An Experimental Comparison of Touch Interaction on Vertical and Horizontal Surfaces

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ABSTRACT
Touch input has been extensively studied. The influence of display orientation on users' performance and satisfaction, however, is not well understood. In an experiment, we manipulate the orientation of multi-touch surfaces to study how 16 participants tap and drag. To analyze if and when participants switch hands or interact bimanually, we track the hands of the participants. Results show that orientation impacts both performance and error rates. Tapping was performed 5% faster on the vertical surface, whereas dragging was performed 5% faster and with fewer errors on the horizontal surface. Participants used their right hand more when dragging (85% of the trials) than when tapping (63% of the trials), but rarely used bimanual interaction. The vertical surface was perceived as more physically demanding to use than the horizontal surface. We conclude by discussing some open questions in understanding the relation between display orientation and touch.

Author Keywords
Tabletop computing, multitouch, pointing, vertical surface, horizontal surface, bimanual input, Fitts' law

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): User input devices and strategies (e.g., mouse, touchscreen)

General Terms
Experimentation, Human Factors

INTRODUCTION
A key invention in user interface technology is to use touch on display surfaces for input. The use of touch originates in the 1960s [6], and today touch input is seen on smartphones [17], tablets [36], information kiosks [4], and large displays [26]. With the arrival of touch-enabled consumer products (i.e., Apple's iPhone, Microsoft's Surface table), the literature on touch and related interaction techniques like multi-touch and direct-touch gestures has exploded [24, 34].

The research on touch has characterized the pros and cons of touch and compared it to other input modalities. For instance, touch seems to perform as well as mouse input [13, 29, 30] and the difficulties in selecting small targets with touch can be alleviated with appropriate interaction techniques [2, 25]. Algorithms for inferring the intended touch point have been significantly improved [18] and interaction techniques with touch for non-flat displays have been proposed [28].

While touch input has been studied separately on both tabletop interfaces and wall displays, it remains unclear how the orientation of the display affects interaction. Are vertical and horizontal surfaces equally suited for different types of tasks or is one orientation faster or more precise than the other? Do we use our hands the same way on vertical and horizontal surfaces and if not, how does that affect performance? These questions are becoming increasingly relevant as touch interfaces begin to allow both horizontal and vertical operation.

We attempt to answer these questions in a controlled experiment that measures the interaction speed and accuracy of participants who use a horizontal and a vertical surface. Moreover, we analyze differences in touch behavior on horizontal and vertical surfaces by tracking the participant's dominant and non-dominant hand. The main contribution of this paper is an investigation of how orientation impacts touch input. Thereby, we aim to help designers make informed decisions on the placement and size of graphical elements and to choose the most appropriate orientation when designing touch interfaces.

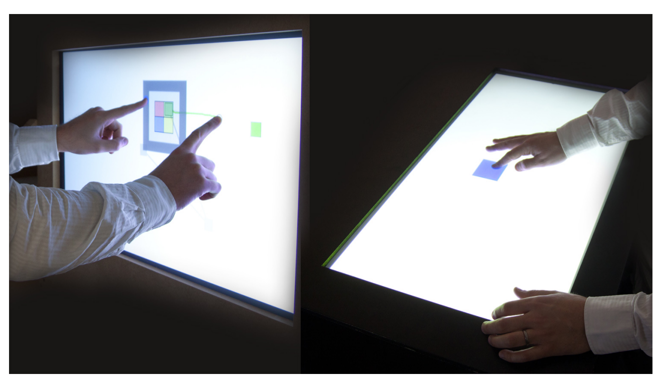

Figure 1. A user interacts with a vertical and a horizontal surface.

NordiCHI '12, October 14–17, 2012, Copenhagen, Denmark

RELATED WORK

An early study of non-stylus touch input, which compared mouse input to touch input on a vertical screen, was reported in 1991 by Sears and Shneiderman [30]. They found that for targets larger than 4 pixels (0.17×0.22 cm) touch input and mouse input performed equally fast. Later studies by Sasangohar et al. [29] and Forlines et al. [13] found touch input to be faster than mouse input, but observed much higher error rates for touch than did Sears and Shneiderman. Forlines et al. [13] suggested that the difference was an effect of the orientation, but this speculation has neither been confirmed nor rejected.

A prominent quality of touch is to allow several touch points and two-handed input. Bimanual input has been widely studied in HCI with various input devices, and several studies have found it to be more efficient than unimanual input [7, 8, 16]. Kin et al. [21] studied bimanual interaction on a horizontal surface and found that it reduced selection time. Users' preference for and effectiveness with bimanual input may, however, depend on the orientation of the display surface.

A number of studies have compared horizontal and vertical displays, but without focusing on touch. Rogers and Lindley [27], for instance, compared collaboration around interactive displays with varying orientations; input was done with an electronic pen. Bi et al. [5] studied the usability of different planar regions for touch in a desktop setting with seated participants.

Recent research projects have attempted to combine horizontal and vertical touch displays [22, 33, 35] into one system. Curve [35] and BendDesk [33] are both designed as desktop workstations and feature a continuos screen in which the horizontal and vertical surfaces are joined by a curve. Wimmer et al. [35] described the design process of Curve and reported on early evaluations using paper prototypes – the final design was described but not evaluated. While Weiss et al. [33] investigated dragging across the curve, it remains unclear how touch interaction differed between the horizontal orientation and the vertical orientation.

In summary, the above survey lists much research related to vertical and horizontal touch input. However, we are unaware of studies that focus on comparing vertical and horizontal touch input.

METHOD

The aim of this study was to investigate the effect of orientation of touch surfaces on speed, accuracy, and fatigue. To investigate and explain possible differences, we tracked the dominant and non-dominant hand of participants. With this study we test five hypotheses:

H1 Vertical surfaces are operated more slowly than horizontal surfaces because users cannot support their arms (Bi et al. [5]).

H2 Horizontal surfaces produce more errors than vertical surfaces. The reason for this is that on horizontal surfaces the angle between finger and surface (and thus the shape of the contact area) changes for different areas (Forlines et al. [13]).

H3 Smaller targets are more likely to be selected by the dominant hand as the dominant hand is preferred for fine-grained actions (Jones and Lederman [19]).

H4 Dragging is more demanding than tapping as the finger must remain in contact with the surface (Forlines et al. [13]). Therefore, dragging is more likely to be performed with the dominant hand than tapping (Jones and Lederman [19]).

H5 Horizontal surfaces promote two-handed interaction more than vertical surfaces as it is tiring to keep both arms stretched in front of the body for an extended period of time.

Participants

Sixteen right-handed participants (12 male, 4 female) aged between 18 and 37 ($M = 23$) were paid an equivalent of 20 US dollars to participate in the experiment. The heights of the participants varied between 155 and 200 cm ($M = 179$). None of the participants had prior experience with vertical or horizontal surfaces of the size used in this study. However, all had experience with touch devices (tablets and smartphones) and all but two participants currently owned such devices.

Apparatus

We used two touch surfaces that were similar in every aspect except for their orientation. Orientation was varied between vertical and horizontal. Whereas intermediate orientations and flexible switching between vertical and horizontal are explored in the literature [22, 35], most orientations in research prototypes and commercial applications continue to be either vertical or horizontal. The touch surface was 80 x 46 cm, with a backprojected resolution of 1280 x 720 pixels (0.63 mm/pixel). The surfaces relied on camera-based, infrared touch detection and used Community Core Vision[1] for tracking. With this setup, finger touches could be detected at a resolution of approximately 0.2 mm with no noticeable latency.

As we wanted to investigate fatigue, the exact placement of the surfaces was important. Both surfaces were designing to be used in a standing position. The heights were adjusted in accordance with the ergonomic guidelines found in [32] and [1] to fit an European adult of average height (169 cm). The top of the horizontal surface was placed at a height of 115 cm, ideal for precision work. The bottom edge of the vertical surface was placed at the same height as the average height of the elbow (109 cm) and could thus be touched with the elbow joint in a 90° angle. The top edge of the vertical surface was around the height of the eyes (163 cm).

Tasks

The four tasks used in this study were chosen so as to cover the actions commonly performed by users of touch surfaces. Tapping was investigated in two tasks (*selection* and *grid*), whereas dragging was studied in a separate task (*dragging*).

[1] http://ccv.nuigroup.com/

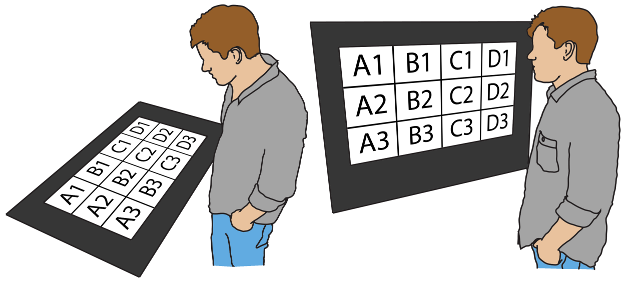

Figure 2. Overview of the 12 cells used to generate targets in the grid task.

Finally, bimanual touch behavior was investigated in a compound task (*compound*).

The selection and the dragging task follow the Fitts' law paradigm. The performance of an input device can be described using Shannon's formulation of Fitts' law [11, 23]. With this law movement time (MT) can be predicted using the following equation:

$$MT = a + b \cdot ID, \text{ where } ID = log_2(\frac{D}{W} + 1) \qquad (1)$$

In this equation the index of difficulty (ID) is expressed by the width (W) of targets and the distance between targets (D). The values a and b are determined using linear regression. The standard measure used for comparing the performance of input devices is the index of performance (IP), which is defined as $1/b$. We have chosen this formulation over that of Douglas et al. [10] in order to be able to compare our results with those of Forlines et al. [13].

In the following we describe the design of the four tasks.

Selection task

The selection task required participants to tap circular targets of varying width, spaced at varying distances. Only one target was visible at a time. Three target widths (W = 20, 50, 100 pixels measuring 1.26, 3.15, 6.30 cm) were combined with three distances (D = 300, 600, 900 pixels measuring 18.9, 37.8, 56.7 cm) to produce nine index of difficulty values (ID). The hardest task had $ID = 5.5$, while the easiest had $ID = 2.0$. The dataset comprised 20 blocks each containing 9 selections (one per ID), resulting in a total of 180 selections. The order of targets and their location was randomly generated. To ensure that all parts of the surface were being touched equally frequent, the 20 blocks were selected from a pool of 100 randomly generated blocks using an optimization algorithm. The algorithm divided the surface into 16 cells (4 × 4) and found a combination of blocks in which each of the cells were touched equally frequent.

Grid task

The Fitts' law selection task helps characterize the performance of the two orientations in a reliable way. However, we also wished to describe which hands participants used to operate particular areas of the surface, and what would trigger a switch of hand. For this purpose we designed a secondary selection task based on a division of the surface into a grid of 12 cells (3 × 4), each measuring 320 × 240 pixels or 20×15 cm (see Figure 2). The cells were only used to position targets and were not visible to the user. In this task, the participants selected a 50 pixel (3.15 cm) circular target placed close to the center of the cell (i.e., randomly translated within a 75 pixel (4.73 cm) radius from the center of the square). The task required the participants to tap pairs of all cells (e.g., for cell A1 : [A1→A2, A1→A3, ..., A1→D3]). This resulted in a total of 12 × (12 - 1) = 132 selections. To prevent the participants from anticipating the position of targets, the order of targets was randomized.

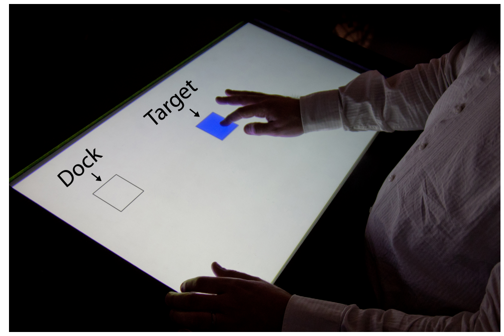

Figure 3. A user performs the dragging task on the horizontal surface. To complete the task the user drags a target (blue square) to a dock (black/white square). Labels and arrows were added as illustration.

Dragging task

We wished to investigate whether the participants' preference for using one hand or the other changed between selecting and dragging (H4). We thus included a traditional docking task [13] with widths and distances similar to the ones used in the selection task (W = 20, 50, 100 pixels and D = 300, 600, 900 pixels). Participants started the block by tapping a green square labeled "start", which revealed a solid blue square (target) and a white square with a black border (dock), see Figure 3. The participants docked a target by moving the center of the target within 10 pixels (0.63 cm) of the center of the dock and releasing it. Doing so revealed the next target and dock. The 10 pixel margin was included so as to minimize the effect of differences among participants in how accurately they felt the target should be aligned with the dock [13]. The dataset was generated using the procedure described for the selection task. As with the selection task, each block contained 9 dockings (one per ID). Our pilot study showed that the dragging was physically straining and we thus included only 15 blocks, resulting in a total of 135 dockings.

Compund task

To investigate bimanual input, we chose a colorized compound task introduced by Kabbash et al. [20] and later used by Balakrishnan and Hinckley [3]. In this task participants connected 12 squares (40 x 40 pixels, 2.52×2.52 cm) by drawing colored line segments between them (Figure 4). To successfully connect squares A and B, the participant had to draw a line from square A to square B of the same color as square B. To do so the participant dragged a semitransparent color palette on top of square A, tapped the square and dragged a

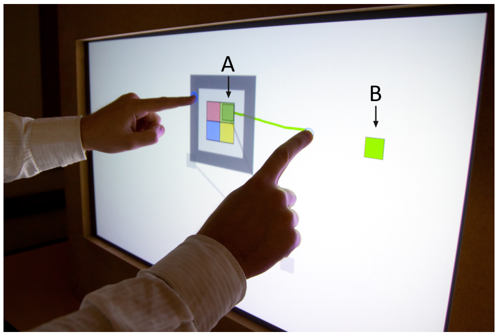

Figure 4. A user performs the compound task on the vertical surface. To connect squares, the participant draws a colored line from square A to B. The color of the line to be drawn is given by the color of square B.

finger to square B. The next square was revealed as soon as the previous squares had been connected. By manipulating the color palette with one hand and drawing with the other, participants can connect the squares sequentially and avoid having to go back to the previous square to fetch the color palette. We deliberately chose a task that could be completed both unimanually and bimanually, as we wanted to investigate if the horizontal orientation invited more bimanual use than the vertical orientation (H5).

We replicated the task setup used in [3]. For each condition, participants performed 5 blocks of trials. Each block consisted of 2 sets of 12 squares. In one set, squares were 200 pixels (12.60 cm) apart, in the other set 400 pixels (25.20 cm). The location of the squares was randomly chosen, but with the constrain that no line segment within a set could cross another segment. The order of the 200 pixel set and 400 pixel set was randomized within each block.

Experimental design

The experiment used a 2×4 within-subjects design. The first independent variable (orientation) had two levels (horizontal, vertical), whereas the second independent variable (task) had four levels (selection, grid, dragging, compound). The starting orientation alternated between participants and the order of the tasks was shifted using a latin square. In summary, the experiment consisted of:

$$\begin{aligned}&\text{16 participants} \times \\ &\text{2 orientations (horizontal, vertical)} \times \\ &\begin{pmatrix}\text{1 task of 180 trials (selection)} + \\ \text{1 task of 132 trials (grid)} + \\ \text{1 task of 135 trials (dragging)} + \\ \text{1 task of 120 trials (compund)}\end{pmatrix} \\ &= \text{18144 trials}\end{aligned}$$

Dependent variables

The dependent variables we measured were completion time, task specific errors, and subjective satisfaction. Completion time was measured as the time between a target was shown and successfully tapped; errors did not finish a trial. Task specific errors included taps outside a target (selection and grid tasks), letting go of a dragged target outside the dock (dragging task), and coloring line segments in the wrong color (compound task).

Subjective satisfaction was measured with a questionnaire based on Douglas et al. [10]. In contrast to Douglas et al., we used continuous graphical rating scales to avoid constraining participants by the original 5-point rating scale. Also, we only used 8 questions from Douglas et al. (see Table 2 for the questions we did include) because some questions were expected to be confusing to participants in the present context. Between tasks we asked participants to rate the mental and physical effort (taken from NASA's TLX [15]) and complete a questionnaire about fatigue. Satisfaction questions were quantified based on the position of the slider used to answer the question, resulting in a value between 0 and 100.

Logged data

For each touch event, a timestamp was logged. The experiment was recorded using two cameras per surface. By synchronizing the video files from the experiment with the log files, we identified which hand had performed the touch event. Two raters used a custom-developed video software to perform the identification. An analysis of interrater reliability using the Kappa statistic showed almost perfect agreement [12] among raters ($\kappa = .93, p < .001$).

Procedure

First, the participants were welcomed and given an introduction to the study. To prevent influencing how participants used their hands, the purpose of the study was presented as a study of the speed and accuracy of the two surfaces. The participants completed the four tasks on both orientations. They were told that they could interact with the surfaces in whatever way they pleased, using one or multiple fingers and one or multiple hands. For each type of task, the participants were first presented with a training task during which the experimenter explained the task verbally. Participants could repeat the training task until they were comfortable completing the task. Then the participants completed the actual task, which was followed by a questionnaire asking participants to assess the mental and physical demand of the task. When all four types of tasks were completed, participants rated the surface with a questionnaire. Before repeating the above procedure at the other orientation, participants were offered a short break. Finally, during debriefing participants were asked to select the surface they preferred and to explain the differences they had identified. The total duration of the experiment was approximately 55 minutes per participant.

RESULTS

We initially conducted a repeated measures analysis of variance (ANOVA) on the mean completion times, with orientation and task as independent variables. This analysis shows no main effect of orientation on completion time ($F_{1,15} = 4.325, p > .055$). We did, however, find an interaction between orientation and task ($F_{3,13} = 3.508, p < .05$). Post-hoc test showed that the tasks involving tapping (selection and grid) were performed faster on the vertical surface, whereas the tasks involving dragging (dragging and compound) were performed faster on the horizontal surface. Figure 5 illustrates these interactions between orientation and task. In the following we investigate tapping, dragging and

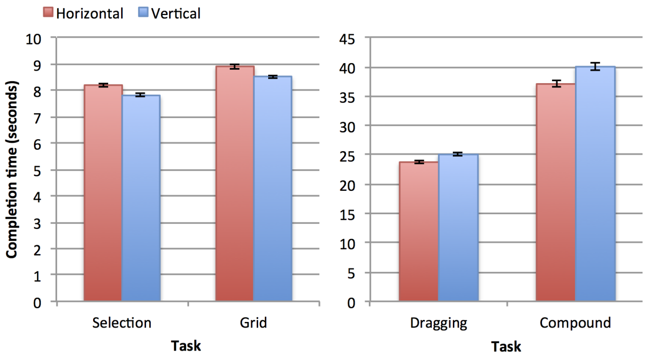

Figure 5. Mean block completion time (+/- standard error of the mean, SEM) by orientations and task.

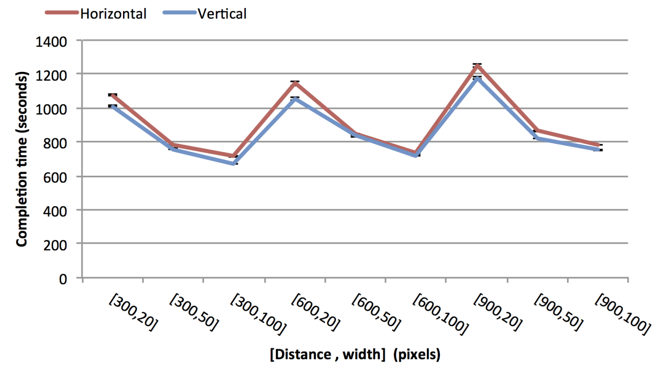

Figure 6. Mean block completion time (+/- standard error of the mean, SEM) for the nine conditions in the selection task.

bimanual interaction separately. First, we concentrate on time and errors, next we analyze the hand interaction.

Tapping

In this section we investigate the effects of orientation on tapping performance by examining the data from the selection task and the grid tasks.

Time analysis

Selection time was measured as the time from a target was displayed to the successful selection of that target. For the selection task we found a main effect of orientation on selection time ($F_{1,15} = 10.203, p < .01$), with mean selection times of 0.91s ($SD = .39$s) and 0.87s ($SD = .35$s) for horizontal and vertical orientation, respectively. Using Cohen's terms [9], the partial eta-squared value for this difference is large ($\eta^2 = .41$).

This difference in selection time was supported by the data from the grid task. In this task the participants also performed significantly faster on the vertical surface ($F_{1,15} = 5.526, p < .05$), with mean selection times of 0.81s ($SD = .23$s) for the horizontal surface and 0.78s ($SD = .17s$) for the vertical surface. Figure 6 shows the average completion time per trial for the nine conditions. As expected, smaller and more distant targets took longer to select than larger and closer targets. Especially the 20 pixel target caused longer completion times.

Error analysis

An selection error was recorded when the participants failed to hit the target on their first attempt. However, when participants did not use both hands, some of them unintentionally touched the surface with their free hand. To avoid false error detection, all touch events that were more than 150 pixels (9.5 cm) away from the target were not counted as errors.

The orientation of the surface did not affect the number of errors in the selection task ($p > .5$) or the grid task ($p > .1$). Participants on average failed to select 11.5% of the targets ($SD = 5.0\%$) in the selection task. One common challenge faced by users of touch interfaces is that their fingers occlude small target (viz., the fat finger problem [31]). This problem is also present in our data as the width of targets had a strong effect on the number of errors ($F_{2,14} = 54.599, p < .001$). The small 20 pixel targets were by far the most difficult to select. 84.1% of all errors were registered with this target size and the participants failed to select approximately every third small target ($M = 29.11\%$, $SD = 11.0\%$).

Fitts' law analysis

Table 1 summarizes the results of linear regression of error-free selection times against index of difficulty. The high r^2 values suggest a good fit of the linear model. Our IP values are high compared to the 8.05 found by Forlines et al. [13]. One reason for this could be that we allow two handed interaction, which earlier studies did not. In a study using Fitts' reciprocal tapping task, Sasangohar et al. found an IP 5.53 for touch interaction [29]. However, this IP is calculated using another formulation of Fitts' law [10], which include error trials and thus yield lower IP values.

Orientation	a	b	IP	r^2
Horizontal	0.51	0.09	11.11	.94
Vertical	0.51	0.08	12.5	.95

Table 1. a **and** b **parameters, Index of Performance (**IP**), and linear fit for each orientation.**

Dragging

Whereas the tapping tasks were completed faster on the vertical surface, the dragging task was completed significantly faster on the horizontal surface ($F_{1,15} = 6.067, p < .05$). On the horizontal surface the average completion time was 2.65s ($SD = .91$s), on the vertical surface it was 2.79s ($SD = 1.05$s). This is a large effect size ($\eta^2 = .36$).

Docking time

Each trial in the dragging task consisted of two actions: (a) acquiring the target and (b) docking the target. There was no significant difference between the two surfaces in terms of acquiring a target ($p > 0.05$). Docking of targets, however, were done significantly faster on the horizontal surface ($F_{1,15} = 8.731, p < .01$). Similar to tapping, we observed that the width of a target affected the docking time strongly ($F_{2,14} = 11.495, p < .001$) with the 20 pixel targets taking the longest to dock. This is interesting as the threshold for

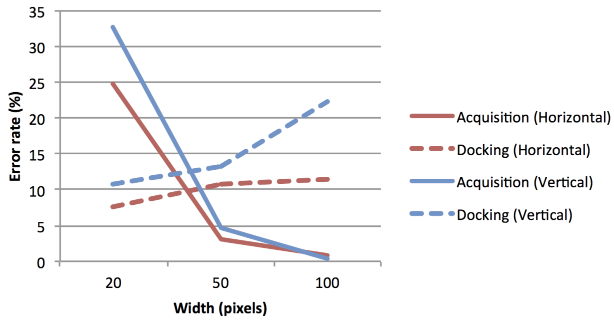

Figure 7. Average selection and docking error rates by orientation and target width.

acceptable docking was constant for all widths (10 pixel); the docking of small targets did thus not require greater precision. Forlines et al. [13] found a similar effect and explained it by the fact that participants occluded the smallest targets with their finger. This might also be the case in our study. Certainly, our data show bigger differences in docking time between 20 pixel targets (which were almost occluded by the finger) and 50 pixel targets than between 50 pixel target and 100 pixel target.

Error analysis

We distinguish acquisition errors and docking errors. An acquisition error occurred when the participants failed to acquire the target on their first attempt, whereas a docking error occurred when the participants failed to dock the target on their first attempt. Orientation affected both types of errors in the dragging task, as we observed significantly fewer acquisition errors ($F_{1,15} = 12.044, p < .01$) and docking errors ($F_{1,15} = 10.546, p < .01$) on the horizontal surface compared to the vertical surface. On average 9.6% ($SD = 3.5\%$) of the acquisitions and 9.9% ($SD = 6.3\%$) of the dockings failed on the horizontal surface; on the vertical surface 12.6% ($SD = 3.8\%$) of the acquisitions and 14.8% ($SD = 3.9\%$) of the dockings failed.

We found an interaction between both width and the number of acquisition errors ($F_{2,14} = 9.529, p < .01$) and between width and the number of docking errors ($F_{2,14} = 9.919, p < .01$), which merit explanation. As Figure 7 shows, the majority of acquisition errors occurred with the 20 pixel target and as the widths increased, the error rates decreased. This relation is to be expected as larger targets are easier to select than smaller targets. Surprisingly, we observed the opposite relation between docking error rate and the width of target; the docking error rates were lowest for 20 pixel targets and increased with target width. This indicates that participants were more careful when docking smaller targets.

Bimanual interaction

The compound task, in which participants connected squares by drawing colored lines between them, was completed by performing a series of dragging actions. The data from this task support the results from the dragging task, as the block completion time was significantly lower with the horizontal orientation than with the vertical ($F_{1,15} = 4.559, p < .05$).

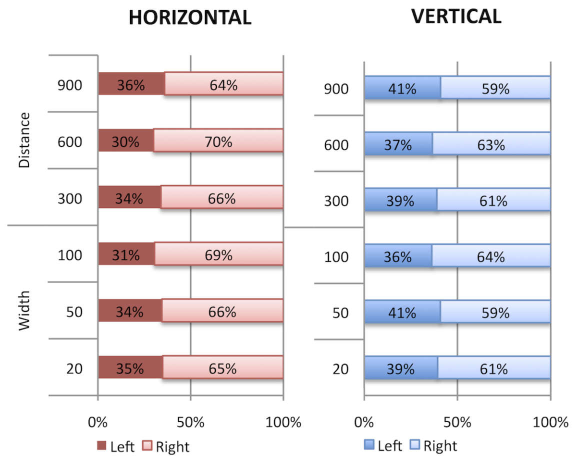

Figure 8. Choice of hand for the selection task divided by distance and width for each orientations.

The average block completion time was 37.1s ($SD = 7.4$s) on the horizontal surface and 40.0s ($SD = 7.5$s) on the vertical surface. With $\eta^2 = .23$, this is a large effect size. The purpose of the compound task was mainly to investigate bimanual interaction. For this reason, we will not investigate time or error data in detail.

HAND ANALYSIS

In this section we analyze the data on the hand interaction of the participants and relate it to the time/error analysis. Again, we examine tapping, dragging, and bimanual interaction separately.

Tapping

The orientation of the surface had no significant effect on the participants' choice of hand in neither the selection task ($F_{1,15} = 3.882, p > .05$) nor the grid task ($F_{1,15} = 0.325, p > .5$). On average the participants used their right hand for 63.9% ($SD = 14.39\%$) of the targets in the selection task. Recall that all participants were right-handed. Three participants (18%) completed the selection task using only their right hand on the horizontal surface, whereas all participants used both hands on the vertical surface.

Figure 8 shows participants' hand interaction divided by distance and width for both orientations. Width had a significant effect on the choice of hand ($F_{2,14} = 18.741, p < .001$), as did distance ($F_{2,14} = 16.369, p < .001$). The 900 pixel distance caused participants to use their left hand more frequently than the other distances. The reason for this result is probably that targets with 900 pixel distances were more likely to result in a movement across the middle of the surface. Considering the high error rate for 20 pixel targets, we expected that the participants would use their right hand more frequent for selecting these targets than for selecting larger targets. However, the data show that the 100 pixel targets were more frequently selected by the right hand compared to targets of other sizes.

Whereas the primary objective of the selection task was to investigate differences in time and error, the grid task was

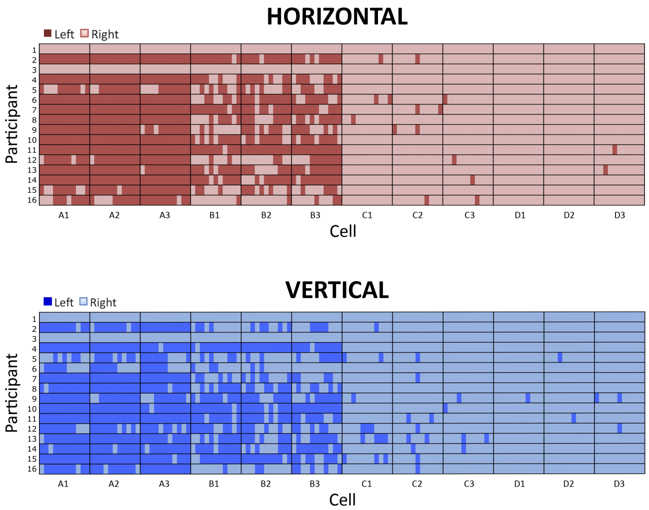

Figure 9. A plot of the hand activity in the grid task for both orientations. In the plot rows represent participants and columns represent cells.

designed to uncover how participants use their hands on different parts of the surface. Recall that this task divided the surface into twelve cells (see Figure 2) and required participants to tap a target in every cell and subsequently in every other cell. Figure 9 shows a plot of all taps on both orientations; the 132 selections have been sorted by cell. Dark colors represent left hand tapping and light colors represent right hand tapping. If a cell is only colored dark or light, this means that the participant used the same hand for selecting all 11 targets. This can for example be observed with participant 1 and 3, who only used their right hand for tapping the cells.

Figure 9 shows that the column of a cell strongly affected the participants' choice of hand ($F_{3,13} = 27.656, p < .001$). Pairwise comparisons between the columns showed a significant trend: The right side of the surface was strongly dominated by the right hand (99% right hands selections for column D, 95% for column C). Column B was operated almost equally frequent by the left and the right hand (47% right hand selections), whereas column A was dominated by the left hand (21% right hand selections). In total, 66.5% ($SD = 14.7\%$) of the selections were performed with the right hand. This number is similar to the 63.9% ($SD = 14.4\%$) observed in the selection task.

Some areas of the surfaces were operated faster than others ($F_{11,5} = 19.117, p < .05$). Figure 10 shows the average selection time per cell for both orientations; lighter colors mean faster selection time. The boxed cells were shown to be significantly faster than the remaining cells in a post-hoc test. On the horizontal surface these cells are the ones closest to the user. The lower corner cells (A3 and D3) were slow compared to the center cells (B3 and C3). We believe this is due to the fact that participants often occluded these cells with their hands and thus did not see the targets initially. On the vertical surface the fastest area is the two center cells (B2 and C2), which corresponds to the natural homing position of the hands.

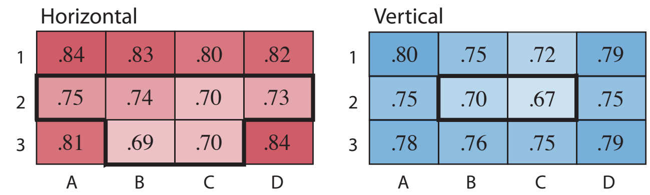

Figure 10. Average selection time in seconds per cell for both orientations. The boxed cells are operated significantly faster than the remaining.

Error rates also differed significantly across cells ($F_{11,5} = 1.672, p < .05$). Post-hoc test showed that for both orientations, the error rate was significantly higher for the two outer columns than for the two middle columns ($p < .05$).

Dragging

We observed a main effect of orientation on the choice of hand in the dragging task ($F_{1,15} = 6.505, p < .05$). The participants used their left hand less frequent when dragging a target on the horizontal surface ($M = 10.2\%, SD = 15.1\%$) than on the vertical surface ($M = 18.7\%, SD = 17.1\%$). With the horizontal orientation, seven participants (43%) completed the dragging task using only their right hand, whereas four participants (25%) did so on the vertical surface. Figure 11 shows the choice of hand divided by distance and width for each orientation. Even though smaller targets were difficult to select (as seen in the error analysis), the width of a target did not affect which hand participants used for dragging it ($p > .05$).

It is interesting to note that the participants were slower and committed more errors on the vertical surface even though they used both hands more on this surface. To gain more insights into how participants used their hands, we plotted the hand activity of each participant for both orientations (Figure 12). In the plots, columns represent blocks (each containing 9 trials). The plots confirmed the increased use of the left hand on the vertical surface (i.e., as seen by the increased

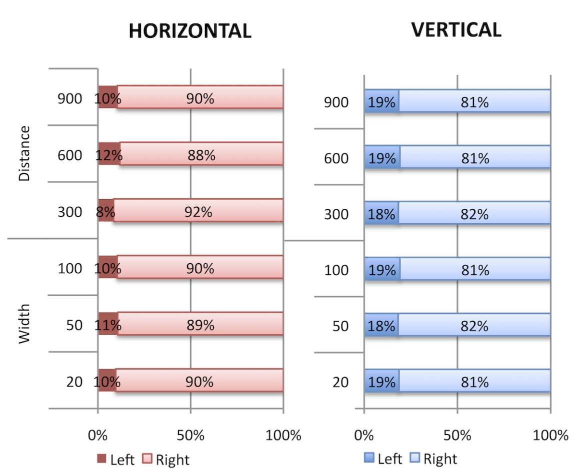

Figure 11. Choice of hand for the dragging task divided by distance and width for each orientations.

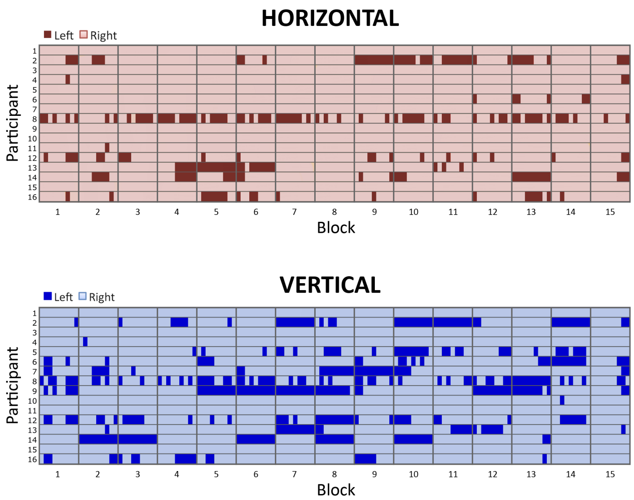

Figure 12. A plot of the hand activity in the dragging task for both orientations. Rows represent participants and columns represent blocks.

number of dark areas). However, when comparing the number of dark colored areas of the plots, it became apparent that participants did not switch hands more often on the vertical surface. An ANOVA on the number of hands switches confirmed this ($F_{1,15} = 1.463, p > .245$). Instead, participants used their left hand for longer periods on the vertical surface. During debriefing, participants explained that they found the dragging task fatiguing and thus relieved their right hand by switching to their left. Only one participant (participant 8) completed the task by alternating between hands.

Bimanual interaction

The compound task was designed to promote asymmetric bimanual interaction, but interestingly it was mainly completed with one hand. Eleven participants (68%) did so on the horizontal surface, ten (62%) on the vertical surface. To investigate whether there was a relation between the level of bimanual activity and completion time, we plotted time and bimanual activity (Figure 13). The level of bimanual activity was calculated based on a the number of times a participant used a different hand for aligning the palette and for drawing the line. As seen on Figure 13, all four trendlines have negative slopes, which indicates that a higher levels of bimanual activity leads to lower completion times. We found no significant effect of orientation on the level of bimanual activity ($p > .05$) and no clear pattern in when participants used their left or right hand. Three participants moved the palette with their left hand, one participant used only the right hand, while two participants used their left and right hand alternately.

QUALITATIVE RESULTS

Figure 14 shows the results from the TLX questions that the participants answered after each task. We analyzed the questionnaires using multivariate analysis of variance and found a main effect of orientation on the task load index ($F_{1,15} = 7.183, p < .05$). Pairwise comparisons on each measure showed that participants found the dragging task, grid task, and compound task physically more demanding to

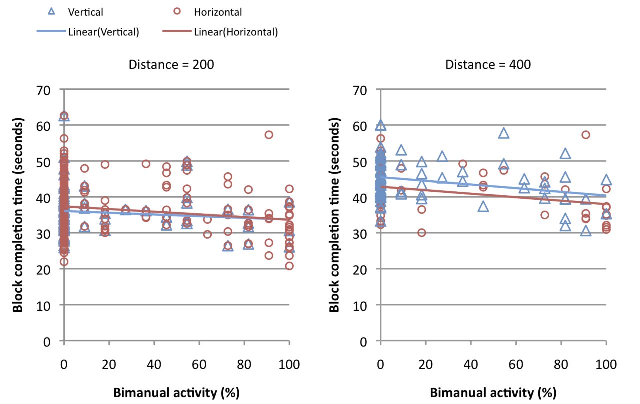

Figure 13. Mean block completion time against orientation and level of bimanual activity.

complete on the vertical surface compared to the horizontal surface ($p < .05$).

After having completed the task set on either surface, the participants answered a questionnaire containing ten questions (see Table 2). The difference in physical demand observed in the TLX questions was supported by this questionnaire. Participants found that the vertical surface required a higher physical effort and that it was more uncomfortable ($p < .05$). The participants felt significantly more fatigue in their shoulders when using the vertical surface. During debriefing 13 participants preferred the horizontal orientation, and explained that they felt less tired when using that surface. The 3 participants that preferred the vertical orientation explained that the vertical surface offered a better overview of the surface, as the hands were less likely to occlude objects on the screen.

DISCUSSION

In terms of speed we found no superior orientation. Tapping on the vertical surface was about 5% faster than on the horizontal surface. In contrast, dragging was 5% faster on the

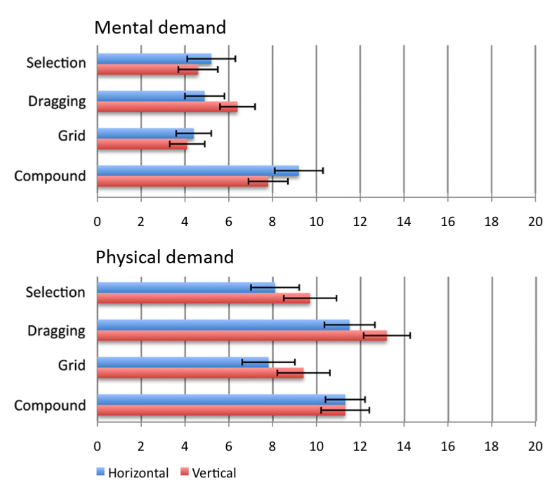

Figure 14. Results from TLX Questions. For TLX, less is better.

horizontal surface, mostly due to higher error rates on the vertical surface. The hypothesis that horizontal surfaces are operated faster than horizontal surfaces (H1) thus only holds true for dragging tasks. Designers of touch interfaces should therefore consider whether their application involves primarily tapping or dragging when deciding on an orientation.

Forlines et al. [13] suggested that the relatively high error rates found in their study of horizontal touch were an effect of surface orientation. They argued that horizontal surfaces would produce more errors than vertical surfaces (H2) because the shape of the contact area between finger and surface changes for different areas of the horizontal surface (as opposed to the vertical surface). We find no evidence in our data to support this hypothesis. On the contrary, analysis of the dragging task showed significantly lower error rates for the horizontal surface. The participants successfully acquired more targets on the horizontal surface (91.4% vs. 87.4%) and also docked slightly more targets successfully (95.5% vs. 94.1%). This difference might be a consequence of the fact that the left hand was used more by some participants on the vertical surface to relieve their right hand.

Our results show that 20 pixel (1.26 cm) targets are to small to be successfully selected on a touch screen of the size used in our study. Approximately every third target (29.1%) was missed and 84.1% of the errors in the selection task and 86.0% of the acquisition errors in the docking task were recorded with this target size. Interestingly, the higher error rates of the 20 pixel targets did not lead participants to use their dominant hand more often, and the hypothesis that smaller targets are more likely to be selected by the dominant hand (H3) cannot be accepted.

The participants' choice of hand was strongly affected by the action being performed. Whereas the participants used their right hand for only 63.9% of the targets in the selection task, they used their right hand for 85.6% of the targets in the dragging task. This confirms the hypothesis that the right hand is more likely to be used for dragging than selecting (H4). Dragging was found to be significantly more fatiguing on the vertical surface and many participants verbally expressed discomfort during the vertical dragging task. Participants explained that it was more difficult to maintain contact with the vertical surface when dragging (especially in the lower part of the surface). In order to drag a target from the right side of the surface to the left, participants had to rotate their arm and wrist into awkward positions. This was not the case on the horizontal display.

Question	Horizontal		Vertical		Sig.
	M	SD	M	SD	
The mental effort required for operation was too low/too high	3.7	2.4	3.2	2.1	
The physical effort required for operation was too low/too high	4.8	2.0	6.5	2.2	*
Accurate touch was easy/difficult	4.3	2.8	4.5	2.7	
Finger fatigue (none/very high)	3.0	2.6	4.2	3.2	
Wrist fatigue (none/very high)	3.3	1.7	3.3	2.4	
Shoulder fatigue (none/very high)	3.9	2.9	7.0	2.4	*
Neck fatigue (none/very high)	4.6	3.1	3.8	3.2	
Back fatigue (none/very high)	3.6	2.8	4.2	2.9	
General comfort (very comfortable/very uncomfortable)	4.1	2.2	6.0	1.4	*
Overall, the surface was very easy to use/very difficult to use	2.8	2.1	3.7	2.4	

Table 2. Results from final questionnaire. Significant differences are marked with *

We found low levels of bimanual interaction; many participants chose to use one hand even when the task afforded switching hands or using bimanual interaction. We found no evidence that horizontal surfaces promote more two-handed interaction than vertical surfaces (H5). Guiard's Kinematic Chain Model [14] describes how humans use asymmetric division of labor when doing physical task. Put differently, the dominant and non-dominant hand play different but dependent roles. The non-dominant hand performs coarse actions that frame the more fine-grained actions of the dominant hand – for example, like holding a painter's palette in the non-dominant hand and using a brush in the dominant hand to blend colors and make strokes on the canvas. What is surprising, though, is that few participants did the compound task bimanually. Also, according to the Kinematic Chain Model, one would expect that participants operated the paint palette using their left hand. However, three participants operated it with either right hand or left and right hands alternately. It seems that more studies are needed to investigate whether the Kinematic Chain Model can be used to explain differences caused by orientation.

In terms of subjective satisfaction, the participants' preference was clear: The horizontal surface was preferred over the vertical surface by 13 out of 16 participants. Participants found the horizontal surface more comfortable and less physically demanding to use than the vertical display.

Our study has a number of limitations that should be addressed in future work and which influences the extent to which the findings may be generalized. In particular, participants were standing while interacting, not seated as in many previous studies of touch input with horizontal surfaces. Moreover, we studied high intensity use only, meaning that the participants interacted with the screen constantly. This might have led to more fatigue and affected the participants' preference for the horizontal surface. Finally, we used only one type of bimanual task; we could have included tasks that even more directly encourage bimanual interaction.

CONCLUSION

We have compared the performance, hand choices, and satisfaction of 16 participants who tapped and dragged on comparable vertical and horizontal touch surfaces. Our results show that tapping was performed 5% faster on the vertical surface, whereas dragging was performed 5% faster and with fewer errors on the horizontal surface. Participants used their right hand more when dragging (85% of the trials) than when tapping (63% of the trials), but rarely used bimanual interaction. The horizontal surface was preferred by 13 of 16 participants as the vertical surface was found physically more demanding to use.

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