlimmer obtained from the UCI Machine Learning Repository [16]. We randomly scaled each data point from 0.5 to 1.5 times of their original values for each trial. As such, the visualization will be different for each trial. This will prevent participants from adopting the same strategies for selecting data points. For the navigation task, the data points were randomly generated using a normal distribution function. μ was set 10 times of the viewport size, and σ was set to 150. The parameters were chosen to minimize the possibility that users might pan through empty areas.

Additionally, for the selection task, we selected three different selection targets (15, 60, or 240 points) to avoid participants learning a fixed strategy and to cover different scenarios. Similarly, we also selected three distances of the target point from the starting point (2400, 4000, or 6000 pixels) for the navigation task.

3.4 Vibrotactile Cues

As covered in Section 2, several parameters can be changed for vibrations: amplitude, frequency, waveforms, etc. Among them, amplitude is the most commonly used one in previous research due to its rather high expressiveness [14, 18, 20]. Furthermore, as we change the opacity of color for our visual cue, a parameter of vibration that is similar to the color opacity would make the different cues more comparable in our study. Thus, the change of amplitude, which is usually characterized as the intensity of vibration, was chosen as the main focus.

Through the SteelSeries GameSense SDK of the used mouse, we could set 5 different amplitudes for each vibration pattern. As suggested in Section 2, a non-linear profile usually provides better user performance and experience, and we therefore fitted the 5 different amplitudes to a polynomial curve in our prototype. Figure 3 shows an example of such curve for the increasing vibrotactile cues in the selection task with the goal of 240 targets based on a quadratic formula, where the number of selected points x and vibration amplitude y have a relationship of $x = 2.4 \times (y \div 10)^2$ before the highest point, then it has a reversed pattern after the highest point.

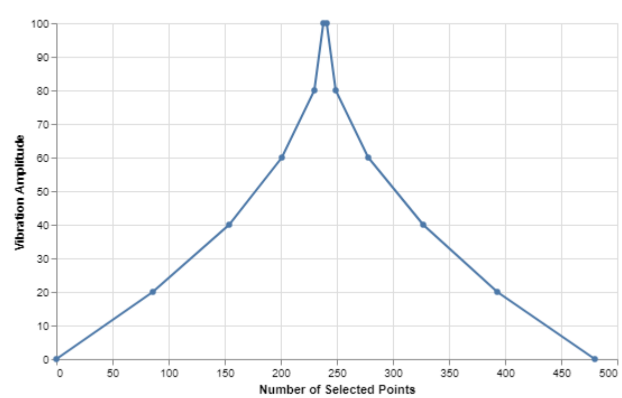

Figure 3: The Polynomial Curve for Increasing Vibrotactile Cues in Selection Task with the Goal of 240 Targets

During the development and pilot testing of the tasks, we also realized that even with a non-linear curve for the increment of vibration amplitude, it was hard to tell which vibration amplitude is the highest. Therefore, we also tested out a decreasing pattern with the same curve as the increasing one. A threshold pattern, where the vibration will only be triggered when hitting the right target/path, was added, as it provides a discrete and thus more accurate cue compared to continuous ones.

3.5 Type of Cues for Guidance

Combining the color cues and vibrotactile cues, seven types of cues were tested for guidance in our experiment. These were color, increasing vibration, decreasing vibration, threshold vibration and combinations of color with the three vibrations respectively.

3.5.1 Color (C). For color cues, we used a gray (#808080) visual cue with different opacity to guide a user's action. The opacity was generated using a polynomial curve. We used opacity instead of hue for the visual cue, as we found in the pilot study that it is more comparable to the amplitude parameter we use for the vibrotactile feedback. Participants in the pilot study stated that both opacity and amplitude denote the intensity of the corresponding feedback.

In the selection task, the color of the brushed background indicates how close the number of brushed points is to the target number. The closer the number of brushed points is to the target, the darker (higher opacity) the color becomes. In the navigation task, an arc following the panning direction indicates how fast the cursor is moving towards the target. The faster the cursor is moving towards the target, the darker its color.

While there are plenty of other visual cues one could use, every added cue significantly increases the number of possible combinations to test during our user study. As the focus of our study is on different vibrotactile cues, we only chose one visual cue based on the feedback we got in the pilot study.

3.5.2 Increasing Vibration (IV). For increasing vibration, a polynomial pattern was applied for the amplitude of vibration. In the selection task, the increasing vibration indicates how close the number of brushed points is to the target number. The closer the number of brushed points is to the target, the higher the amplitude. In the navigation task, the increasing vibration indicates how fast the cursor is moving towards the target. The faster the cursor is moving towards the target, the higher the amplitude.

3.5.3 Decreasing Vibration (DV). For decreasing vibration, a reversed polynomial pattern was applied for the amplitude of vibration. In the selection task, the decreasing vibration indicates how close the number of brushed points is to the target number. The closer the number of brushed points is to the target, the lower the amplitude. In the navigation task, the decreasing vibration indicates how fast the cursor is moving towards the target. The faster the cursor is moving towards the target, the lower the amplitude.

3.5.4 Threshold Vibration (TV). The third vibrotactile cue uses a threshold for triggering the vibration. In the selection task, the highest amplitude of vibrotactile feedback is provided only when participants select the target amount of points with an error margin of one. In the navigation task, the highest amplitude would be triggered when the cursor is moving at over 80% of the full speed towards the target. Otherwise, the vibration is not triggered. Again, the chosen threshold was informed by the feedback from our pilot studies.

3.5.5 Combinations of Color and Vibration. In addition to the individual visual and vibrotactile cues, three combinations of color and vibration were also tested. They were color combined with increasing vibration (C + IV), color combined with decreasing vibration (C + DV), and color combined with threshold vibration (C + TV).

3.6 Hypotheses

Our experiment was designed to evaluate the efficiency and experience of different visual and vibrotactile cues as guidance in data visualization tasks. Through it, we aim to gain a better understanding of how these cues work differently for target unknown and path unknown types of guidance. According to the research on the bandwidth of different sensory systems [34], eyes (visual feedback) have a higher bandwidth than skin (tactile feedback). Thus, we expected visual cues to outperform vibrotactile cues.

Hypothesis 1. *Color cue elicits better performance in time and accuracy than vibrotactile cues.*

Furthermore, we expect vibrotactile cues along with visual cues might outperform individual (singular) cues, as it utilizes two sensory channels of users simultaneously.

Hypothesis 2. *Combinations of both visual and vibrotactile cues elicit better performance in time and accuracy than visual or vibrotactile cues alone.*

3.7 Procedure

We established a set of protocols before we started the experiment. First, the participants were asked to fill out a demographic questionnaire regarding age, gender, handedness, the health of eyes, and experience with computer-based graphic user interfaces before they started the experiment. Before each task, we went through the task and the different types of visual and vibrotactile cues to make sure the participants understood the experiment clearly. Then they had a few minutes to familiarize themselves with the prototype. After each task, the participants were asked to fill in a short experience questionnaire and briefly discuss their overall experiences with different cues in that task. All participants were also provided the opportunity to take a break between the two tasks. At the end of the sessions, they were also asked to talk about how the cues worked differently in the two tasks.

3.7.1 Tasks. The experiment was done in a within-subjects design. Half of the participants started with the selection task, and the other half started with navigation. During each task, there were three rounds of tests that consisted of 21 different scenarios in each round. The order of the 21 scenarios was randomly generated for each round.

In the selection task, participants were asked to brush a certain number of points in a scatter plot. The number of points that the participants should select varied between 15, 60, and 240. When participants brushed through the points, seven different cues (visual cue, three vibrotactile cues, and three combinations of both visual and vibrotactile cues) were generated accordingly to guide their actions. As such, we had 21 (3 numbers × 7 cues) different combinations of the target number of points and cues. Both, the target number of points and the type of cues, were generated in a random order. Three rounds of these 21 scenarios – a total of 63 (21 scenarios × 3 rounds) trials – were performed by each participant.

In the navigation task, participants were asked to navigate through a scatter plot to find a specific point on the screen. The scatter plot was generated with a normal distribution function. The distance of the target point from the starting point could be 2400, 4000 or 6000 pixels, and the direction of the target point was generated randomly. Similar to the selection task, when participants panned to the target points, seven different cues (visual, three vibration, or three combinations of both visual and vibration) were generated accordingly to guide their action. As such, we had 21 (3 distances × 7 cues) different combinations of distances and cues. Both the distances and types of cues were generated in a random order. Three rounds of these 21 scenarios – a total of 63 (21 scenarios × 3 rounds) trials – were performed by each participant.

3.7.2 Variables. In this study, the independent variables are the type of cues and target number of points for the selection task or distance for the navigation task. However, the type of cues is the main focus of our study.

The dependent variables are as following: In the selection task, both time and accuracy were measured. Time was measured through the moment participants pushed down the mouse button to brush until the moment they released the button and finished brushing. Accuracy was measured by the deviation of the selected number of points from the target number of points. The time and accuracy was measured for the last attempt of brushing, if participants made several attempts in one trial. In the navigation task, only time was measured. Time was measured from the moment participants started to pan through the visualization until the moment they clicked on the target point.

3.7.3 Questionnaire. While the experiment would provide us with user performance data like time and accuracy, subjective evaluation can help us to interpret the performance data better. Thus, we decided to include a 7-point Likert scale in our study to investigate the experience of different cues in the tasks. A short question on their overall experience with different cues was included and participants were asked them to rate it as "extremely bad" to "extremely good" on the scale of 1 to 7.

3.7.4 Interview. A semi-structured interview was also conducted to help us explain the results from the performance and questionnaire data [17]. Seven questions focusing on the users' subjective experiences with each cue were proposed during the internal discussions and tested out with two participants during the pilot study. The questions revolved around participants' overall experience as well as the comparison of different cues. Such as, "did you notice anything unexpected or interesting?", "which feedback stood out the most for you?", and "how do you feel the feedback work differently for you in the two tasks?".

4 RESULTS

The user study took around 45 minutes for each participant. Typical time spent was around 10 minutes for the selection task, and around 20 minutes for the navigation task. Among the 14 participants, 12 of them finished both tasks for 63 trials. Two participants finished all the 63 trials for the selection task, but only finished 42 trials for the navigation task due to fatigue. However, as they only skipped the last round of trials, they still went through the same number of trials for each type of cue and scenario. Therefore, this is not impacting the results they had obtained up to that point. In total, 882 trials of the selection task (14 participants × 3 target numbers × 7 cues × 3 rounds of trials) and 840 trials of the navigation task were completed.

The results of our user study were automatically captured through logged timestamps as well as positions of each click with the corresponding feedback cue and scenario. The deviation from target number of points was recorded additionally for the selection task. From these raw data, we computed task durations and average selection accuracies per trial.

4.1 Selection Task

For the selection task, we calculated the means of performance time and accuracy for each participant in each type of cue and target number, then reported their mean and standard deviation.

4.1.1 Time and Error. For time, cues with only vibration performed the worst, while color with threshold vibration cue outperformed the color cue. For accuracy, color with threshold vibration cue had the highest accuracy, followed by threshold vibration individually. Accuracy for color, color with increasing vibration, color with decreasing vibration and decreasing vibration were similar to each other. Increasing vibration individually had the worst performance in both time and accuracy. Detailed results are presented in Table 2 and their boxplots are given in Figures 4 and 5.

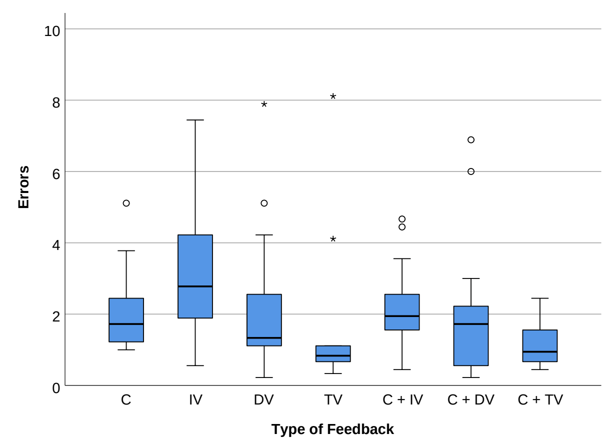

Figure 4: Boxplot of Errors in the Selection Task for Different Cues. Circles represent outliers (between 1.5 and 3 times the interquartile range) and asterisks represent the extremes (more than 3 times the interquartile range). The same applies to the following figures.

As some of the results deviate from the normal distribution, a Friedman test adjusted by the Bonferroni correction for multiple tests was done to validate the difference between the results from different cues. For both error and time, the differences between the 7 cues are significant. However, the significance differs pairwise. For selection time, we summarize the following insights:

[ST1] C > {IV, TV} ($p < 0.01$)
Color had better (shorter) performance time than increasing vibration and threshold vibration.

[ST2] C + IV > IV ($p < 0.01$)
Color combined with increasing vibration had better (shorter) performance time than increasing vibration.

[ST3] C + TV > IV ($p < 0.01$)
Color combined with threshold vibration had better (shorter) performance time than increasing vibration.

For selection accuracy, we summarize the following insights:

[SA1] C + TV > IV ($p < 0.01$)
Color combined with threshold vibration was better (less error-prone) than increasing vibration.

[SA2] TV > IV ($p < 0.05$)
Threshold vibration was better (less error-prone) than increasing vibration.

[SA3] C + DV > IV ($p < 0.05$)
Color combined with decreasing vibration was better (less error-prone) than increasing vibration.

For the three tested scenarios (15, 60, and 240 targets), the time and number of errors both increased with more targets for each type of cue. No particular irregularities were observed from the results. Moreover, no significant learning effect was observed.

4.1.2 Questionnaires. A Friedman test adjusted by the Bonferroni correction for multiple tests was also done on the results from the questionnaire. The significant insights are summarized as following:

[SQ1] C + DV > {IV, TV} ($p < 0.05$)
Decreasing vibration with color was considered better than increasing vibration or threshold vibration individually.

The distribution of the questionnaire results is presented in Figure 6.

4.1.3 Interviews. These results were also reflected and further explained in our post-study interviews. Three participants (P1, P4, and P13) mentioned that the threshold vibration provided more sense of accuracy. Adding color cues to it helped them to find the rough area of the right number of points, while the threshold vibration allowed them to pinpoint the exact number of points to select. This gave them "a sense of security" (P1). Finally, for the increasing and decreasing vibration cues, some participants commented that decreasing vibration was better as "it is hard to tell when it is the highest vibration, but you know it when it stops vibrating" (P6).

4.1.4 Summary. Results from the selection task were mostly consistent with our hypotheses – overall color outperformed vibrotactile cues [ST1], while the appropriate combination of visual and vibrotactile cues, in this case, color and threshold vibration, outperformed color alone in accuracy ($p = 0.09$). Moreover, the performance in all combinations of visual and vibrotactile cues were improved compared to individual vibrotactile cues, although the significance varies [ST2, ST3, SA1, SA3, SQ1].

4.2 Navigation Task

For the navigation task, we calculated the means of performance time for each participant in each type of cue and distance, then reported their mean and standard deviation.

4.2.1 Time. Among the 7 different cues, increasing vibration individually performed the best, followed by color cue. For the combinations of color and vibration cues, results for both color with increasing vibration and with decreasing vibration was worse than their corresponding individual vibration cues, but color with threshold vibration outperformed the corresponding individual vibration cue. Detailed results are presented in Table 3. Their boxplot is shown in Figure 7. As done for the selection task, a Friedman test was also done for the performance in the navigation task. The only significant result before correction for multiple tests is:

[NT1] IV > TV ($p < 0.05$)
Users performed faster with increasing vibration than with threshold vibration.

However, there is no significant result after the Bonferroni correction for multiple tests.

For the three tested scenarios (2400, 4000 and 6000 pixels from the starting point), overall the completion time also increased with the target point further away from the starting point. Each participant went through three rounds of tests, and the average completion time was generally shorter in the later rounds.

4.2.2 Questionnaires. A Friedman test adjusted by the Bonferroni correction for multiple tests was also done on the results of the questionnaire:

[NQ1] {C + IV, C + TV} > DV ($p < 0.05$)
Increasing vibration with color and threshold vibration with color cues were considered better than decreasing vibration.

The distribution of the questionnaire results is presented in Figure 8.

4.2.3 Interviews. There were also some interesting insights from the post-study interviews of the navigation task. First, although most participants preferred the combinations of color and vibration cues, three participants (P2, P8, and P12) mentioned that the individual vibration cues were better than the combinations. In particular, one participant (P2) said that "you will worry more when the color is getting less dark, then you will panic and start to change the direction", but with the vibration "you will know right away if you are on the right direction". Second, the decreasing vibration was heavily criticized by several participants because "it vibrates all the time". However, on the metaphors of different vibration, one participant (P14) mentioned that the decreasing vibration might be helpful. "The vibration is constant, and you are searching for 'nothing'. It feels more game-like for me." They further explained that the action of "searching for nothing" means they were looking for the direction of "no vibration", which made them more at ease when they were on the right track. This participant subsequently argued that such metaphor feels more consistent, as one is rewarded with a more relaxed, calm feedback when something is done correctly.

Finally, for the threshold vibration cue, several participants mentioned that it did not work for them because it is too hard to trigger, and they had to search for it for a long time, while adding the color cue to it helped to find the rough direction first (P1, P9, and P12).

Table 2: Mean and Standard Deviation for the Number of Errors and Completion Time in the Selection Task

	C	IV	DV	TV	C + IV	C + DV	C + TV
AVG Number of Errors	2.08	3.30	2.28	1.54	2.22	2.03	1.10
SD of Errors	*1.16*	*2.05*	*2.13*	*2.11*	*1.24*	*2.06*	*0.62*
AVG Completion Time	6.10s	8.92s	8.66s	8.76s	6.69s	6.76s	5.68s
SD of Completion Time	*3.46s*	*3.79s*	*4.62s*	*3.34s*	*4.23s*	*2.36s*	*1.55s*

Table 3: Mean and Standard Deviation for Completion Time in the Navigation Task

	C	IV	DV	TV	C + IV	C + DV	C + TV
AVG Completion Time	14.93s	13.68s	15.33s	16.88s	15.06s	16.16s	14.95s
SD of Completion Time	*5.76s*	*5.88s*	*4.06s*	*5.77s*	*4.43s*	*4.73s*	*4.02s*

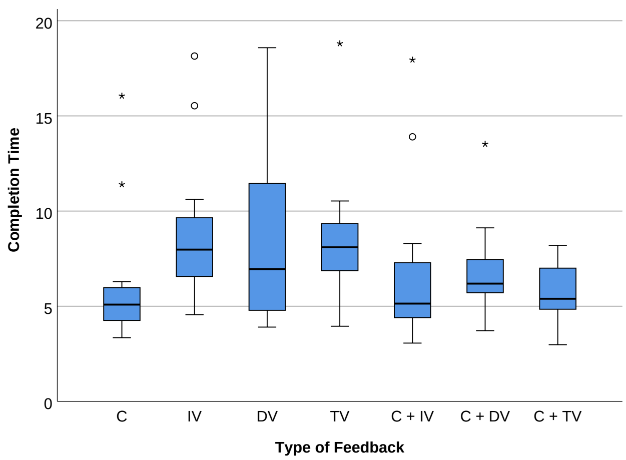

Figure 5: Boxplot of Completion Time in the Selection Task for Different Types of Feedback.

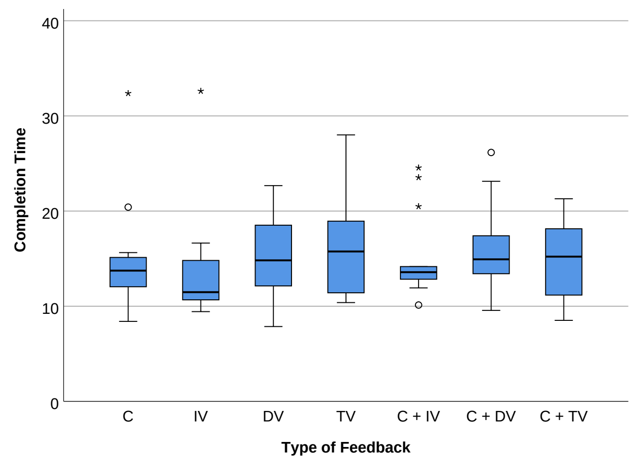

Figure 7: Boxplot of Completion Time in the Navigation Task for Different Types of Feedback.

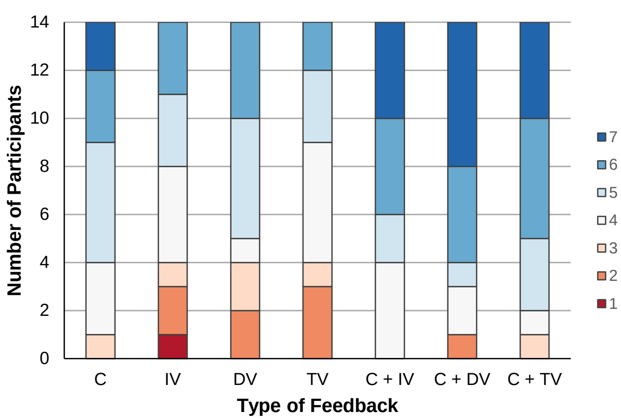

Figure 6: Distribution of Subjective Ratings in the Selection Task for Different Types of Feedback.

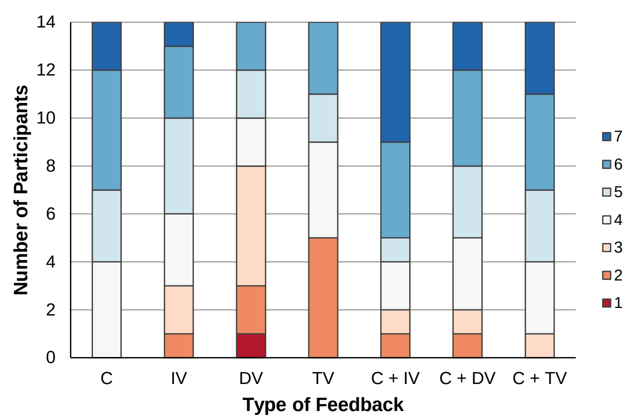

Figure 8: Distribution of Subjective Ratings in the Navigation Task for Different Types of Feedback.

4.2.4 Summary. In the navigation task, the results were mostly inconsistent with our hypotheses. Among vibration-only cues, only the individual increasing vibration cue had slightly better performance than the color cue. For both increasing and decreasing vibration cues, the performance deteriorated when they were combined with color cues, while the performance of threshold vibration was improved combined with color. However, these differences were not statistically significant, which might be due to the relatively small sample size and overall long performance time.

5 DISCUSSION

From our results, we conclude some meaningful insights for using vibrotactile guidance in data visualization.

First, the same cues can work differently under different guidance scenarios. For the selection task under the *target unknown* scenario, the threshold vibration cue facilitated better performance, higher accuracy in particular [SA2], than increasing vibration, while for the navigation task under the *path unknown* scenario, the threshold vibration cue had the worst performance among all cues, and is particularly worse than increasing vibration [NT1]. The results from the post-study interview suggested that it might be due to the fact that the threshold vibration cue is better suited to communicate discrete guidance such as the ideal number of selected points and unable to effectively represent continuous information like path and speed.

Second, the visual cue alone in some cases significantly outperformed [ST1] vibrotactile cues, while a combination of visual and vibrotactile cues for guidance might not necessarily improve the user performance compared to visual or vibrotactile cues alone, potentially under more mentally taxing tasks. In the selection tasks, both time and accuracy were improved when vibration cues were combined with color, especially the performance time for increasing vibration [ST2]. However, in the navigation task, none of the user performances for combinations of color and vibrations was significantly better than their corresponding vibration cues alone or color cues, and some even deteriorated, although not significantly. Indeed, some participants reported the navigation task was "harder" than the selection task, and the combination of both cues can be confusing and distracting for some of the participants.

Finally, user experience and user performance might differ for the same guidance cues. specially in the navigation task, user performance was the best with increasing vibrotactile cues (see Table 3 and [NT1]). However, the user experience rating was not the highest for increasing vibration (see Figure 8). This suggests that user experience should be considered in addition to user performance when designing vibrotactile guidance.

6 LIMITATIONS AND FUTURE WORK

After discussing on the design of vibrotactile guidance and our experiment on vibrotactile cues, there is still room for improvements and extensions. Here we identified some possible areas of research moving forward.

First, contextual user studies will provide additional insights. The tested tasks in our study were isolated from the context of usage. The intention was to exclude any other variables and focus on the user performance in these tested tasks. However, implementing them in an existing visual analytics system could provide new understanding of how vibrotactile cues work and should be designed to work in combination with complex user interfaces and as part of full-fledged analytic workflows.

Second, more vibrotactile patterns in user guidance can be further explored. In our study, three different patterns were prioritized due to the user study design. With the seven different combinations of cues and two tasks, the user study already ran about 45 minutes for each participant. We are also aware that the hardware in our user study limited the options we have, and might have caused some bias in the results due to its limitation of five discrete amplitude levels. Therefore, in future work, vibrotactile cues with different parameters, hardware as well as additional visual cues can be further explored and compared to help us understand how each pattern of vibrotactile cue would match which scenario and task, as well as how they should be used in accordance with different visual cues.

Moreover, standards for subjective evaluation metrics of vibrotactile guidance can be further investigated. While user performance can be easily evaluated with time and error, we found that traditional subjective evaluation metrics like the User Experience Questionnaire (UEQ) or System Usability Scale (SUS) did not align well with the comparison of different cues for guidance in our pilot study. This might be due to the fact that these questionnaires are meant to evaluate the overall experience and usability of an entire system instead of individual cues. As a result, the characteristics used by them are rather hard to ascribe to a single cue like vibration – e.g., "organized vs. cluttered" or "friendly vs. unfriendly" from the UEQ [38], or the statement "I thought there was too much inconsistency in the system" from the SUS [3]. A deeper investigation on how vibrotactile guidance can be evaluated subjectively to gain more insights on their user experience and usability constitutes thus a formidable research challenge for future work.

7 CONCLUSIONS

To facilitate user interactions in data visualization, especially under visually overloaded scenarios, and provide a more immersive experience, non-visual guidance offers a largely unexplored design option. In this paper, we opened up the potential design space for one promising non-visual form of guidance – vibrotactile guidance – and reported on an experiment with different vibrotactile cues under two guidance scenarios. Our results suggest that while certain vibrotactile cues and their combination with visual cues outperformed visual cues alone, some other combinations can actually deteriorate user performance. Therefore, extra caution on aligning the cues with corresponding tasks and scenarios should be taken. Furthermore, a recurring theme from the observations and interview was the distraction that continuous vibrotactile feedback introduces, and how it might be stressing in combination with more mentally demanding tasks and confusing when used with visual cues. These observations suggest that vibrotactile cues are probably best suited to provide guidance at particular instances (e.g., a short pulse at the threshold) instead of using them over periods of time.

The experimental prototypes, anonymized data as well as devices considered in the vibrotactile design space are available at https://vis-au.github.io/vibrotactile/

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