Using Variable Movement Resistance Sliders for Remote Discrete Input

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ABSTRACT
Despite the proliferation of screens in everyday environments, providing values to remote displays for exploring complex data sets is still challenging. Enhanced input for remote screens can increase their utility and enable the construction of rich data-driven environments. Here, we investigate the opportunities provided by a variable movement resistance slider (VMRS), based on a motorized slide potentiometer. These devices are often used in professional soundboards as an effective way to provide discrete input. We designed, built and evaluated a remote input device using a VMRS that facilitates choosing a number on a discrete scale. By comparing our prototype to a traditional slide potentiometer and a software slider, we determined that for conditions where users are not looking at the slider, VMRS can offer significantly better performance and accuracy. Our findings contribute to the understanding of discrete input and enable building new interaction scenarios for large display environments.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords
Slider; haptic feedback; input methods.

INTRODUCTION
Providing input for displays that are in sight, but not in arm-reach is a common task. Users often need to control the content presented on public large or wall-sized displays in a variety of contexts ranging from the comfort of the home to exploring exhibits in a museum. Currently available technologies provide limited support for those tasks. Traditional remote controls offer an excessive amount of buttons. Using smart phones and tablets, while versatile, offers no haptic feedback and requires the user to focus on the smaller device visually. Unless the user is highly proficient in manipulating the controls, the process is often cumbersome. The task is especially difficult when a user needs to provide accurate and fast input on a discrete scale.

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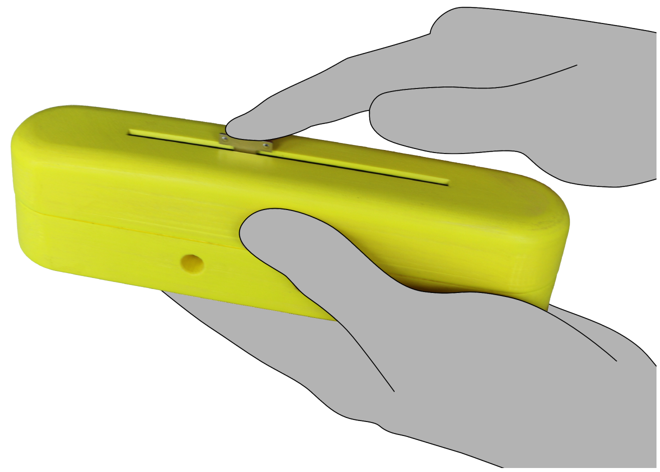


Figure 1. A variable movement resistance slider (VMRS) device with a 3D-printed case.

When working in multi screen or large-display environments, users often focus on the content of the screen or conduct visual search [19]. This expends the limited amount of attention that can be devoted to input devices. Most past approaches utilized input methods which either require excessive tracking [24] or require the user to look at the device [3]. Inspired by early attempts to create seamless interfaces [16], the iStuff project presented a toolkit to help overcome perceptual and motor limitations, offering physical props such as iSlider, iKnob, and iButton [2]. In line with early work on haptic feedback [21], we investigate how to design devices with physical properties that require no visual attention. Tangible user interfaces could offer a solution. However, as they are based on coinciding action-perception spaces requiring direct contact with the screen [17] they are infeasible for providing remote input. On the other hand, haptic feedback was shown to be effective for interacting with remote objects without looking at the input device [18]. Consequently, we are investigating how haptic feedback can be used to improve remote discrete input.

In this paper, we propose readdressing the issue of remote discrete input by designing an input device that employs a variable movement resistance slider (VMRS) to provide haptic feedback. We envision providing input to remote screens while focusing on the content. Through haptic feedback, we aim to reduce the need for looking at the input device and provide a more seamless experience of interacting with remote screens. We then conduct a study to understand how users can provide input with haptic feedback. In particular, we investigate the effects of providing input while the users are not looking at the input device.

Haptic feedback can support exploring large visual data sets [6] or understanding system dynamics [29]. In both cases, users might have a large number of parameters to adjust. While focusing on input parameters, users might lose the focus on the resulting visualization.

This paper contributes the following: (1) The design and implementation of a VMRS device for discrete remote input; (2) a user experiment comparing the device with `variable movement resistance sliding` (`VMR`), with only `tangible sliding` (`tang`), and a software slider implemented on an Android tablet using `touch sliding` (`touch`); (3) implications for the design of haptic feedback for discrete remote input.

RELATED WORK

The concept of VMRS is based on previous work about tangible interaction and slider interfaces. We readdress these findings to design a new input device for interaction in visually rich environments.

Tangible Input

MacLean [20] investigated when and how haptic feedback can be used to best effect in interactive applications. Fitzmaurice and Buxton [9] compared graspable to non-graspable user interfaces (UIs) and demonstrated that graspable UIs can increase user performance. Also, a comparison between direct touch and graspable UIs revealed that users perform better when using a graspable UI [33]. Based on these findings, there is a large body of work about touch interaction in comparison or connection to graspable controls. Weiss et al. [38] designed a series of tangible controls, such as knobs, sliders, and keyboards, made from silicone for interaction on an interactive tabletop. In a lab study, the authors showed that the tangible controls allowed faster data input with fewer overshoots than when using the touch interfaces. Furthermore, tangible sliders required fewer eye fixations in comparison to direct touch manipulation [32]. Thus, tangible sliders appear to be suitable for single-value input.

Other work has shown that tangible interaction positively affects recall and task completion time (TCT). Hence, Müller et al. [25] argue for using tangibles when interacting with large and complex systems, such as in control rooms. Voelker et al. [35] compared tangible knobs to direct touch for rotary input. In the comparison, the authors distinguish between eyes-on and eyes-free interaction. The results presented by Voelker et al. [35], indicate that graspable interfaces are in particular well suited for situations where the user is not able to look at the controls.

Recent studies have shown that the motivation for eyes-free interaction on mobile devices can address environmental, social, device feature, and personal motivational factors [41]. Interaction without direct mapping to the input data and eye-free interaction in mobile and fixed settings motivates us to explore haptic feedback for slider input.

Remote Input

In contrast to most previous work, Jansen et al. [17] utilized the positive effects of graspable UIs for interacting with content on wall-sized displays, instead of interacting with content on interactive tabletops. Greenberg and Fitchett [13] proposed Phidgets; a way to package input and output devices while hiding implementation and construction details. Their concept exposed functionality through a well-defined API and offered an on-screen interactive interface for displaying and controlling device state. While the use of haptic display to overcome the limited size of mobile displays is well understood [4, 15], here we typically study the use of haptic for remote input on large, vertical displays. These are displays located in the same room, but often too far away to be easily reached and touched.

We note that recent works such as Deep Shot [5] and Snap-to-it [7] studied remote control using mobile devices; remote control there was simply a connection mechanism followed by application sharing from a remote display to the handheld one. Here, we study remote input; the phase that follows after connecting to the display.

Our work is inspired by Panelrama [40] and Conductor [14] which presented cross-device interaction frameworks with a rich set of features. Panelrama [40] offered easy specification of cross-device web applications and offered a validated framework for developing cross-device applications. Conductor [14] introduced interaction methods for cross device interaction between smartphone- and tablet-sized devices located next to each other at a table. However, these works did not study the specific issues of remote input on displays nor the use of VMRS-like input devices.

Sliders for Data Input

Sliders are widely used in software applications. Ahlberg et al. [1] showed that graphical user interfaces (GUIs) using sliders for database queries are more efficient than text based queries. Software sliders are also often used in online surveys as visual analog scales [11]. he visual appearance of sliders can influence the input provided by the users [23]. We assume that not only visual feedback influences user's behavior but also haptic feedback can have an impact on the input. With this paper, we provide a starting point for comparing value selection on physical and software sliders with different feedback modalities.

The affordances of hardware sliders inspired Weichel et al. [37] to build calipers for designing physical objects in a virtual environment. Inspired by music mixing tables, various interaction concepts using motorized faders have been presented. Gabriel et al. [12] explored applications for music performance. Using the same device concept, Shahrokni et al. [29] proposed to use motorized sliders for teaching system dynamics. This scenario pointed out the potential of motorized sliders to communicate data through different modalities. This might also support interaction with complex financial data [27]. In a qualitative study, Crider et al. [6] indicated that motorized sliders could help users keep focus while exploring 3D-visualizations. However, none of these concepts provided a detailed, quantitative analysis of user performance using motorized sliders for input. Furthermore, all previous designs that used motorized sliders addressed pseudo-continuous input (i.e. users would input an analog value, and it would be later digitized). Our work is interestingly different as it addresses discrete input, which is often needed for everyday devices.

Haptic Feedback as Output

Visual information overload can be a threat to the interpretation of displays presenting large data sets. In such cases, haptic feedback can be a means of information transmission [31]. To provide a perception of texture, Wolf and Bäder [39] proposed using electrotactile stimuli. In contrast, Marquardt et al. [22] designed a puck for exploring data haptically on tabletops. The puck provided feedback through pressure against the user's finger, and through adjusting the sliding resistance on the surface. Snibbe and MacLean [30] built a rotary knob for controlling multimedia application. To provide additional feedback, the authors explore different haptic feedback patterns.

Parkinson et al. [26] used motorized faders to provide haptic feedback to explore sound waves with an additional sense. In particular, visually impaired users get a novel representation of sound waves. Follmer et al. [10] used a combination of visual projection with a 2.5D shape-changing display. Here, we study input tasks requiring the input of discrete data, such as integer values, enumerators (e.g. day or month), or other accurate values. The haptic representation of such values is typically a detent; a Dirac-like (i.e. double cone-shaped) feedback felt by the user when passing the slider over one of the multiple equidistant positions, giving discrete input. Such detents were originally suggested to provide the user with physical feedback during media browsing. While Ullmer and Ishii [34] suggested detents to support browsing, in this work, we propose detents to support accurate input when visual feedback is not available.

While mobile haptic support for input on handheld and desktop proximal displays is well understood, here we study haptic support of distal input on large vertical displays. Our work is oriented to the needs of data-intensive visualization, and it targets a research gap less charted than mobile haptics.

DESIGN

In our search for new effective ways to provide discrete remote input, we were mainly inspired by two past designs. Firstly, we saw the effectiveness of SLAP tangible widgets [38] interacting with large screens [17]. Secondly, we noticed that professional soundboards, used in studios or during concerts are often manipulated by their operators without visual attention. Professionals focus on the task content (e.g. sound engineers while manipulating sliders) and use present that require the board to adjust slider positions with motors. Consequently, the current state of a particular setting can be perceived by simply touching to feel the position of the slider. However, that usage scenario is limited to highly trained users. Consequently, we decided to limit our inquiry to a single slider.

Designing for one-dimensional Input

The next question that we faced was how to implement haptic feedback in a way that would allow even novice users to benefit from the properties of a physical slider fully. Again, we turned our attention to devices used in soundboards. While these usually employ motors to reposition the slider knob, the same motor can also be used to create resistance or decrease friction while moving the slider. After an initial prototyping phase and informal testing, we decided to explore `VMR` further.

Given that one can vary the movement resistance, the question is how and when to do that. Inspired by Matejka et al. [23], we noticed that adding notches to a slider scale may affect input. We inquired how these notches could be manifested in haptic feedback. After several attempts, we determined that a sinusoid function with roots where the notches are located provided the most pleasant experience (as evidenced in our informal studies).

We still needed to determine how many notches our VMRS could accommodate. Here, we were constrained by the hardware — all commercially available motorised slide potentiometers have slideway no longer than $10\,cm$. Hence, we had $10\,cm$ of slideway available. We chose to include ten points on our scale. This implies that the notches are separated by $1\,cm$, and the immediate vicinity of the notch is $0.5\,cm$ on each side of the notch. Consequently, we endeavored to design the feedback so that the user could feel they were within the input space of one of the discrete values when within $0.5\,cm$ from the target. We deemed this value to be reasonable as the perceptual threshold for two-point active touch (i.e. the smallest distance between two points that the users can perceive, as two distinct points) can be as high as $0.34\,cm$ [8].

Feedback design

Finally, we had to design the `variable movement resistance sliding` (`VMR`) feedback so that it facilitated providing discrete values. Figure 2 depicts our design of the resistance feedback. When the user is sliding away from a discrete point, the slider is pushing the finger back to the previous point. However, once the slider notch reaches half the distance to the next point, a critical distance is reached (resistance is pushing with the maximum force), and the slider starts pushing the finger towards the next discrete point. The resistance increases and then decreases along a sinusoidal curve. The discrete values are regions where movement resistance is zero. Our aim was to create an illusion of the discrete notches being present under the user's finger while sliding.

Implementation

For implementing a VMRS, we used a motorized slide potentiometer, often used in professional soundboards. The slide potentiometer we used is manufactured by Bourns (PSM01-081A-103B2) and has a $10\,cm$ travel length. We connected this potentiometer to an Arduino Micro (see Figure 2). The Arduino positions the slider knob by actuating the motor of the slide potentiometer. Furthermore, the Arduino reads the resistance of the slide potentiometer and the capacity measured at the slider knob. On the $10\,cm$ slideway, we can distinguish between 1024 slider knob positions.

The measurement of the capacity at the slider knob allows reacting on touch events triggered by the user. The program running on the Arduino can cause slider actions on its own. Furthermore, the program can send measured slider knob positions to a connected computer. For providing the connection

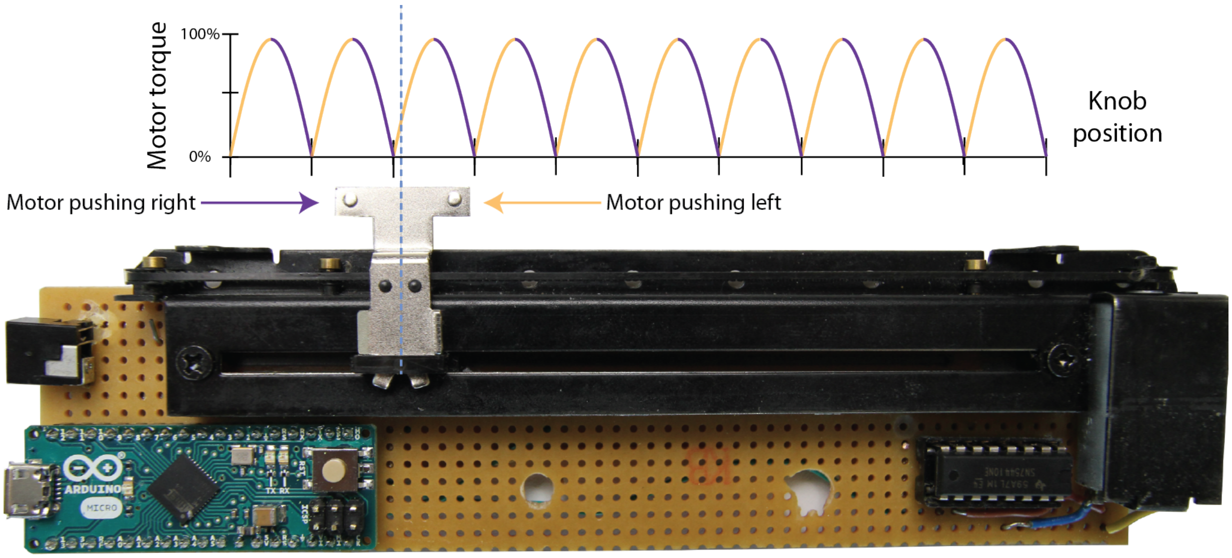


Figure 2. The design of the variable movement resistance in our device. The purple curve depicts the feedback when the user is sliding right; the orange one shows feedback for sliding left.

between the Arduino and a computer, we implemented a USB and a Bluetooth interface.

The motorized slide potentiometer and the Arduino Micro can be powered either by a battery or over a wired connection. Using Bluetooth for communication and a battery for providing power enables the user to hold the device in one hand, move around freely and manipulate the input value with the other hand. For the lab study presented in this paper, we used the wired connection.

We implemented `VMR` by adjusting the torque and direction of the motor while the user moved the slider knob. The combination of the motorized slide potentiometer and the Arduino controller allows bidirectional feedback. The motor can push the slider knob in the direction of the knob movement, and thus the user feels that the slider has less resistance. When the motor pushes the slider knob in the opposite direction of the movement direction, the user perceives more resistance (see Figure 2). By using a combination of the two techniques, we create an impression of a pattern of the discrete value notches.

For interacting with the VMRS, we designed and 3D-printed a case, see Figure 1. This makes handling the device comfortable and safe. The dimensions of the VMRS are determined by the measures of the technical implementation. The VMRS is 19.5 cm long, 5.2 cm high and 4.0 cm wide.

USER STUDY

With the lab study presented in this paper, we are starting to build an understanding of how VMRS influences user behavior. This understanding is important for designing applications using motorized sliders. In this lab study, we focus on the following four hypotheses:

H1: Employing `VMR` will not result in increased task completion time (TCT) compared to the other input methods.

H2: Using a `VMR` will not result in inferior accuracy compared to the other input methods when users are provided with visual feedback.

H3: A `VMR` will offer superior accuracy to the other input methods when users are not looking at the device.

H4: A `VMR` will increase the perceived workload over other input methods when users are able to look at the device.

Previous research [35] showed that tangible controls could lead to shorter TCTs. However, the influence of resistance feedback on TCT and accuracy has not yet been explored. The additional feedback might help to select the correct values. The resistance feedback interrupts the fluent sliding on purpose and has to be processed by the user. On the other hand, the additional resistance feedback could enable users to perform large value changes quickly, and focus only on precise value selection. Hence, we expect that the positive and negative effects on TCT balance each other (**H1**). We assume that the influence of resistance feedback is low in contrast to visual feedback. Hence, we hypothesize that resistance feedback does not influence accuracy when users are able to observe the state of the input device (**H2**). However, if users do not focus on the visual state of the input device, resistance feedback is supportive (**H3**). When users are able to observe the state of the input device, resistance feedback is additional information that has to be processed by the user. Hence, we assume that resistance feedback increases the perceived mental effort (**H4**).

Study Design

To compare data input using a VMRS, with and without `variable movement resistance sliding` (`VMR`) as feedback and a software slider displayed on a touch display, we conducted a lab study. We recruited 17 participants (6 female) aged between 21 and 39 ($M = 26.88$, $SD = 5.17$). For the study, we used a repeated measures design; hence every participant performed 32 trials for all five conditions.

(a) Selecting a target value using the VMRS with `VF`.

(b) Selecting a target value on the VMRS covered by a cardboard box (`NVF`).

(c) Selecting a target value on the tablet with `VF`.

Figure 3. Participant is performing trails under different conditions.

Task

To verify our four hypotheses, we asked the participants of the user study to select particular target values indicated by a marker on the visualized slider on the remote display. On this display, we showed, in all conditions, a representation of the slider and the target position indicated by a green arrow below the slider representation. We assumed no differences between moving the slider knob to the left or right-hand side. Hence every trial started with the slider at the far left position. This enabled longer sliding distances than a centered starting position. To select a value, participants had to release the slider knob. In every condition, participants were asked to enter 32 values. The target values were equally distributed on the slider scale. We excluded minimal and maximal values because past studies [23] have shown that sliders have an inherent affordance for providing input at the ends of the scale and these inputs should be excluded from the analysis. We used the same target values in all conditions to get comparable results but randomized the order of the targets for every condition to avoid learning effects.

Conditions

In the user study, we compared discrete data input on a 10-point scale in five modalities. As independent variables, we varied the VISUALFEEDBACK and HAPTICFEEDBACK.

The independent variable VISUALFEEDBACK had two levels, `visual feedback` (`VF`) and `no visual feedback` (`NVF`). The independent variable HAPTICFEEDBACK had three levels, `variable movement resistance sliding` (`VMR`), `tangible sliding` (`tang`), and `touch sliding` (`touch`). To provide the different levels of HAPTICFEEDBACK, we used the VMRS device and an Android tablet with touch screen. When using the VMRS, we provided either `VMR` or `tangible sliding` as HAPTICFEEDBACK. In the `VMR` or `tangible sliding` conditions, participants could touch the slider knob and the slider. Additionally, the `VMR` condition used resistance feedback while sliding. The HAPTICFEEDBACK on the Android tablet is called `touch sliding` as touching the screen surface was the only present haptic feedback.

In the conditions with `visual feedback` (`VF`), the current position of the slider knob was visible on the input device and the remote display. On the tablet, we implemented this by displaying a software slider with a knob (see Figure 3c). For the VMRS, the physical slider knob indicated the current position of the slider (see Figure 3a), and the remote display also showed the current position of the slider. In conditions with `no visual feedback` (`NVF`), the position of the slider knob was hidden on the control as well as on the remote display. In these conditions, we covered the VMRS with a cardboard box (see Figure 3b). The box was large enough to avoid restricting user movements.

Using two independent variables with two and three levels would result in six conditions. During pre-testing, we experimented with the `touch sliding–no visual feedback` condition by displaying only a black screen on the tablet. However, it was excessively difficult to enter data without any indication of the state of the control. Selecting values without any feedback, besides touching the display surface, is not feasible. Hence, we removed the condition where the tablet would be used with `no visual feedback`. In total, this resulted in five conditions, see Table 1.

Measures

We measured the following dependent variables in our study:

Task completion time (TCT) [*seconds*]. The time between the moment the participant was presented with the target and when they stopped moving the slider. The task is considered completed once the user moves their finger away from the slider for more than one second.

Absolute error [*millimetres*]. The distance between the position of the slider provided as input and the target position. The distance is only counted as an error when the distance is more than $2\,mm$. We logged and analyzed absolute error values as they may provide insights on the limits of the granularity of discrete input possible.

Condition	Device	VISUALFEEDBACK	HAPTICFEEDBACK
1	VMRS	VF	VMR
2	VMRS	NVF	VMR
3	VMRS	VF	tang
4	VMRS	NVF	tang
5	Tablet	VF	touch
6	Tablet	NVF	touch

Table 1. Conceptually possible conditions in our study. The grey row was removed due to the physical limitations of the tablet.

Error rate (ER) [%]. The relative number of trials which resulted in an error i.e. where the provided input differed from the target position by more than $2\,mm$.

Backtracking distance (BD) [*millimetres*]. The total slider distance covered after the initial left-to-right slide i.e. the distance of the extra movement used for additional positioning.

Subjective Mental Effort Question (SMEQ) result. A measure of mental effort proposed by Zijlstra [42]. While all other measures were recorded per trial, we employed the SMEQ after all trials in every condition. We decided to apply this scale as it offers a quick 'snapshot' assessment of mental effort that did not interfere with the course of the study [28].

Apparatus

For conducting the user study, we asked every participant to sit in front of a table. On the table, we placed the input device according to the condition. We did not restrict the participants in picking up the device. Thus, we allowed the users to assume the most comfortable position as past work provides no insights on optimal ways to hold a slider. Depending on the condition either the VMRS or a Samsung Galaxy Tab S 8.4 Android tablet was used. The VMRS device was used in the `tangible sliding` and `VMR` conditions. The `tangible sliding` was implemented by deactivating the slider motor. At a distance of $1.5\,m$, we placed a $50''$ remote display. This display presented all instructions and target positions. Furthermore, the current state of the slider was visualized in the `visual feedback` conditions. All content presented on the remote display was implemented as a web application, running on a Python web server. This web server also handled the communication with the input devices. The slider interface on the Android tablet was implemented as a native Android App. To generate comparable results, the slider is shown on the tablet also had a slideway of $10\,cm$ with 1024 steps like the VMRS which were sent on change for comparable accuracy. For analyzing a participant behavior, the server application continuously logged the position of the slider knob as well as start and end times of every trial. To rate the perceived mental effort, we handed out printed SMEQ scales.

Procedure

After welcoming every participant, we asked them to read the consent form and agree to the terms. Afterward, we invited them to take a seat at the apparatus and to fill in a demographics sheet. As soon as a participant was ready to start the actual study task, the first assigned condition was displayed. In the preparation phase of every condition, the participants could familiarize themselves with the input method and the provided feedback through performing uncounted test trails. They were instructed to focus on accuracy. As soon as they felt comfortable with the condition, the set of 32 trails started. After performing all trials of one condition, we asked them to rate the mental effort on SMEQ scale [42]. We alternated the order of the input devices (VMRS and Tablet) and randomized the provided HapticFeedback and VisualFeedback. At the end of the study, every participant received 5 EUR as compensation for participating in the study.

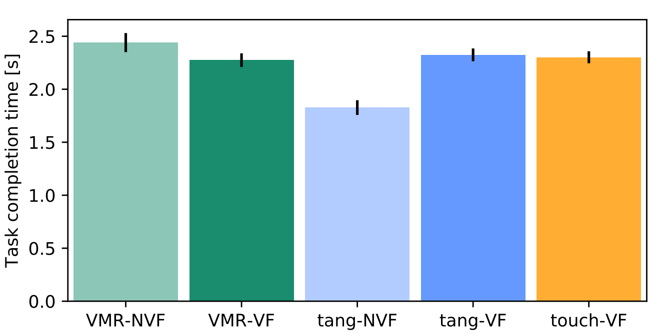


Figure 4. Mean task completion times (TCTs) per HapticFeedback × VisualFeedback in *s*. The error bars show standard error.

Results

During the study, the apparatus continuously logged the slider knob position and touch events and recorded TCT. The perceived mental effort was measured using pen and paper. Based on this data, we analyzed the measurements.

Task completion time (TCT)

TCTs were extracted from the logs generated by the study software. The grand mean was $2.23\,s$ ($SD = 1.25\,s$). Using `tangible sliding` with `visual feedback` was the fastest ($M = 1.83\,s$, $SD = .06\,s$) while a VMRS with `NVF` was the slowest ($M = 2.44\,s$, $SD = .09\,s$). We conducted a two-way repeated measures ANOVA to investigate the effect of HapticFeedback used and the presence of VisualFeedback on TCT. The main effect of HapticFeedback on TCT was statistically significant ($F_{2,1647} = 8.60$, $p < .001$). The presence of VisualFeedback also had a significant effect ($F_{1,1647} = 6.52$, $p < .05$). The results by HapticFeedback × VisualFeedback are shown in Figure 4. There was a significant HapticFeedback × VisualFeedback interaction effect ($F_{1,1647} = 23.44$, $p < .001$). We then conducted post-hoc analysis using Tukey's Honest Significant Differences (HSD) test. There were significant differences for the HapticFeedback pairs `tangible sliding` – `VMR` and `tangible sliding` – `touch sliding`. The analysis revealed that using the `VMR` was significantly slower than `tangible sliding` in the `NVF` condition ($p < .001$). There was no significant effect for conditions with `visual feedback`.

Absolute error

Absolute error distances were extracted from application logs. The grand mean of absolute error was $2.65\,mm$ ($SD = 4.30\,mm$). The two conditions that produced the largest error were `VMR` with `no visual feedback` ($M = 4.95\,mm$, $SD = 5.30\,mm$) and `tangible sliding` with `no visual feedback` and ($M = 7.46\,mm$, $SD = 5.02\,mm$). In contrast, `tangible sliding` with `visual feedback` produced the lowest error ($M = .34\,mm$, $SD = .64\,mm$), see Figure 5. A two-way ANOVA revealed a significant effect of HapticFeedback and the presence of VisualFeedback on absolute error. The main effects of HapticFeedback ($F_{2,1647} = 123.66$, $p < .001$) and VisualFeedback ($F_{1,1647} = 1045.25$, $p < .001$) were statistically significant.

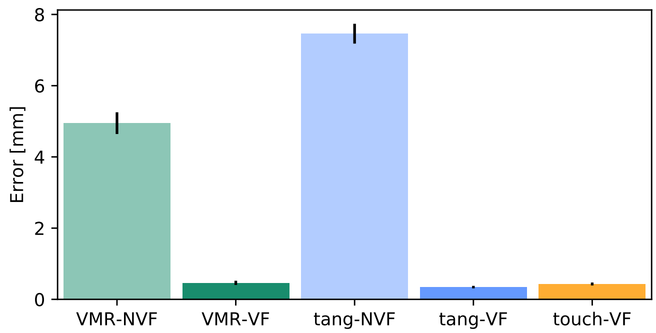


Figure 5. Mean absolute errors per HAPTICFEEDBACK × VISUALFEEDBACK in *mm*. The error bars show standard error.

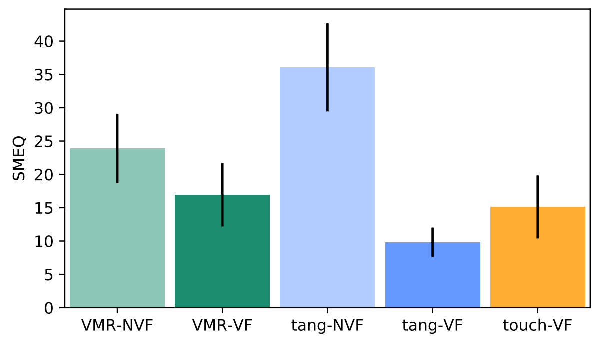


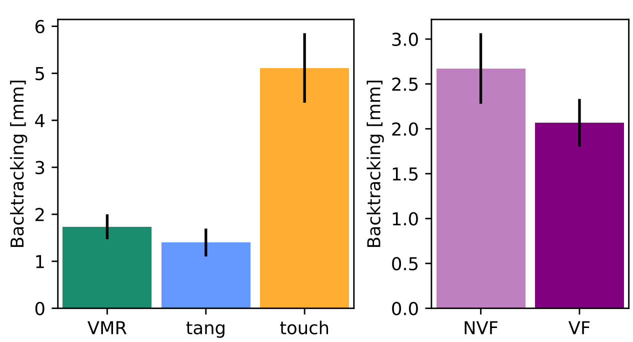
Figure 7. Average ratings of the perceived mental effort per VISUALFEEDBACK × HAPTICFEEDBACK on the SMEQ scale. Error bars show standard error.

A significant HAPTICFEEDBACK × VISUALFEEDBACK interaction effect was observed ($F_{1,1647} = 53.05$, $p < .001$). Post-hoc analysis with Tukey HSD showed significant differences for all HAPTICFEEDBACK pairs under the `no visual feedback` condition. `VMR` produced significantly less error than `tangible sliding` and `touch sliding` with `no visual feedback` ($p < .001$). There were no significant differences for HAPTICFEEDBACK with `visual feedback`.

Error rate (ER)

ER results were similar to absolute error. The mean ER for all conditions was $M = 25\%$ ($SD = 34\%$). Using `tangible sliding` with `no visual feedback` produced the highest number of errors ($M = 80.30\%$, $SD = 39.83\%$). `tangible sliding` with `visual feedback` produced the lowest ER ($M = .88\%$, $SD = .93\%$). After conducting a two-way ANOVA, we determined that significant effect of HAPTICFEEDBACK and VISUALFEEDBACK on error rate was present. The main effects of HAPTICFEEDBACK ($F_{2,1647} = 208.6$, $p < .001$) and HAPTICFEEDBACK ($F_{1,1647} = 1502.7$, $p < .001$) were statistically significant. A significant HAPTICFEEDBACK × VISUALFEEDBACK interaction effect was observed ($F_{1,1647} = 121.2$, $p < .001$). Tukey HSD revealed that significant pair differences were observed only for pairs in the `no visual feedback` condition, all with $p < .001$.

Backtracking distance (BD)



(a) Input correction per HAPTICFEEDBACK (b) Input correction per VISUALFEEDBACK

Figure 6. Input correction measured as mean backtracking distance (BD) in *mm*. Error bars show standard error.

Figure 6 illustrates our backtracking measurements. The grand mean backtracking distance was $2.30\,mm$ ($SD = 9.05\,mm$). `touch sliding` produced the largest backtracking distance ($M = 5.13\,mm$, $SD = 13.67\,mm$) and `tangible sliding` with `visual feedback` required the least amount of backtracking distance ($M = .27\,mm$, $SD = 3.69\,mm$). A two-way ANOVA revealed a significant effect of device used ($F_{2,1647} = 21.83$, $p < .001$) and presence of feedback ($F_{1,1647} = 19.05$, $p < .001$). No significant effect was observed for HAPTICFEEDBACK × VISUALFEEDBACK interaction. Post-hoc analysis with Tukey HSD showed significant differences for `touch sliding` – `tangible sliding` and `touch sliding` – `VMR` (both with $p < .001$) which was due solely to the difference with `visual feedback`.

Subjective Mental Effort Question (SMEQ)

Lastly, we look at SMEQ results. The mean score was $M = 20.36$, $SD = 21.76$. `tangible sliding` with `no visual feedback` producing the highest reported mental effort ($M = 36.06$, $SD = 27.26$) while `tangible sliding` with `visual feedback` was perceived as least demanding ($M = 9.82$, $SD = 9.08$), see Figure 7. Ziljstra [42] indicated that an ANOVA may be used to analyze SMEQ results. A two-way ANOVA revealed that there was a significant effect of the presence of feedback on the SMEQ result ($F_{1,80} = 11.41$, $p < .01$). No effect was observed for HAPTICFEEDBACK or VISUALFEEDBACK × HAPTICFEEDBACK interaction.

DISCUSSION

The results show that the VISUALFEEDBACK has a significant effect on TCT as well as on ER and SMEQ. The condition with `visual feedback` using `tangible sliding` was statistically significantly faster than `touch sliding`. This is in line with the results Jansen et al. [17] presenting a comparison between touch slider input and tangible sliders. Furthermore, Voelker et al. [35] showed comparable results for rotating tangible knobs. When `visual feedback` was provided, using `VMR` did not cause a longer TCT than `touch sliding`. However, in conditions without visual feedback, `tangible sliding` was significantly faster than `VMR`. Hence, **H1** is only supported for conditions with visual feedback. This indicates that the added sliding resistance required for implementing `VMR` does come at the cost of increased input time.

Regarding ER, we found no statistically significant differences when visual feedback was provided. Hence, we can conclude that using `VMR` has no negative influence on the accuracy when users can see the result of their input. This supports **H2**. The results also support **H3**. When no visual feedback was provided, participants exhibited significantly higher accuracy using `VMR`. This shows that the use of VMRS is particularly beneficial when users are not provided with direct visual feedback on their input. Combining the results for ER and TCT, we can conclude that, when no visual feedback is available, `VMR` offers superior accuracy at the cost of increased TCT. With `VMR`'s accuracy being as much as 66% higher than `tangible sliding`. Therefore VMRS should be the input technique of choice for tasks where accuracy is the key measure.

As expected, participants perceived the task as more mentally demanding when `no visual feedback` was provided. HAPTICFEEDBACK, `tangible sliding` as well as `VMR` had no influence on the perceived mental effort when selecting values. This shows that our assumption that users might perceive more effort when processing multi-modal feedback was not correct and **H4** is to be rejected. As a consequence, we see that VMRSs can be deployed in lieu of existing remote discrete input methods without increasing the mental effort of the users. Overall, all resulting SMEQ scale values are relatively low. This can be explained by the atomic interaction that was required during our study. Independently of HAPTICFEEDBACK and VISUALFEEDBACK, each of the trials represented a facile input task.

Surprisingly, participants had to correct more, regarding backtracking distance, using the slider on the touch display than using a tangible slider knob (`tangible sliding` or `VMR`). Both the `tangible sliding` as well as VMRS provide a physical resistance. This might incline participants to select values carefully. Also, this resistance seems to lower the movement speed, because the longer backtracking distance distance neither influenced the TCT nor the final accuracy of the selected value. A further explanation for the effect could be the fact that users are accustomed to using a touch surface on a daily basis. As a consequence, they tend to use rapid movements with which they are familiar and apply corrections later. We also found no significant difference between `tangible sliding` and `VMR`, which suggests that the additional resistance in the slider does not introduce an added need for corrections.

Based on the results, we can conclude that VMRSs offer superior accuracy at the cost of increased TCT when the users are provided no visual feedback. Using VMRSs does not cause added mental effort or increase the need for correcting input. The results show that `VMR` enables more accurate data input when no direct visual mapping to the input can be provided. We believe that this fact suggests that VMRSs can be useful in scenarios such as exploring large data sets in visually rich environments, e. g. in front of a wall-sized display. In such scenarios, not all variables which can be adjusted can be visually observed at once. When multiple variable input has to be performed, a set of VMRS could be used. For example, a multivariate function for more than four variables is impossible to visualize statically. We suggest that users could perceive some of the variables as slider positions and modify them through the variable resistance. This raises the question of whether data analysts can profit from such multi-VMRS and adapt the technology to their work like to how sound engineers use soundboards.

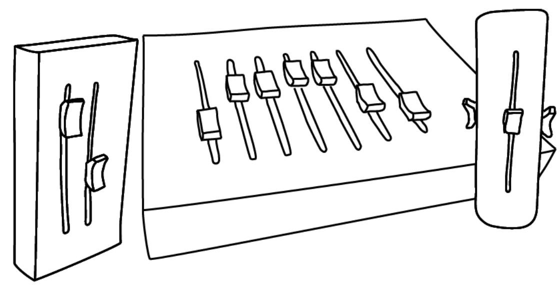


Figure 8. Bar, tablet and cylindrical slider devices. We propose those three form factors as starting points for designing devices that use VMRSs.

The question of form factor

We established that VMRSs can provide more accurate input and multiple application domains can benefit from their use. We now wonder what questions need to be answered before VMRSs can be deployed in real-life tasks. Looking back at past work [6, 17], we can observe that slider or slider-like devices need to be mobile to be applicable to large-screen environments. Past research offers few answers concerning what such devices may look like or even how many sliders they should contain. Previous studies explored only slider devices that look like parts of a soundboard — large boxes with an array of vertical sliders or single slider. The form factor of a slider device remains an open question. Based on our experiences of designing and implementing slider prototypes, we suggest three possible form factors. To illustrate our vision, we built low-fidelity cardboard prototypes of the devices shown in Figure 8. We suggest three form factors that can serve as an initial step in a design inquiry.

The bar device (see Figure 8 left) has four sliders – two in the front and two in the back. The prototype is lightweight and fits easily in a hand. The size is similar to an off-the-shelf smart phone. With this design, we show the need for exploring slider input and output on both sides of the device. An open question is how users can perceive changes in slider position while holding the device in hand.

The tablet-like device (see Figure 8 middle) is similar to devices investigated in previous work. This form factor has several advantages. Users may find it more familiar as it is possible that they may have previously seen similar devices (e.g. soundboards). The seven sliders arranged in parallel enable displaying complex patterns or even curves. However, the bulkiness of the device is a significant disadvantage, especially when one considers a scenario where the user is walking along a display.

The cylindrical device (see Figure 8 right) uses four sliders located on the sides of a cylinder. There is enough space on the cylinder so that the user can easily hold the device in the hand. It also can be held a bit higher to feel the position of the sliders with the palm. The cylindrical shape permits investigating the usage of sliders together with wand-like interactions, which are known to be effective in some use cases for large screens (e.g. Vogel and Balakrishnan [36]).

Limitations

While we strived to create an exhaustive study, our work is prone to certain limitations. Firstly, we recognize that our design of the VMRS is just a single design instance of an artifact.Further studies can investigate whether using different hardware e.g. a longer potentiometer would result in differences in performance. Furthermore, we still do not know what the influence of the slider device form factor is.

Secondly, we used an abstract atomic task in our experiment. As no prior systematic research has been conducted on `VMR` input, we decided to investigate the details of the single-value input first. However, we see that a more complex task, perhaps involving multiple sliders, may have revealed different properties of the VMRS. A longer study, incorporating multiple inputs, could also investigate the effects of fatigue. Furthermore, because of the atomic task, we did not look at the influence of the HAPTICFEEDBACK feedback type on recall and distraction from the actual task, besides data input. As indicated by previous work [6, 25], these two measurements might reveal important results.

Lastly, we note that we used a single implementation of `VMR`. While our design process suggested that the sinusoidal curve was the best choice, we wonder if further refinements to the feedback pattern are possible. A separate study can be run to compare different feedback curves in the future. However, the feedback curve can also highly depend on the assumed scenario and the study task. Our work shows the usefulness of using VMRSs per se, but we see that the intricacies of feedback design may need further exploration.

CONCLUSIONS AND FUTURE WORK

This paper introduced the notion of using VMRSs for providing discrete remote input. We described the design and implementation of a VMRS. We then evaluated the device in a controlled lab study. We showed how HAPTICFEEDBACK changed users' performance comparing `VMR`, `tang` and `touch`. We found that `VMR` had no negative influence on the ER and the perceived mental effort for value selection. However, `VMR` increased the accuracy of the input when no direct visual mapping to the data could be provided. Using a VMRS caused TCT to increase. In general, participants did less corrections when using `touch sliding` or `VMR`. The results suggest that using `VMR` can be an effective way to provide remote discrete input in scenarios where the users' visual attention on the input device is limited.

To have a coherent and manageable study design, we decided to constrain our study within a number of factors, which can be explored in future work. In this study, we used direct mapping of the input slider to the representation on the remote display. The affordance of the VMRS device allows a user to rotate the device with all degrees of freedom. Also, the representation on the remote display could be rotated. Overall, rotating the VMRS device and the representation on the remote display would result in 16 combinations. An open question is how the orientation of the device would affect interaction and accuracy. Another direction would be to go beyond off-the-shelf devices and build sliders that not only offer `VMR` but also other types of haptic feedback such as vibration or pressure. In the next step, we will also analyze using VMRS for data input in a real-world setting. Here the task could be exploring the influence of different input parameters of a simulation.

As this paper is the first inquiry into VMRS to our knowledge, we hope to inspire further work on how to efficiently use `VMR` in interactive systems. We have shown that the proposed techniques are relevant for remote displays, but we are eager to explore other scenarios, especially in tasks where the users' visual attention is limited. We believe that our first insights into the applications of VMRSs will lead to deploying them in real-life tasks and enable in-the-wild evaluation.

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