Knobology Revisited: A Comparison of User Performance between Tangible and Virtual Rotary Knobs

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ABSTRACT

We present an experimental comparison of tangible rotary knobs and touch-based virtual knobs in three output conditions: *eyes-on*, *eyes-free*, and *peripheral*. Twenty participants completed a simple rotation task on a interactive surface with four different input techniques (two tangibles and two virtual touch widgets) in the three output conditions, representing the distance from the locus of attention. We found that users were in average 20% faster using tangible knobs than using the virtual knobs. We found that tangible knobs retains performance even if they are not in the locus of attention of the users. We provide four recommendations of suitable choosing knobs based on tasks and design constraints.

Author Keywords

Tangible user interfaces; tabletop interaction; rotary widget

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces Input Devices and Strategies

INTRODUCTION

Rotary *tangible knobs* on multi-touch surfaces have be proposed for video navigation [3, 5, 13], menu selection [3], and interactive data exploration tasks [4, 7]. In comparison to touch-based *virtual knobs*, they provide haptic feedback that guides the user input. However, one drawback of tangibles is that they are not as dynamic as virtual controls, they cannot be created, modified, or removed as easily as *virtual controls* [11]. Also, tangibles need to be constructed and maintained. Because of these trade-offs, designers have to choose between using tangible knobs or virtual knobs. To make this decision, they need to better understand if, how, and in which scenarios the physicality of tangibles knobs improves the users' performance.

The literature does not provide a clear answer to these questions. The results of a study of SLAP Widgets favor tangible knobs [13], but the results from a study of CapWidgets suggest the opposite [5]. Although the tasks in both studies are similar (using the rotary knobs to navigate a video and mark outstanding frames) several other possible factors differ: SLAP Widgets were placed out of the users' sight (eyes-free input), CapWidgets were placed on top of the video (eyes-on input). They used different knob diameters (5 cm vs. 2 cm, respectively), and different tracking technologies (FTIR + DI vs. capacitive). Because of these different factors, it is difficult to identify why these two studies are contradicting each other.

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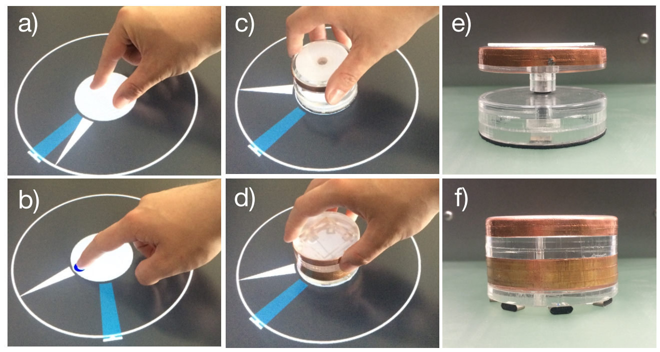

Figure 1. Four types of rotary widgets compared: (a) one- and (b) two-touch virtual knobs, (c,e) a tangible knob, of which rotor is independent of the base, and (d,f) a tangible puck: the entire widget is a rotor

We hypothesize that the main factor of these contradicting results was the difference of eyes-free vs eyes-on input. In an eyes-free task, the tangible knob provides haptic feedback that guides the users input. However, in an eyes-on task the tangible is blocking parts of the interface which makes it complicated for the user to see the target area. To verify this hypothesis we present the results of an experiment in which we compared two tangible knobs with two virtual knobs in terms of speed and accuracy in eyes-on and eyes-free tasks. To ensure that we only test these two factors we kept all other factors the same.

RELATED WORK

To use a virtual touch widget or a tangible widget, the user first *acquires* the widget with their hands and then *manipulates* the widget to a desired state [2, 11]. Fitzmaurice and Buxton [2] showed that space multiplexed input devices (e.g., tangibles) outperform time multiplexed input devices (e.g., a mouse) in acquisition task involving multiple objects. Tuddenham et al. [11] conducted a very similar experiment, but also included multi-touch as one condition. The results of their study showed that users are also more accurate using tangibles than using multi-touch in acquisition tasks. In these acquisition studies, the users need to constantly switch between multiple input widgets. Thus, the superiority of tangibles may not hold in tasks that focuses on manipulation, which requires more focused movements on single input widget.

As for manipulation phase, tangible sliders were found to be faster than virtual sliders [4, 11], although no notable difference in average tracking error as found [4]. Based on these findings, tangible sliders are preferable to virtual sliders. However, it is uncertain that these findings for sliders are are generalizable to knobs because muscle movements involved are more complex in knobs than in sliders [12]. A study by Tory and Kincaid [10] suggested that tangible knobs outperform virtual knobs. However, in their study both tangibles and output were collocated. To understand user performance in the rotary manipulation, we conduct an experiment to compare tangible knobs vs. virtual knobs.

THE EXPERIMENT

We have two main independent variables: *widget* type and *output* area. All widgets are 7 cm in diameter. All input was done on a horizontal touch screen. We compared four types of rotary widgets (Figure 1):

One-touch virtual knob (a). Similar to an analog telephone dial, this knob can be rotated by dragging a small circle inside the knob to a desired angle.

Two-touch virtual knob (b). This is similar to pinch-to-rotate gesture in touch screen phones. To rotate this knob, the user touches two finger inside the knob area. The orientation of the line connecting the two finger determines the knob orientation.

Tangible knob (c, e) based on the SLAP knob design [13]. The rotor is attached to the base of the knob by a spindle. This allows rotational input without translating the base of the knob.

Tangible puck (d, f) based on a design in from Photohelix [3]. This puck is a single rigid body. To rotate, the users manipulates the entire tangible, resulting in a coupling between translation and rotation.

For all four widget types, the user had to start each trial inside the output area. However, while turning touch knobs the users were able to drag outside of the input area, just like typical touch screen widgets.

We compared three output areas, representing the distance of the tangible from the locus of attention:

Eyes-on: Visual feedback was displayed around the knob, providing single locus of attention. Nevertheless, the hand of the user may occlude the display during rotation.

Eyes-free: Visual feedback was shown on a separate vertical display in front of the user, hence, no hand occlusion. However, the user cannot see the widget while looking at the visual output.

Peripheral: In this condition, the output was display on the horizontal screen with 20 cm offset in front of the user. Although the widgets are outside of the locus of attention, they are still in the peripheral vision.

The size of the visual feedback was 7 cm diameter in all output conditions.

APPARATUS

During the experiment participants stand in front of a horizontal 55″ Microsoft capacitive touch display. The table surface is 90 cm high from the floor. The effective touch frame rate of our setup was 60 Hz.

A 46″ vertical display was placed directly behind the horizontal surface. Both displays had the resolution 1920 x 1080 pixels and were connected to a Mac Pro running the software for the experiments.

TASK

The experiment setup is shown in the Video Figure. We used the task from previous knobology study [8].

In each condition, the system display a gray circle (input area) and white ring with a blue target area and a white orientation indicator (visual output).

The widgets were already placed on the input area prior to each trial. Before each trial, the user turns the widget such that the white orientation indicator was inside a starting area, which is always at the 12:00 position ($= 0°$). After keeping the indicator one second inside the starting area, a blue static target area was displayed. The participants were asked to turn the knob until the indicator was inside the target area. The target area was randomly displayed at one of six predefined target areas, which are roughly equally-spaced around the knob, ($-150°$, $-100°$, $-50°$, $50°$, $100°$, and $150°$ from the starting area. To complete the trial, the used had to keep the indicator one second inside the target area.

DEPENDENT VARIABLES

We measured *movement time*, measured from when the indicator left the starting area until the trial was completed. For data analysis, we deducted the second that the users needed to wait inside the target area to complete the trial. For the accuracy, we count the *number of overshoots*, when the cursor exits the target area.

STUDY DESIGN

A $4 \times 3 \times 6 \times 5$ (input type $\times$ output area $\times$ target area $\times$ iteration) repeated measures experiment was used. All factors where within-subject independent factors, leading to a total of 360 trials per participants (on average, 30 minutes per participant). The experiment was divided into four blocks, one for each knob. All iterations in one block where done with the same knob. The order of blocks (hence also input devices) where determined by a Latin square that ensured counterbalancing.

The hypotheses tested in our experiment was as follows:

- H1: We expect that both tangibles will have faster movement times than the two virtual knobs.

Condition	Movement time	Number of overshoots
One-touch	1.47 [1.39, 1.54]	1.06 [0.91, 1.22]
Two-touch	1.83 [1.78, 1.88]	0.58 [0.49, 0.67]
Tangible Knob	1.21 [1.15, 1.28]	0.60 [0.50, 0.69]
Tangible Puck	1.14 [1.10, 1.18]	0.43 [0.37, 0.49]
Eyes-on	1.40 [1.32, 1.48]	0.66 [0.57, 0.75]
Peripheral	1.38 [1.31, 1.45]	0.67 [0.56, 0.78]
Eyes-free	1.45 [1.37, 1.53]	0.67 [0.55, 0.78]

Figure 2. Overall descriptive statistics by condition (mean [95% CI]

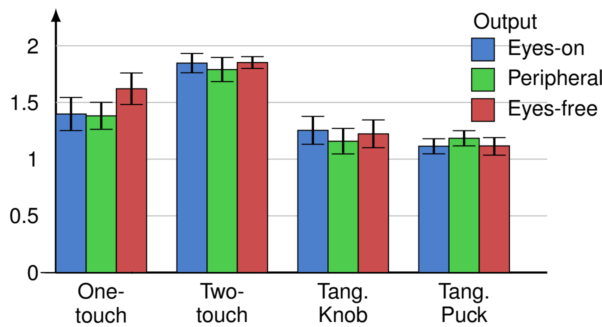

Figure 3. Movement time (mean and 95% CI)

- H2: The domination of tangible knobs will be particularly pronounced for the eyes-free condition.
- H3: We expect tangible knobs to have less errors associated with use (e.g. less overshooting) than virtual knobs.

PARTICIPANTS

20 participants (18 males; 2 females) aged 20 to 36 years ($M = 27$) volunteered for the study. All participants had normal or corrected-to-normal vision. 17 out of 20 participants were right-handed.

RESULTS

Results on iterations and different goal areas were aggregated into mean scores for movement and overshooting. For each multivariate test, we used 4 x 3 (widget $\times$ output) GLM repeated measures analysis [1]. Upon significant effects, post-hoc Bonferroni-corrected paired t-tests were performed (Familywise error rate $\alpha = .05$). Figure 2–4 show descriptive statistics with 95% CIs (unadjusted) Below, the CIs of mean differences were adjusted for paired design and Bonferroni-corrected. We provide extensive statistical results in the supplement.

Movement Time

We found a very large main effect of widget on movement time ($F_{1.68,31.91} = 43.81$, $p < .001$, $\eta_p^2 = .70$). As shown in Figure 2, the two-touch widget was slower than the one-touch widget ($M_{\text{two}-\text{one}} = 0.36$ s, $CI[0.22, 0.50]$). One-touch widget was again slower than puck and knob ($M_{\text{one}-\text{puck}} = 0.33$ s, $[0.07, 0.59]$; $M_{\text{one}-\text{knob}} = 0.26$ s, $[0.02, 0.49]$). The difference between the tangibles was negligible ($M_{\text{knob}-\text{puck}} = 0.07$ s, $[-0.06, 0.21]$).

[1]When Mauchly's sphericity test was significant, the Greenhouse-Geisser correction was used, resulting degrees of freedom with decimal points.

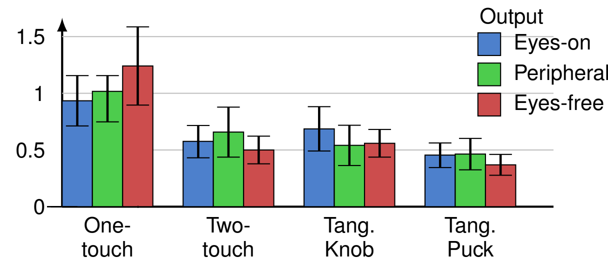

Figure 4. Number of overshoots (mean and 95% CI)

A large main effect of the output was also observed on movement time ($F_{1.18,22.50} = 6.26$, $p = .016$, $\eta_p^2 = .25$). The movements in the peripheral condition was faster than in the eyes-free condition ($M_{\text{free}-\text{perip.}} = 0.07$ s, $[0.05, 010]$). Other differences were negligible ($M_{\text{free}-\text{on}} = 0.05, [-0.01, 0.11]$), $M_{\text{on}-\text{perip.}} = 0.02$, $[-0.05, 0.10]$)).

A large interaction effect between widget and output was also evident ($F_{2.78,52.86} = 9.05$, $p < .001$, $\eta_p^2 = .32$). Figure 3 shows the overview of the interaction effect. In the eyes-free condition (H2), the simple effect of the widgets agreed with the main effect analysis above. In the eyes-on condition, we found that the tangible puck yielded faster movement time than one-touch widget ($M_{\text{one}-\text{puck}} = 0.29$ s, $[0.26, 0.54]$) (cf. [5]). In the one-touch widget, eyes-free output was slower than others ($M_{\text{free}-\text{on}} = 0.22$ s, $[0.10, 0.34]$, $M_{\text{free}-\text{perip.}} = 0.24$ s, $[0.20, 0.28]$).

Number of overshoots

There was a very large main effect of input devices ($F_{1.68,30.78} = 24.17$, $p < .001$, $\eta_p^2 = .560$). The one-finger widget was significantly more error prone than the others ($M_{\text{one}-\text{two}} = 0.49$ s, $[0.20, 0.77]$; $M_{\text{one}-\text{knob}} = 0.47$ s, $[0.22, 0.47]$; $M_{\text{one}-\text{puck}} = 0.64$ s, $[0.30, 0.97]$) However, the two-finger widget was comparable to both tangibles ($M_{\text{two}-\text{knob}} = -0.02$ s, $[-0.18, 0.14]$; $M_{\text{two}-\text{puck}} = 0.15$ s, $[-0.00, 0.30]$). The tangible knob was slightly more error-prone than the tangible puck ($M_{\text{knob}-\text{puck}} = 0.17$ s, $[0.02, 0.31]$).

No statistical or practical main effect of the location of information was found ($F_{2,38} = 0.22$, $p = .979$, $\eta_p^2 = .001$) and the mean number of overshooting was almost identical for all three output areas.

We found a large interaction effect between widget and output $F_{2.84,54,02} = 4.30$, $p = .01$, $\eta_p^2 = .18$). Figure 4 shows an overview of the interaction effect. When focusing on the eyes-free condition, however, the two-touch widget yielded more overshoots than the tangible puck ($M_{\text{two}-\text{puck}} = 0.13$ s, $[0.05, 0.21]$).

DISCUSSION

The results indicated that the tangibles (knob and puck) outperformed both touch widgets (one-touch and two-touch). Specifically, tangibles were faster across the board (supporting H1). For overshooting, the tangibles yielded fewer overshoots than the one-touch widget, but were comparable to the two-touch widget (partially supporting H3).

In the eyes-free condition, the performance of one-touch widget degraded more than others. The two-touch widget retained its performance in in the eyes-free condition. We surmise that the additional friction of the second finger slowed down the input, allowing users to better control the virtual knob. The accuracy of two-touch widget rivaled the tangible knob, but the two-touch widget was still worse than the tangible puck. Both tangibles were superior than touch widgets in terms of the movement time (supporting H2). The tangible knob performed slightly worse than then tangible puck, probably because of the friction from the rotary mechanics inside the tangible knob. This can be improved by a better manufacturing process.

The peripheral condition was faster than the eyes-free condition. We speculate that the awareness of hand movement allow the users to be more confident when manipulating the widgets. Since the speed were comparable between the peripheral and the eyes-on condition, we speculate that occlusion does not influence users' confidence in the rotation movements. For one-touch widget, both speed and accuracy were improved by placing the widget in peripheral vision instead of using it eyes-free.

Our results further support previous research: tangible controls are faster and less error-prone than touch-based controls [6, 9, 11, 13]. However, our data is contrary to the findings of Kratz et al. [5] as the tangible puck outperforms the one-touch widget in both movement time and overshoots. Of practical interest is the finding that differences between tangibles and touch-based interaction techniques are influenced by the locus of attention. This is especially interesting for evaluating the suitability for use of touch-interfaces in operative contexts where the human operator's visual attention must be directed towards an outside world, away from the controller [1].

CONCLUSION AND DESIGN IMPLICATIONS

In this paper, we present an experiment comparing tangible rotary knobs with virtual rotary knobs in eyes-on and eyes-free tasks. We found that tangible knobs are on average 20% faster then virtual knobs. In contrast to virtual knobs, tangibles did not perform significantly worse in eyes-free tasks compared to eyes-on tasks. The users were slower with the two-finger knob than with the one-finger knob, but they were more accurate using the two-finger knob.

Therefore, we draw the following design implications: (1) For the best performance in rotation tasks, we recommend using tangible puck over tangible knob and over virtual touch widgets. (2) If it is not possible to use tangibles, use two-touch widget for the tasks that require accuracy, and one-touch widget for the tasks that requires speed. (3) Design the user interface such that rotary widgets stays in peripheral vision of the users to increase manipulation confidence. (4) In eyes-free task, avoid using one-touch widget. We hope that these design implications help designer to make an informed decision if the should use tangible or virtual knobs for which kind of task and applications.

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