Multimodal Feedback Estimation for Knob Interactions in Virtual Reality for Control Panels

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Abstract: This paper presents findings on the unimodal and multimodal feedback design for the interaction with a virtual knob. Since the physical knob provides haptic feedback while being rotated, we also integrated haptic feedback in the virtual knob. The real and virtual knob consist of a main body and a handle on top. For fine and coarse adjustments, the knob can be grabbed and rotated with a 'Grasp' or a 'Pinch' gesture. In a user study with 30 participants, we evaluated our system using objective measures and subjective metrics. The results show that participants reported a preference for having a haptic feedback and perceived it as more natural.

1 INTRODUCTION

Virtual Reality (VR) is used in many fields, such as industrial training (Hirt et al., 2020). Here, physical control panels are required, where knobs and buttons are used to adjust parameters. While some real knobs have mechanisms that cause them to "snap" at specific increments, implementing appropriate haptic feedback in VR is still challenging. Given the currently existing haptic feedback capabilities of VR controllers, researching button and knob interactions with combinations of different feedback and snapping mechanisms gives valuable insights.

2 RELATED WORK

Approximately 80% of information is acquired through sight, about 10% through hearing, and the remaining 10% through the other channels (Man and Olchawa, 2018). Consequently, there is an interest in providing these sensory inputs in VR to create an increased sense of presence (Gallace et al., 2012). However, feedback systems in consumer-segmented VR devices are primarily limited to visual and audio cues. More recent VR controllers are equipped with haptic feedback mechanisms and can additionally provide vibrotactile feedback to users through their hands (Kreimeier et al., 2019).

(Tatzgern and Birgmann, 2021) used virtual hand and raycasting techniques to explore input modalities on VR control panels. They identified knobs, buttons, and sliders as control elements and compared three interaction methods for manipulation using a VR controller. The interaction possibilities consist of a trigger, a joystick, and an approximating hand gesture method. The joystick performed best for slider manipulations due to its high precision, while the approximate hand gesture was preferred for knobs but did not outperform the trigger method.

Physical proxies can be used to provide haptic feedback when using hand-tracking. This technique was also employed for control panel interactions. (Matthews et al., 2023) designed a physical control panel consisting of buttons, sliders, and knobs and implemented a retargeting technique to map only a third of the physical panel to the entire virtual interface. They observed a decrease in performance when users interacted with the remapped interface.

Instead of attempting to provide all possible types of feedback, researchers propose an approach that integrates task-related information through the best matching one. (Cooper et al., 2018) designed a virtual scenario where participants performed a wheel change in VR while wearing vibration gloves and holding a mock-up wrench. Multisensory cues in

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form of visual, audio and tactile feedback were used to compensate for sensations that are not easily replicable in VR. Results show that the multimodal substitute feedback improves overall task performance. These conclusions align with previous findings suggesting that training with low fidelity simulators is not inferior to high fidelity ones (Lefor et al., 2020).

Research shows that using multimodal feedback may not uniformly improve performance and can increase perceived task load and fatigue. For instance, (Faeth and Harding, 2014) found that, while the bimodal feedback system outperformed the unimodal one, the application of trimodal feedback in virtual button interactions resulted in decreased performance (Bermejo et al., 2021). This occurrence of overstimulation has been reported in other studies as well (Cooper et al., 2018), (Apostolou and Liarokapis, 2022), (Marucci et al., 2021), indicating that unnecessary or incongruent feedback can disrupt immersion.

Marucci et al. (Marucci et al., 2021) explored the impact of multisensory feedback and perceptual load on performance, workload, and presence. Participants engaged in the same task under two conditions: one with high perceptual load and another with low perceptual load, and with either only visual or with additional audio and/or vibrotactile feedback. Results show, that only in the high load condition, multisensory (bi- or trimodal) stimuli significantly enhanced performance compared to visual stimulation alone.

3 METHODOLOGY

3.1 Hardware and Software

The feedback system for knob interactions was developed and assessed using the Meta Quest 2 oaired with the corresponding controllers. They provide vibrotactile feedback and are equipped with capacitive sensors on the buttons, joystick, touchpad, index trigger, and middle finger trigger, facilitating partial finger and thumb tracking.

The implementation was developed in Unity 2022.3.9.f1 as a standalone application. We used the Oculus Interaction SDK for hand prefabs, controller inputs, the VR camera rig, and anchor points. The Quick Outline Asset[1] was used to integrate wireframes as visual feedback. Blender and Shapr3D are used to create the virtual mock-up (Fig. 1(b)) of the physical knob (Fig. 1(a)) on the control panel.

[1] https://assetstore.unity.com/packages/tools/particles-effects/quick-outline-115488, accessed 16.01.24

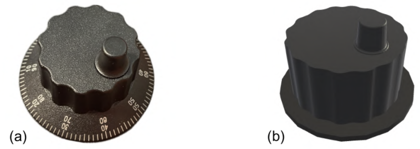

Figure 1: (a) Physical knob. (b) Virtual knob.

3.2 Knob Interaction and Feedback

The design of the virtual knob and the implementation of its interactions replicates the knob from a real control panel. The knob is used to control the position of the machine axis and allows two distinct manipulation possibilities: the body can be gripped using a precision grip and rotated by twisting the fingers. Alternatively, it can be pinched at the handle and rotated through circular motions of hand and forearm. The different hand gestures have designated purposes; a precision grip allows for slow and precise rotation, whereas the pinching gesture and applied circular motion allow for faster rotation. The chosen hand gesture also influences the rotation resistance of the knob. When force is applied to the knob at the handle, it initially presents a notable resistance, demanding a force to overcome the threshold for rotation. However, once surpassed, the knob smoothly rotates without providing the haptic feedback of detents. In contrast, when the knob is rotated at the body, it exhibits a low torque, enabling slow and precise manipulation with rotational force feedback of individual detents.

These two interaction possibilities for the virtual knob are implemented following a concept similar to the approximation of hand gestures proposed by (Tatzgern and Birgmann, 2021). Two specific button combinations are used for those two interaction possibilities. The precision grip is approximated by pressing both the trigger and grasp buttons on the controller and keeping the thumb on the joystick. The pinching gesture is approximated by pulling the trigger button. We will refer to them as 'Grasp' and 'Pinch' further in the text. Additionally, our virtual knob implementation consists of two so-called activation zones for each of the interaction possibilities. The start of each interaction with the body or the handle of the knob can be triggered only in the corresponding activation zone. They are realized as invisible cylinders. For pinching the handle, the middle point between the index finger and thumb needs to be within the handle activation zone (diameter: 25mm, height: 70mm), and the trigger button must be pressed. To grab the knob's body, the center point of the virtual palm must be within the cylinder (diameter: 70mm, height: 70mm), positioned above the knob's body and handle. Simultaneously pressing the trigger and grasp button in this zone will result in the knob body being grasped. This is done to minimize the snapping effects and to encourage users to aim at a specific part of the knob.

We designed three vibrotactile feedback modalities for the interaction with the virtual knob. Table 1 shows all knob conditions studied. We refer to 'NF' as no additional visual and no vibrotactile feedback for the virtual knob.

Table 1: Description of all knob conditions.

Configuration	Visual	Vibrotactile
NF	No	No
SVT	No	Simple
CVT	No	Complex
V	Yes	No
V+SVT	Yes	Simple
V+CVT	Yes	Complex

To simulate the detents of the physical knob, a snapping effect is added to the virtual knob. We set the angular resolution of the knob to 10°, staying within the recommended 5°range by (Hinricher et al., 2023). During our implementation, we noticed that setting the vibration amplitude to 0.3 of the maximum amplitude and the duration of each pulse to 0.01s gave a natural feel both for the slow knob rotation as well as for a faster one. While a higher amplitude provided a stronger clicking sensation which benefits the slow knob turning, it resulted in an uncomfortable strong vibration during fast turns. Therefore, we implemented two types of vibrotactile feedback: one with the maximum amplitude (referred to as 'simple' (SVT)) and one with varying amplitude (referred to as 'complex' (CVT)).

Additionally, for half of the conditions, we implemented visual feedback (referred to as V) in the form of a highlighting wireframe around the knob body and handle. Whenever the hand or fingers were within the grab zone and in a position to grasp either the body or the handle, or both parts, the respective components were highlighted.

3.3 User Study

For the user study, participants were standing in front of the control panel while operating the virtual knob. The design of the virtual control panel is derived from the control panel of a machine tool that we had available on-site. Similarly to the real control panel, we designed the virtual control panel with an inclination angle of 60°.

We designed a simplified scenario in which the knob is rotated to change the position of a cube. The task was to move the cube to a predefined target position. The participants were assigned the same task across all conditions (Tab. 1). The small cube was positioned on top of the control panel, and the target location was indicated by a red square. Rotating the knob to the right moved the cube rightward and conversely for leftward rotation. Upon successful placement, the target color changed to green, as shown in Figure 2.

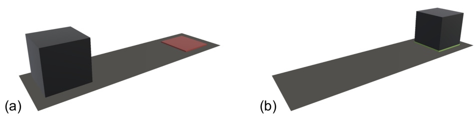

Figure 2: The cube is moved to a red square target, turning green upon success. (a) Start position, (b) Task completed.

As introduced in Table 1, the user study consists of six feedback varieties: no feedback (NF), visual feedback (V), simple vibrotactile feedback (SVT), complex vibrotactile feedback (CVT), visual and simple vibrotactile feedback (V+SVT), and visual and complex vibrotactile feedback (V+CVT). In the user study, the participants can use both manipulation gestures to interact with all six types of knobs. For each feedback variant, three tasks are presented:

- The target position is 1.5cm away from the cube. Participants use the pinching gesture to move the cube to target.
- The target position is 1.5cm away from the cube. Participants only use the grasping gesture to move the cube to target.
- The target position is 20cm away from the cube. Both gestures can be used.

The study started with welcoming participants and filling out a consent form. After introducing the goal of the study, they could test the physical knob. Afterwards, they filled out the pre-questionnaire including demographics and personal well-being before the study. The VR session started with a tutorial on the interaction with the virtual knob. No data is collected during the tutorial. After completing the tutorial, participants performed the tasks in a randomized order. They were instructed to complete the tasks as fast as possible and with as few errors as possible. Upon completion, a final scene was loaded where the user could experience all types of feedback implemented for the knobs without any time constraints for a better subjective comparison.

We measured task completion time (TCT), error count (EC), and overshoot distance (OD) as objective measurements. The TCT measures the time until a correct placement was reached. The timer starts when the knob is first grabbed and stops once the knob is released. The EC is the number of times the cube passes the target location in both forward and backwards direction. For every error, the distance of the target over- or undershot is measured. For subjective measurements, participants' well-being was assessed through the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). The Presence questionnaire (Slater et al., 1999), NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988), and System Usability Scale (SUS) (Brooke, 1996) are also included.

We formulate the following hypotheses regarding the impact of multimodal feedback on user performance and preferences:

- **H1:** Vibrotactile feedback or visual feedback, alone or combined, does not improve performance.
- **H2:** User has no preference over different types of feedback.
- **H3:** Using grasping or pinching gesture has no effect on performance.

We used R for the statistical analysis. The significance level is set 0.05. In results section, We analyzed and ran statistical tests on task performance (TCT, EC and OD) and subjective responses for different gestures and different feedback modalities.

4 RESULTS

30 participants (19 male, 11 female) aged between 20 and 31 were recruited. 16 participants had less than 20 hours of VR experience, and 7 were using VR for the first time. Three subjects had 20 - 100 hours, and four had more than 100 hours of VR experience.

4.1 Objective Performance

Feedback Modalities. For the pinching gesture, SVT and CVT provide knob vibration. The vibration intensity in CVT only changes to max for the grasp gesture. Figure 3 (a) - (c) shows the user performance (TCT, EC, OD) of the different conditions for pinching gesture. The data did not meet the assumption of normality, as indicated by p-values smaller than 0.05 obtained from the Shapiro-Wilk test. The non-parametric Friedman tests show no significant results: $p_{\mathrm{TCT}} = .1886$, $p_{\mathrm{EC}} = .5663$, $p_{\mathrm{OD}} = .9694$. Figure 3 (d) - (f) shows the user performance under the different feedback conditions for grasping gesture. The Friedman tests show no significant results: $p_{\mathrm{TCT}} = .9257$, $p_{\mathrm{EC}} = .4853$, $p_{\mathrm{OD}} = .8415$. When users are free to choose gesture(s), the Friedman tests show no significant results in task completion, error rate, and overshoot distance: $p_{\mathrm{TCT}} = .7941$, $p_{\mathrm{EC}} = .3822$, $p_{\mathrm{OD}} = .7504$ (Figure 3 (g) - (i)). This indicates that no significance for the feedback (visual or vibrotactile) is found for all knob conditions.

Interaction Gestures. Each user tried grasping, pinching or both gesture to complete the task. The non-parametric Friedman tests showed no statistical significance (Table 1). When participants were free to choose between grasping and pinching gestures, they used the 'Pinch' gesture 85.2% and the 'Grasp' gesture 14.8% of the time. In 47.8% of the tasks, the 'Grasp' gesture was never used. 3 participants (10%) completed their first task (cube distance = 15mm (Figure 2 (a)) using only the grasp gesture. Afterwards, like the other 27 participants, they began with the pinching gesture and in some cases, eventually switched to a grasp once the cube got close to the target or they overshot the target with the pinching gesture.

Table 2: p-Values from the Friedman tests when comparing the performance between 'Pinch' and 'Grasp'.

	p_{TCT}	p_{EC}	p_{OD}
NF	.273	.841	1
SVT	1	.297	.297
CVT	.715	.819	.297
V	.465	.683	.683
V+SVT	.715	.127	.251
V+CVT	.068	.67	1

4.2 Subjective User Experience

Knob Evaluation. Participants rated the feedback of the knobs on a 7-point scale (4 = neutral). To determine if the obtained scores significantly differ from the neutral score, we conduct two-tailed one-sample Wilcoxon signed-rank tests with the same confidence level of 0.05. The hypothesis (H2) states that the median of the population from which the sample is drawn, equals the neutral score ($\mu_0 = 4$).

Visual Highlighting. The results of highlighting indicates that participants found the highlighting of the knob parts to be helpful, with a significant higher rating than 4 ($p = .037$) and an average score of 4.73. While the highlighting was not perceived as distracting, as reflected by the significantly higher rating than 4 ($p = .001$) and a mean score of 5.5, participants had varying perceptions of its realism, yielding in an average score of 4.03 and $p = .908$.

Vibration. Participants perceived the knob vibrations as highly helpful, with a mean score of 5.77 and a significantly higher rating ($p = 3.33 - 05$). Generally, participants did not perceive the vibrations to be distracting, as indicated by a mean score of 5.13 and $p = .015$. However, the high SD of 2.26 suggests variability in responses, with 4 subjects finding the vibra-

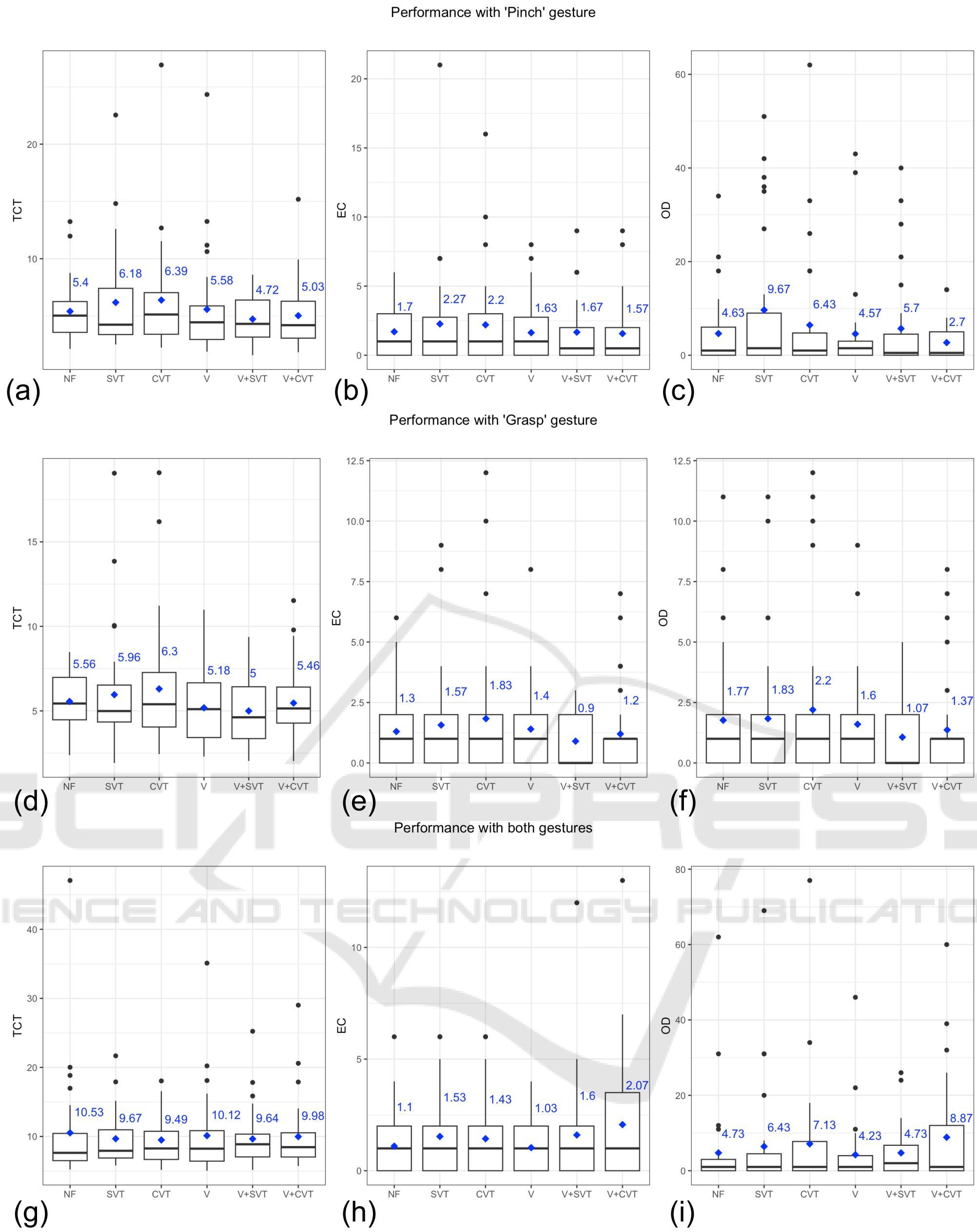

Figure 3: Task performance. (a) TCT with pinching gesture. (b) EC with pinching gesture. (c) OD with pinching gesture. (d) TCT with grasping gesture. (e) EC with grasping gesture. (f) OD with pinching gesture. (g) TCT with both gestures. (h) EC with both gestures. (i) OD with both gestures.

tion to be extremely distracting and another 4 finding it moderately distracting. Moreover, the knobs equipped with vibration were perceived as realistic and significantly rated higher than 4 ($p = 4.37e-05$), with an average score of 5.47. As for the question comparing vibration and non-vibrating knobs, most participants perceived the latter as less realistic compared to the vibrating ones, as indicated by the average score of 2.67 and $p = .002$.

Standardized Questionnaires. The average SUS score is 84.5 with an SD of 11.93. The final score of the Presence Questionnaire is on average 4.52 with an SD of 1.184. The average overall workload score is 17.37 with an SD of 9.32.(Hart and Staveland, 1988). The results of the SSQ pre- and post-study indicate that 10 participants had higher scores after the study. Among them, eight participants had score differences below 10, one had a difference of 11.22, and another one had a difference of 22.44. On average, the score of the pre-questionnaire was 15.334 with SD = 21.593, and for the post-questionnaire, the mean was 14.212 with SD = 20.09. The average difference is -1.122 with SD = 10.766. These results indicate that there were no remarkable differences in the participants' well-being before and after the study.

5 DISCUSSION

The results from our VR knob implementation questionnaire reveal a positive user experience. Participants reported a moderately high presence score, indicating a satisfactory level of immersion. Additionally, the implementation generated minimal perceived workload, minimal simulator sickness, and is user-friendly, providing an engaging and comfortable interaction with the VR knobs.

5.1 User Evaluation of Knob Feedback

Although the performance was not significantly impacted by the knob feedback, our analysis revealed significant findings from the knob questionnaire that participants generally favored knob feedback. A summary of the results obtained by the one-sample Wilcoxon signed-rank tests can be seen in Table 3.

5.1.1 Visual Feedback

Although wireframe highlighting is not present in the real world, participants rated its realism relatively neutral. This suggests that visual feedback by a wireframe might disturb surface fidelity, but won't significantly increase the perceived workload. Whether such visual feedback could lower the workload depends on personal preference, as half of the participants found highlighting very helpful, while the rest ranked it as not helpful or more or less neutral. This is also reflected in the knob rating inside the virtual environment, where 43.3% found the knob with visual feedback easier to control, 26.7% preferred the knob with no feedback, and 30% had no preference.

5.1.2 Vibrotactile Feedback

The knob vibration was rated as very helpful. This is supported by the rating in the VR scene, with 86.7% rating the knob with SVT feedback as easier to control. Our findings suggest that vibrotactile feedback technique can assist users in completing their tasks, but it could also lead to a higher perceived workload depending on the individual. Our results indicate that vibration pulses are an appropriate way to mimic knob detents. This suggests that when using the grasping gesture, a higher vibration intensity can be perceived as more beneficial, without impacting user experience in terms of distraction level and realism. However, the answers from the questionnaire contradict to the participants' rating inside the VR scene, as 46.7% found the knob with strong vibration easier to control and 40% the knob with weak vibration.

5.2 User Performance

We noticed throughout the study, that some participants encountered the same issue: once the cube reached its correct position, they started moving their hand away from the knob before the virtual hand fully released the grip, causing the cube to unintentionally move by one unit distance. This led to a cycle where attempts to correct overshoots resulted in undershoots and vice versa, significantly increasing both, task completion time and error count. We observed this particularly among inexperienced users. Thus, in hindsight, our implementation may have been overly sensitive to user input, despite efforts to address this by introducing an angular resolution of 10°. The problem could have been avoided, for example, by providing a slightly larger target for the cube, where one over- or undershoot would still be considered correctly placed.

1. "Visual feedback does not improve user performance compared to no feedback". Our results across all three manipulation conditions (Pinch, Grasp, Both) and performance metrics (TCT, EC, OD) indicate that participants performed similarly in both the NF and V conditions. This outcome could be explained by participants' familiarity with the grabbing process, as it was introduced during the tutorial, suggesting that the additional visual feedback might not have significantly altered their performance.

2. "Vibrotactile feedback does not improve user performance compared to no feedback". The results indicate that participants performed equally when any type of vibration (SVT or CVT) was present compared to no feedback (NF). While not significant, we can observe that with the 'Pinch' gesture the performance tends to be slightly worse when vibration is present, as participants overshot more often and by a lot more under the conditions SVT and CVT compared to NF. These results could be attributed to the task's simplicity, aligning with Marucci et al.'s research (Marucci et al., 2021), which suggests that additional feedback modalities primarily enhance performance when the task requires a high perceptual load.

Table 3: Summary of the results for user evaluation of knob feedback that consists of visual and vibrotactile feedback.

Question	Hypothesis	Interpretation	Type of feedback
1a	Reject H_0	The *Helpfulness* score of the highlight mechanism is significantly higher than the neutral score 4.	Visual
1b	Reject H_0	The *Distraction* score of the highlight mechanism is significantly higher than the neutral score 4.	Visual
1c	Accept H_0	The *Realism* score of the highlight mechanism is not significantly different from the neutral score 4.	Visual
2a	Reject H_0	*Helpfulness* score of the vibration mechanism is significantly higher than the neutral score 4.	Vibrotactile
2b	Reject H_0	*Distraction* score of the vibration mechanism is significantly higher than the neutral score 4.	Vibrotactile
2c	Reject H_0	*Realism* score of the vibration mechanism is significantly higher than the neutral score 4.	Vibrotactile
3	Reject H_0	*Realism* of vibration compared to no vibration is significantly higher than the neutral score 4.	Vibrotactile
5a	Reject H_0	*Helpfulness* of strong vibration compared to weak vibration is significantly higher than the neutral score 4.	Vibrotactile
5b	Accept H_0	*Distraction* of strong vibration compared to weak vibration is not significantly different from the neutral score 4.	Vibrotactile
5c	Accept H_0	*Realism* of strong vibration compared to weak vibration is not significantly different from the neutral score 4.	Vibrotactile

3. "Visual and vibrotactile feedback combined does not improve user performance compared to no or only one type of feedback". We determined that neither visual (V) nor vibrotactile (SVT, CVT) feedback improved user performance. Upon comparing the unimodal conditions to the bimodal conditions (V+SVT, V+CVT) for the 'Pinch' gesture, we noted that with bimodal feedback participants completed tasks slightly faster than in the SVT and CVT conditions only. Additionally, they exhibited lower overshoot distance. Similarly, using the 'Grasp' gesture with bimodal feedback resulted in slightly faster task completion compared to only vibrotactile feedback (SVT, CVT).

4. "Strong vibration does not improve user performance compared to weak vibration". In our experiment, weak and strong vibrations were exclusively compared with the 'Grasp' gesture, as we noticed an uncomfortable strong vibration during fast turns with the pinching gesture. Our data shows that there is no noticeable performance difference between SVT and CVT or V+SVT and V+CVT, suggesting that weak vibrations might suffice to simulate the detents of the knob.

5. "'Grasp Rotation' does not allow for finer motor control compared to 'Pinch Rotation', thus, won't lead to a lower EC and OD". Although there is no statistical evidence, our results align with this hypothesis. While subjects did not exhibit fewer errors with the 'Grasp' gesture, we observed a higher overshoot distance for the 'Pinch' gesture. Additionally, there were instances of notably high overshoots with the pinching gesture, indicated by the high standard deviations ranging between 3.99 and 15.27.

6 CONCLUSION

In this paper, we introduced a knob implementation with visual and haptic feedback and proposed two different interaction possibilities, i.e., grasping the body of the knob and pinching the handle. The pinching and grasping gestures are triggered through different controller inputs that approximate the same gesture in real life. We explored the effects of no feedback compared to unimodal feedback and bimodal feedback. Visual feedback is implemented as a wireframe, highlighting the graspable knob part that appears once the virtual hand approaches the knob to assist the user in aiming. Vibrotactile feedback is realized to mimic the haptic feedback that a real knob provides while being manipulated. Different vibration intensities were investigated by implementing interactions with the knob with low and high vibration amplitude.

We conducted a user study that revealed a positive user experience. Overall, the participants deemed the proposed feedback cues as appropriate and showed a preference for knobs with feedback. However, objective measurements did not yield significant results, indicating that visual, vibrotactile, or their combination had no effect on user performance.

6.1 Limitations and Future Work

Our implementation of the knob manipulation is sensitive to hand motions. That caused some overshoots and additional errors, when participants were placing the cube to the target position. This can be improved in two possible ways: either by decreasing the sensitivity of the knob by increasing the angular resolution, or by creating a slightly bigger target area to avoid those overshoots that are caused by a small hand motion before the release of the virtual knob.

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