Which Tangible Control for Which Visual Task?

Mesure de performance d'outils tangibles selon la représentation visuelle de la tâche

Céline Coutrix
CNRS, Université Grenoble Alpes
Grenoble, France
Celine.Coutrix@univ-grenoble-alpes.fr

Yann Laurillau
Université Grenoble Alpes
Grenoble, France
Yann.Laurillau@univ-genoble-alpes.fr

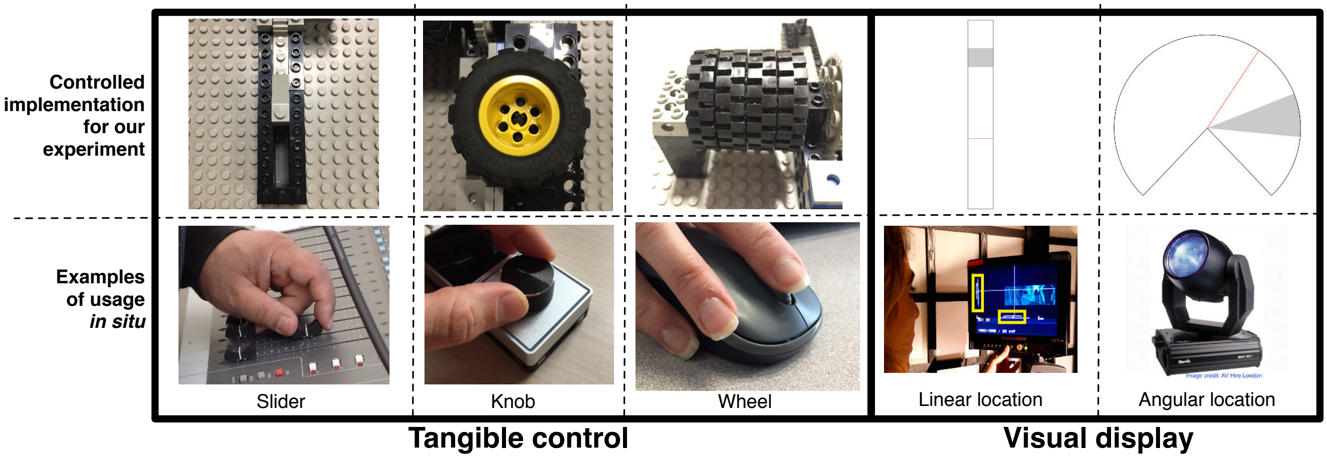

Figure 1: The 3 tangible controls and the 2 visual displays whose combinations we compared in our experiment, and ecological examples of their use.

ABSTRACT

Many parameters may impact the performance of users while engaged in tangible user interaction. In this paper, we explore the impact of the combination of the tangible control and the visual display on the performance of a 1D target acquisition task. We consider three tangible controls: a slider, a knob and a wheel, and two visual displays for the same 1D target acquisition task: a circular cursor and a linear cursor. We found that matching the visual and motor task has an impact on the performance. This work has implications ranging from current design of Tangible User Interfaces to research on shape-changing Tangible User Interfaces.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Laboratory experiments**; **Pointing devices**.

KEYWORDS

Tangible User Interaction, Visual Display, Performance

RÉSUMÉ

De nombreux paramètres peuvent avoir un impact sur la performance des dispositifs tangibles. Dans cet article, nous explorons l'impact de la combinaison du dispositif tangible en entrée, et de la représentation visuelle, sur les performances d'une tâche de pointage. Nous considérons trois dispositifs tangibles : un curseur linéaire, un bouton rotatif et une molette. Nous considérons aussi deux représentations visuelles, pour une même tâche de pointage : un curseur circulaire et un curseur linéaire affichés à l'écran. Nous constatons que la combinaison de tâches visuelles et motrices a un impact sur la performance. Ces travaux ont des implications pour la conception de l'interaction tangible, mais aussi pour la recherche sur les interfaces tangibles qui changent de forme.

MOTS CLÉS

Interaction tangible, Représentation visuelle, Performance

IHM '19, December 10–13, 2019, Grenoble, France

ACM ISBN 978-1-4503-7026-4/19/12…$15.00
https://doi.org/10.1145/3366550.3372249

1 INTRODUCTION AND RELATED WORK

In the literature on Tangible User Interfaces (TUI), different tangible controls have been used for different visual tasks. For example, a slider was used to zoom in a map [27], sliders and knobs to point at targets presented on a linear display [25], sliders to point at targets presented on a linear display and knobs for targets presented on a circular one [26], etc. However, the choice to use these particular devices with these particular displays is often intuited.

Previous work has ecologically observed how professionals use tangible interfaces today [16]. It shows that sliders, knobs and wheels are widespread. It shows that the visual tasks they allow performing ranges from angular display (e.g., controlling a projector angle) to linear display (e.g., controlling a distance between stereoscopic cameras). However, again, the reason to map a particular device with a particular display is never explicit.

The literature explores the performance of the different combinations between the motor and visual tasks in a limited way. Most of the designers' knowledge is intuitive, not always verified scientifically [3].

Design handbooks (e.g., [3, 17]) do not provide guidelines about the best display alternatives for each tangible control. Norman's action theory [21] advises to map the physical variables (i.e., motor space) and the psychological variables (i.e., perception of the visual space) in number (e.g., one-to-one) and semantically (e.g., turning a steering wheel (angle) of a car impacts the car's direction by that angle). Many times this advice is not followed in ecological settings, e.g. LoupeDeck [1] tangible controls do not necessarily match the Photoshop widgets they control. This advice is also not always followed in the literature, e.g., a knob might be associated with a linear representation [19, 25]. For this reason, we set out to evaluate the performance on a 1D acquisition task of 6 of these device × display combinations. We consider three tangible controls: a slider, a knob and a wheel, and two visual displays for the same 1D acquisition task: a circular cursor and a linear cursor, as these combinations are widespread. We classified these combinations according to the degree of compatibility of the instrumental interaction model [4]. Table 1 shows that the slider+line and knob+circle are supposed to have the highest degree of compatibility, because we map the same variable (respectively a distance and an angle) and have parallel axes of movements on both the tangible device and the visual display. Knob+line and slider+circle are supposed to have the lowest degree of compatibility. The combinations with the wheel are supposed to lie inbetween, with the wheel+circle having a higher degree of compatibility than the wheel+line. Our research question is then: has the combination a real impact on performance? In this work we experimentally address this question and discuss the results compared to theory.

Combination	**Compatibility**	**Mappings**	
		Variable	**Axes**
slider+line	++	*distance* → *distance*	$\parallel$ *axes*
knob+circle	++	*angle* → *angle*	$\parallel$ *axes*
wheel+circle	+	*angle* → *angle*	$\perp$*axes*
wheel+line	-	*angle* → *distance*	$\parallel$ *axes*
slider+circle	- -	*distance* → *angle*	$\perp$*axes*
knob+line	- -	*angle* → *distance*	$\perp$*axes*

Table 1: Classification of the six combinations according to their degree of compatibility [4].

Early works compared existing devices for pointing tasks. Epps [10] compares six devices for the same visual display of a pointing task: an absolute touchpad, a relative touchpad, a mouse, a trackball, a rate-controlled displacement joystick and a rate-controlled force joystick. MacKenzie et al. [18] compare a mouse (2 DOF), a trackball (3DOF) and a stylus with tablet for the same pointing task (2D and pressure). These devices vary in the number of control dimensions they offer to users. On the contrary we want to focus only on the motor-visual mapping. To do so, our devices will all be one-dimensional, absolute and isometric.

For a scrolling task, i.e. pointing at a target that is very far and not always visible at the beginning of the movement, it was shown that a good device is a touchpad scroll ring [29]. On the contrary, the devices that offered the same motor and visual directions were found less efficient. However, the resolution of each device is not reported, even though the resolution might have an impact on the results [5]. In this work, we take care of having a high resolution for all devices. We also consider a slightly different task, namely a 1D acquisition task where the target is always visible. Users perform this task very often too.

Most of the performance studies of TUI tackle the comparison with other paradigms, like a mouse [6, 11, 15, 26] and/or a touch surface [6, 15, 25, 26, 28]. In some of these works, user's focus is not collocated with input location [6, 11, 15, 25]. In others, both input and output focus are collocated [13, 20, 24, 26, 28]. Overall, when no implementation problem is reported, tangible interaction performs better. A first exception is found for visualization tasks [15], where the graphical user interface performs better. A second exception is found on a combined task of 3 degrees of freedom (2D translation and 1D rotation) [13]. The touch technique is more efficient in this case than the tangible one. As the motor and visual tasks were collocated, the rather large tangible device might have caused occlusion. In this paper, like in most of this previous work, we focus on distant visual task, as this is often the case in ecological settings (see, e.g., [16]).

On the one hand, the manipulation of the tangible device does not always match the visual representation: for instance a knob might be associated with a linear representation [19, 25] such as the time line of a movie. On the other hand, the manipulation of the tangible device can match the visual representation: for instance a slider might be associated with a linear representation, or a knob with an angular representation [28]. A study shows that tangible sliders and knobs lead to similar task completion time [20]. However, this work evaluates the combinations of a slider with a linear display and a knob with a circular display, as the display matched the shape of the device. In this paper, we would like to investigate if this combination has a real impact on performance. The display was also collocated with the tangible controller [20], which seldom occurs in ecological settings (see, e.g., [16]).

Chipman et al. [8] compared a slider and a wheel for scrolling and pointing tasks. A non-significant gain in performance and preference was measured, mainly for short distances to targets. Through this paper, we wish to explore other combinations of devices and displays.

Rotary knobs and sliders have been compared for the creation of a musical sample [12]. Knobs and sliders were mapped to the parameters of the sound synthesis model. The authors found very little difference in preferences. However, as they state themselves, "*factors that might have distorted the results are most likely found in the quality of the actual sensors*". To avoid this problem, we take great care of the resolution of the tracking in our experiment, and also focus on a less subjective performance measure.

As Jacob et al. state [14], "*selecting an appropriate input device for an interactive task requires looking [at] the interrelationship between the perceptual structure of the task and the control properties of the device*". Towards this end, we study the impact of the device × display combination on performance. For this, we conducted a study comparing six combinations of devices and displays for a distant 1D target acquisition task.

2 PARTICIPANTS

Nine right-handed participants took part in the study (5 female), aged from 22 to 38 years old (M=31, SD=4.87). All had normal or corrected vision. Five participants reported using a wheel on a daily basis and three occasionally (mostly through the mouse wheel). Four participants reported using a knob on a daily basis and five occasionally (e.g., through sound volume knob, guitar, washing machine, oven). One participant reported using sliders on a daily basis and three occasionally (e.g., through light, piano).

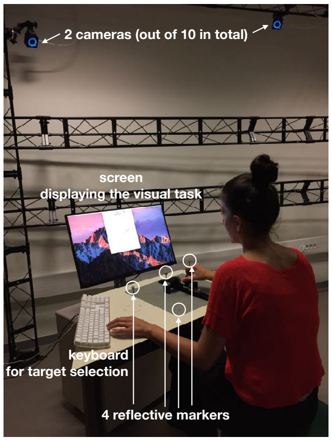

Figure 2: The experimental setup.

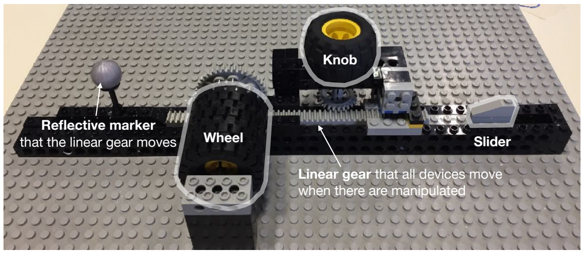

Figure 3: The tangible devices.

3 APPARATUS

Participants sat at a 120 cm wide table (Figure 2) on top of which were the tangible devices. A keyboard was placed on their left side to press the key necessary to validate a selection. The display was a 60 Hz DELL U2715H of 596.74 × 335.66 mm (2560 × 1440 px) at a distance of around 75 cm from their eyes. We made the tangible devices with LEGO© (Figure 3). We chose this design over using standard devices because it allowed to control the amplitude of movement for each tangible device, especially for the knob and the wheel. We could not find any commercially available devices that allowed to control the amplitude of movement in motor space for all three devices. We chose this design over making custom devices because it allowed for more precise positioning of tracking markers and for smoother manipulation. To ensure minimal friction for optimal smoothness, we used silicone lubricant before each experimental session. The manipulation of the three devices made the same reflective marker move (Figure 3, left), ensuring the same quality of tracking.

The support surface of the tangible devices presented four reflective infra-red markers (Figure 2), that were tracked by 10 cameras (OptiTrack Prime 41 infrared cameras[1]). One marker was attached to the mobile cursor (Figure 3, left), and three markers were attached to the support surface (Figure 2) ensuring that participants could freely manipulate the device on the table. The tracking system is placed around the room to allow for both comfortable manipulation of the devices and precise and accurate tracking.

The tracking resolution is a variable of the cameras, their number and their position. We measured the resolution of the devices by four standard deviation of the sensed position of the static cursor in a static device [5]. Throughout ~900 frames, we measured the resolution of the tangible input devices to be 955 dpi. For the slider, this translates as 0.047 % of the whole range. As a comparison, the smallest target width in the experiment was 1.25 % of this range. This resolution ensured that the visual display of the cursor was very stable. As a consequence, we do not expect the resolution to limit the interaction, even with the smallest targets.

The Tracking Tools software[2] ran on a MacPro4.1 desktop computer with 2.66 GHz Quad-Core Intel Xeon processor and 6 GB of memory, running Windows 7 Pro. The software sent the markers positions over the local wired network to a MacBook Pro laptop computer running macOS 10.12.6 with Intel Core i7 2.2 GHz processor and 4 GB of memory. This computer ran software developed with Python 2.7 for the experimentation.

4 EXPERIMENTAL DESIGN

The experiment used a within-subject design, with three independent variables:

- The index of difficulty (ID), with five different values: 1.58, 2.32, 3.17, 4.09 and 5.04 bits. The values resulted from fully crossing three widths of targets (1.25 %, 2.5 % and 5 % of the whole range) and three distances to the targets (10 %, 20 % and 40 % of the whole range). The reason why IDs are not above 6 is that the interaction we tested was not relative, but absolute target acquisition task, which prevents from having very large distances through clutching or dynamic gain.
- The visual display: a vertical linear display with a cursor in a range of 766 px (179.5 mm) (Figure 1) and a circular display with a cursor in a range of 273 degrees (diameter of 766px and 242.7 mm of partial circumference, Figure 1).
- The tangible device used to perform the task, described above: a slider, a knob, and a wheel.

The orders of visual display and ID were randomized within each block. The order of presentation of the tangible devices was counterbalanced using a Latin square.

5 PROCEDURE

Participants sit in front of the device and screen (Figure 2). After a short introduction, they trained by performing 5 target acquisition tasks with a single combination of device and display. When they were ready, they performed a block of 27 1D target acquisition tasks (3 repetitions × 3 widths × 3 distances) with the same combination of device and display. The next target appeared randomly on one or the other side of the current target. After this block, they took a break and answered a questionnaire. Then they performed the next block, with a new combination of device and display. At the end of the experiment, they additionally answered a demographic questionnaire. The experiment lasted around 35 minutes per participant.

6 TASK

Participants performed 3 repetitions of each 1D target acquisition task. As in previous work [7], participants had to successfully validate their selection in order to complete the task, in order to better resemble a typical 1D target acquisition task. The next trial started right after participants successfully pressed the key.

7 MEASURES

We recorded 9 participants × 3 widths × 3 distances × 2 displays × 3 devices × 3 repetitions = 1458 measures of movement time and error, i.e. 243 measures for each device × display combination. To compute these, we recorded the participant’s ID, time, target distance, width, keyboard validation, the display and the device around every 10 ms. We also asked them to complete a SUS questionnaire after each combination. After all the tasks with the 6 combinations were completed, participants ranked the 6 combinations in terms of preference.

8 RESULTS

In order to get a good estimation for movement time (whose distribution is skewed), we used the geometric mean [23]. In all figures, error bars show 95 % confidence intervals[3].

Movement time

Movement time was computed by considering the time to a successful validation. Table 2 and Figure 4 (left) show the mean movement time for each of the two visual tasks and for each of the three physical devices.

A Shapiro-Wilk test showed that we could not assume the normality of the data ($W = 0.90288, p < .0001$). Therefore, we performed an analysis of variance (ANOVA) of the aligned rank transformed data [30]. We found a significant effect on the movement time of the device ($F = 30.42125$, $Df = 2$,

---

[1] http://www.optitrack.com/support/hardware/prime-41.html

[2] https://www.optitrack.com/software/

[3] see supplementary material for computation details

	circle	line
knob	1.49 [1.39, 1.55]	1.62 [1.46, 1.68]
slider	1.58 [1.47, 1.64]	1.32 [1.24, 1.37]
wheel	1.91 [1.69, 2.00]	1.66 [1.50, 1.73]

Table 2: Rounded mean movement time (s) and 95 % confidence intervals.

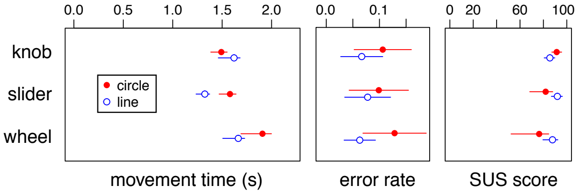

Figure 4: Mean Movement time (left), Error rate (center) and SUS scores (right) for each visual task and each tangible device. The higher the SUS score, the better.

$p < .001$), of the display ($F = 9.00819$, $Df = 1$, $p < .01$), of the ID ($F = 30.37782$, $Df = 4$, $p < .001$), and of the interaction between device and display ($F = 13.23202$, $Df = 2$, $p < .001$).

We performed post-hoc cross-factor pairwise comparisons using Wilcoxon signed-rank tests, using Holm’s sequential Bonferroni procedure for p-value correction. For a *circular display*, we found that:

- The difference between the knob and the slider (-0.09 s, i.e. 5.5 % faster) is not significant ($W = 327$, $p > .05$).
- The knob is significantly faster than the wheel (-0.42 s, i.e. 22 % faster; $W = 120$, $p < .001$).
- The slider is significantly faster than the wheel (-0.33 s, i.e. 17 % faster; $W = 222$, $p < .001$).

For a *linear display*, we found that:

- The slider is significantly faster than the knob (-0.30 s, i.e. 18 % faster; $W = 924$, $p < .001$).
- The difference between the knob and the wheel (-0.04 s, i.e. 2.6 % faster) is not significant ($W = 476$, $p > .05$).
- The slider is significantly faster than the wheel (-0.34 s, i.e. 20 % faster; $W = 74$, $p < .001$).

For a *knob*, the circular display is significantly faster than the linear display (-0.04 s, i.e. 2.6 % faster; $W = 286$, $p < .05$).

For a *slider*, the linear display is significantly faster than the circular display (-0.25 s, i.e. 16 % faster; $W = 887$, $p < .001$).

For a *wheel*, the linear display is significantly faster than the circular display (-0.24 s, i.e. 13 % faster; $W = 789$, $p < .01$).

Error rate

Error rate was computed by considering the first validation for each target. Figure 4 (center) shows the mean error rate for each visual display and for each physical device. Note that the error rates are comparable (slightly higher than 4 %) to similar experimental tasks (see, e.g., [7]).

A Shapiro-Wilk test showed that we could not assume the normality of the data ($W = 0.61001$, $p < 0.001$). Therefore, we performed an ANOVA of the aligned rank transformed data [30]. We find a significant effect on the error rate of the display ($F = 7.94094$, $Df = 1$, $p < .01$) and the ID ($F = 4.96840$, $Df = 4$, $p < .001$). The device, and the interaction between device and display, had no significant impact on the error rate (resp. $F = 0.94764$, $Df = 2$, $p > 0.05$ and $F = 0.43277$, $Df = 2$, $p > 0.05$). We performed post-hoc cross-factor pairwise comparisons using Wilcoxon signed-rank tests. However, after using Holm’s sequential Bonferroni procedure for p-value correction, the differences between the device and display combinations were not statistically significant. The differences between the combinations exist, but confidence intervals are indeed large (Figure 4, center). Overall, the line display lead to less error than the circle display (Figure 4, center) .

Usability and Preference

Figure 4 (right) shows the SUS score for each combination of device and display. A Shapiro-Wilk test showed that we could not assume the normality of the data ($W = 0.83678$, $p < 0.001$). Therefore, we performed an ANOVA of the aligned rank transformed data [30]. We find a significant effect on the SUS score of the interaction between device and display ($F = 5.1449$, $Df = 2$, $p < .05$). We performed post-hoc cross-factor pairwise comparisons using Wilcoxon signed-rank tests. However, after using Holm’s sequential Bonferroni procedure for p-value correction, the differences between the device and display combinations was not statistically significant. The subjective differences between the combinations exist, but are indeed small (Figure 4, right).

The preference rankings (Figure 5) show that the slider+line, knob+circle, but also surprisingly the wheel+line were mostly preferred.

9 DISCUSSION AND CONCLUSION

This section analyzes the results summarized in Table 3, uncovering design implications for tangible and shape-changing user interfaces. It also addresses the limitations of this work with questions opening on future work.

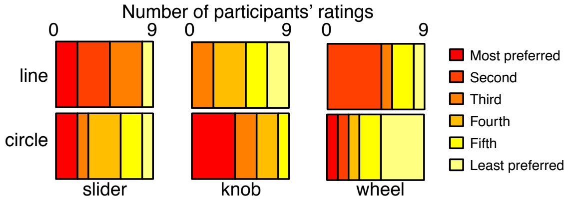

Figure 5: Preference for each combination of device × display.

combination	efficiency	preference
slider+line	fastest	+++
knob+circle	fast	+++
wheel+circle	slowest	- - -
wheel+line	slow	++
slider+circle	fast	0
knob+line	slow	-

Table 3: Efficiency and preferences for the six combinations.

Summary and analysis of results

Both movement time and usability questionnaires show with some evidence that two combinations are the most efficient and preferred: slider+line and knob+circle. They also show that one pair is the least efficient and least preferred: wheel+circle. For the other combinations, the results show differences but without clear evidence.

For the most efficient and preferred combinations (slider+line and knob+circle), the results are consistent with Norman's action theory [21] in terms of mapping between the physical variables (i.e., motor space) and the psychological variables (i.e., perception of the visual space). The one-to-one mapping of the linear distance for slider+line (resp. of the angle of rotation for knob+circle) made the task easier. The highest performance also matches the expected higher degree of compatibility (Table 1). Most participants commented that they felt that these matching combinations made the choice of direction at the start of the movement easier. With combinations that did not match the device with the display (e.g., slider+circle, knob+line), they commented starting their movement in the wrong direction, and consequently loosing time. Their lower performance matches the expected lower degree of compatibility (Table 1).

The wheel+circle combination lead in our experiment to low results both in performance and preference. This is unexpected as this combination was supposed to have a rather high degree of compatibility (Table 1). Its design may be intrinsically a source of confusion as it relies on a rotation of the wheel induced by a rectilinear movement of the hand perpendicular to the rotation axis. The mapping is less obvious as we map a distance to an angle. This may explain the bad results of the wheel+circle combination.

Analyzing each device individually, the slider+line combination provides a better movement time over the slider+circle combination with strong evidence. This is consistent with the usability questionnaire. About the knob, the knob+circle combination is very little better than the knob+line combination (~2.5 %). We hypothesize the knob is more versatile compared to the two other devices. The wheel+line combination was supposed to have a rather low degree of compatibility (Table 1). However, even though wheel+line leads to a high movement time until a successful selection, the wheel+line combination was unexpectedly among the most preferred combinations (Figure 5). The high preference of wheel+line could be explained, either by its lowest error rate (6.3 %) among all combinations and/or by the familiarity with the mouse wheel often used with vertical scroll bars.

Limitations

For one participant, the direction of the wheel in the experiment was the contrary of the direction of his/her own wheel. We hypothesize that this caused a delay at the beginning of the movement. The training involved 5 repetitions of the combined motor+visual task. With a longer training, participants might have overcome this difficulty and learn the mappings.

The fact that participants went in the wrong direction could be explained by the fact that the direction of the next target was randomly decided in the experimental software. We will consider in future work to implement a reciprocal 1D target acquisition task.

P5 and P8 commented that they felt static friction, i.e. a resistance when starting the movements, with the slider and the knob respectively, even though we sprayed silicone spray before each session. P5 also commented that the wheel had some backlash. However, this drawback was the same for all conditions, as all three controllers were connected. Moving one meant driving the other two. As a consequence, we think the comparison still holds for commercial devices. This could be further evaluated in future work. Using existing devices could ensure a better (i.e. industrial) implementation. However, we found that it was hard to control the devices in this context. For instance, most wheels provide haptic ticks, which would introduce a confounding factor.

P7 found the slider too small. Given previous work that compared different sizes of sliders [9], a larger slider would probably lead to even better results for the slider. This comment raises the question of the motor movements and how to control and compare them. In our experiment, the knob measured 42 mm in diameter and allowed for 270 degrees of rotation, which made a partial circumference of 198 mm. The slider had a range of 56 mm, as the reflective marker movement. The wheel measured 43 mm in diameter and allowed for 161 degrees in rotation, which made a partial circumference of 121 mm. We could have controlled the (curvilinear) distance for each device. However, we felt that the nature of each manipulation was very different, and that it was difficult to be sure that each movement was at its best. Looking at the results (Figure 4), the smaller motor movement on the slider compared to the knob could explain the larger difference between visual tasks for the slider compared to the smaller difference between visual tasks for the knob. With a smaller tangible device, a match between the motor and visual task could have a greater impact. This hypothesis should be further tested in future work.

In terms of movement time between two combinations, we observe that the highest gain is limited, between 0.24 s and 0.42 s. This gain may become significant with intensive use of knobs and sliders. Indeed, professionals like sound engineers or pilots use a lot these devices for their professional activity [16]. For instance, for repetitive tasks like setting the distance between stereoscopic cameras, where the users can perform this action many times in a day, using a particular device for a particular display has a noticeable benefit in movement time.

This paper focuses on 1D target acquisition performance. In the future, we plan to consider other tasks such as selecting an item in a list. Indeed, knobs and wheel are currently used to browse lists (e.g., train stations in tickets vending machines). Another task we plan to consider is a pursuit [9, 15, 22] as this is also representative of ecological tasks, such as following a person on a stage with a projector. These new tasks will allow us to deeper investigate on the performance of device × display combinations.

Design implications

For some of the combinations, this experiment confirmed some of our assumptions based on Norman's theory [21] and the degree of compatibility [4]. In particular, the slider+line and the knob+circle combinations are suitable. Comparing combinations of tangibles with a display is insightful and, in this section, we identify design implications on tangible interfaces as well as shape-changing interfaces.

Tangible interfaces. Our current knowledge of TUI is based on isolated experiments (e.g., [8, 12, 20, 25]). We wish that the HCI community builds solid scientific knowledge on the performance of these interfaces.

For some situations, the design may impose a chosen input tangible control (e.g., in the cockpit). For such situations, a matching display is appropriate, i.e. a linear display if the device is a slider or a wheel, and a circular display is the device is a knob. Conversely, if the display is imposed, a knob will perform best with the circular display while the slider will perform best with a linear display.

Shape-changing interfaces. Our study can inform the design of shape-changing interfaces, as it shows that changing the shape of the control, for instance between a knob and a slider [22][16] is worth doing according to the display. Shape-changing interfaces need to formally prove the benefit of the field in order to convince, the community and the general public, that these are not gadgets. Further knowledge is needed to identify the benefits of other shapes like, e.g., a shape-changing knob. The HCI community acknowledges that this is a grand challenge of shape-changing interfaces [2]. In this paper, we wish to contribute to this challenge.

ACKNOWLEDGMENTS

The authors thank Nicolas Belleville, Benjamin Lausenaz and Hyunyoung Kim for their help with earlier versions of this work. This work has been partially supported by the LabEx PERSYVAL-Lab (ANR-11-LABX-0025-01), the PhyFlex project (ANR-15-CE23-0011-01) and FabMSTIC.

REFERENCES

[1] [n. d.]. LoupeDeck. https://loupedeck.com/. Accessed: 2019-11-07.

[2] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *the CHI 2018 Conference*. New York, New York, USA, 1–14. https://doi.org/10.1145/3173574.3173873

[3] Konrad Baumann and Bruce Thomas. 2002. *User Interface Design of Electronic Appliances.* CRC Press.

[4] Michel Beaudouin-Lafon. 2000. Instrumental Interaction: An Interaction Model for Designing post-WIMP User Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '00).* ACM, New York, NY, USA, 446–453. https://doi.org/10.1145/332040.332473

[5] François Bérard, Guangyu Wang, and Jeremy R. Cooperstock. 2011. On the Limits of the Human Motor Control Precision: The Search for a Device's Human Resolution. In *Human-Computer Interaction – INTERACT 2011*, Pedro Campos, Nicholas Graham, Joaquim Jorge, Nuno Nunes, Philippe Palanque, and Marco Winckler (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 107–122.

[6] Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Mouse, Tactile, and Tangible Input for 3D Manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17).* ACM, New York, NY, USA, 4727–4740. https://doi.org/10.1145/3025453.3025863

[7] Olivier Chapuis and Pierre Dragicevic. 2011. Effects of motor scale, visual scale, and quantization on small target acquisition difficulty. *Transactions on Computer-Human Interaction (TOCHI* 18, 3 (July 2011), 1–32. https://doi.org/10.1145/1993060.1993063

[8] Leslie E Chipman, Benjamin B Bederson, and Jennifer A Golbeck. 2004. SlideBar: analysis of a linear input device. *Behaviour & Information Technology* 23, 1 (Jan. 2004), 1–9. https://doi.org/10.1080/01449290310001638487

[9] Céline Coutrix and Cédric Masclet. 2015. Shape-Change for Zoomable TUIs: Opportunities and Limits of a Resizable Slider. In *Human-Computer Interaction – INTERACT 2015*, Julio Abascal, Simone Barbosa,

Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 349–366.

[10] B W Epps. 1986. Comparison of Six Cursor Control Devices Based on Fitts' Law Models. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 30, 4 (Sept. 1986), 327–331. https://doi.org/10.1177/154193128603000403

[11] George W. Fitzmaurice and William Buxton. 1997. An Empirical Evaluation of Graspable User Interfaces: Towards Specialized, Space-multiplexed Input. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. ACM, New York, NY, USA, 43–50. https://doi.org/10.1145/258549.258578

[12] Steven Gelineck and Stefania Serafin. 2009. A Quantitative Evaluation of the Differences between Knobs and Sliders. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. Pittsburgh, PA, United States, 13–18. http://www.nime.org/proceedings/2009/nime2009_013.pdf

[13] Mark Hancock, Otmar Hilliges, Christopher Collins, Dominikus Baur, and Sheelagh Carpendale. 2009. Exploring Tangible and Direct Touch Interfaces for Manipulating 2D and 3D Information on a Digital Table. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '09)*. ACM, New York, NY, USA, 77–84. https://doi.org/10.1145/1731903.1731921

[14] Robert J. K. Jacob, Linda E. Sibert, Daniel C. McFarlane, and M. Preston Mullen, Jr. 1994. Integrality and Separability of Input Devices. *ACM Trans. Comput.-Hum. Interact.* 1, 1 (March 1994), 3–26. https://doi.org/10.1145/174630.174631

[15] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2012. Tangible Remote Controllers for Wall-size Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2865–2874. https://doi.org/10.1145/2207676.2208691

[16] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. 2018. KnobSlider: Design of a Shape-Changing UI for Parameter Control. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 339, 13 pages. https://doi.org/10.1145/3173574.3173913

[17] Karl Kroemer, Henrike B Kroemer, and Katrin E Kroemer-Elbert. 2001. *Ergonomics: How to Design for Ease and Efficiency*. Prentice Hall.

[18] I. Scott MacKenzie, Abigail Sellen, and William A. S. Buxton. 1991. A Comparison of Input Devices in Element Pointing and Dragging Tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '91)*. ACM, New York, NY, USA, 161–166. https://doi.org/10.1145/108844.108868

[19] G. Michelitsch, J. Williams, M. Osen, B. Jimenez, and S. Rapp. 2004. Haptic Chameleon: A New Concept of Shape-changing User Interface Controls with Force Feedback. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems (CHI EA '04)*. ACM, New York, NY, USA, 1305–1308. https://doi.org/10.1145/985921.986050

[20] Jens Müller, Tobias Schwarz, Simon Butscher, and Harald Reiterer. 2014. Back to Tangibility: A post-WIMP Perspective on Control Room Design. In *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces (AVI '14)*. ACM, New York, NY, USA, 57–64. https://doi.org/10.1145/2598153.2598161

[21] Donald A. Norman and Stephen W. Draper. 1986. *User Centered System Design; New Perspectives on Human-Computer Interaction*. L. Erlbaum Associates Inc., Hillsdale, NJ, USA.

[22] Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3793–3805. https://doi.org/10.1145/2858036.2858097

[23] Jeff Sauro and James R. Lewis. 2010. Average Task Times in Usability Tests: What to Report?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 2347–2350. https://doi.org/10.1145/1753326.1753679

[24] Lucia Terrenghi, David Kirk, Hendrik Richter, Sebastian Krämer, Otmar Hilliges, and Andreas Butz. 2008. Physical Handles at the Interactive Surface: Exploring Tangibility and Its Benefits. In *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI '08)*. ACM, New York, NY, USA, 138–145. https://doi.org/10.1145/1385569.1385593

[25] Melanie Tory and Robert Kincaid. 2013. Comparing Physical, Overlay, and Touch Screen Parameter Controls. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces (ITS '13)*. ACM, New York, NY, USA, 91–100. https://doi.org/10.1145/2512349.2512812

[26] Philip Tuddenham, David Kirk, and Shahram Izadi. 2010. Graspables Revisited: Multi-touch vs. Tangible Input for Tabletop Displays in Acquisition and Manipulation Tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 2223–2232. https://doi.org/10.1145/1753326.1753662

[27] Brygg Ullmer and Hiroshi Ishii. 1997. The metaDESK: Models and Prototypes for Tangible User Interfaces. In *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology (UIST '97)*. ACM, New York, NY, USA, 223–232. https://doi.org/10.1145/263407.263551

[28] Malte Weiss, Roger Jennings, Ramsin Khoshabeh, Jan Borchers, Julie Wagner, Yvonne Jansen, and James D. Hollan. 2009. SLAP Widgets: Bridging the Gap Between Virtual and Physical Controls on Tabletops. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems (CHI EA '09)*. ACM, New York, NY, USA, 3229–3234. https://doi.org/10.1145/1520340.1520462

[29] Elaine Wherry. 2003. Scroll Ring Performance Evaluation. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*. ACM, New York, NY, USA, 758–759. https://doi.org/10.1145/765891.765973

[30] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963