Multi-Touch Rotation Gestures: Performance and Ergonomics

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ABSTRACT
Rotations performed with the index finger and thumb involve some of the most complex motor action among common multi-touch gestures, yet little is known about the factors affecting performance and ergonomics. This note presents results from a study where the angle, direction, diameter, and position of rotations were systematically manipulated. Subjects were asked to perform the rotations as quickly as possible without losing contact with the display, and were allowed to skip rotations that were too uncomfortable. The data show surprising interaction effects among the variables, and help us identify whole categories of rotations that are slow and cumbersome for users.

Author Keywords
Rotation; multi-touch interaction; gestures; ergonomics.

ACM Classification Keywords
H.5.2. User Interfaces: Evaluation/Methodology, Input Devices and Strategies.

INTRODUCTION
Recent advances in technology have brought multi-touch interaction capabilities to a variety of displays including mobile phones, tablets and large screens. Rotation is a widely used multi-touch gesture but has yet to be studied in-depth with respect to human factors such as performance and ergonomics. We define a *rotation* as a radial motion of the thumb and index finger around a fixed point. These motions of the fingers can convey a specific meaning or action that is acted upon by the computer [1]. Unlike simple gestures such as tapping, rotation gestures are difficult to analyse due to their complex biomechanical nature. For example, the average dominant wrist extensor muscle activity has been shown to be much higher for gestures that employ two fingers as opposed to one [6].

This paper presents a thorough empirical investigation of multi-touch rotation gestures with a focus on the performance of such gestures. Using a novel experimental methodology we study many within-gesture factors affecting rotation in a single experiment. In terms of the performance of multi-touch rotation interaction, we focus on the effects of within-gesture variables such as direction, diameter, angle and spatial location. When considering ergonomics, we report the variable combinations that result in rotations that are physically impossible to do with a single continuous movement. The results of this research will help designers to create optimal multi-touch interfaces and will reveal the most efficient ways to employ rotation gestures.

RELATED WORK
Several recent research projects have proposed different multi-finger and hand gestures, including rotation, for use with multi-touch displays [4, 5]. For example, Wu and Balakrishnan [8] describe the use of a rotation widget that allows users to manipulate the orientation of an object using a two-point gesture with the thumb and index finger.

A small number of researchers have discussed the usability or performance of rotation gestures in comparison to other techniques. Hancock *et al.* [4] presented a comparison of different multi-touch techniques with a focus on the input/output degrees of freedom, while Kruger *et al.* [5] examined the speed and accuracy of traditional rotation gestures in comparison to Rotate'N Translate. Zhao *et al*. [9] combined the Mahalanobis distance metric and Fitts' law to create a model of movement time for translation, rotation, and scaling. The model shows a linear relationship between movement time and their model. However, in all of these studies, the participants in the experiments used combinations of gestures. This means it is difficult to isolate the performance of rotations. Furthermore, an evaluation of the individual within-gesture parameters was not completed.

Examining gestures with respect to their speed, accuracy and degrees of freedom can be an extremely fruitful approach. However, there are other important factors too, such as ergonomics. Muscovich and Hughes [7] noticed that it can be difficult to complete large rotations without positioning the hand in an awkward manner. This is because of the physical limitations of finger and wrist movement. There are also musculoskeletal issues to be considered. Lozano *et al.* [6] found that multi-touch interaction can place high levels of stress on the musculoskeletal system. In particular, two-finger gestures generated high levels of muscle activation and the position of the device also affected musculoskeletal stress. The existing literature lacks gesture evaluations that analyse performance and ergonomic issues as part of a single experimental method. In this paper we contribute to the literature by evaluating the usability of rotations by measuring users' biomechanical ability to perform movements across a systematic decomposition of the within-gesture design space.

EXPERIMENT

An experiment was conducted to investigate the performance of single-handed dual-finger 90° rotation gestures with a focus on trial completion times and ergonomic factors. We chose 90° rotations as they are common in many applications (e.g. to flip images from portrait to landscape), and are also suggested by guidelines (e.g. the Windows 8 and Apple iOS guidelines recommend 90° constrained rotations as opposed to free rotations).

We study the effects of *Angle*, *Direction*, *Diameter*, and *Position*. These effectively cover most of the design space of rotation gestures on a surface. More precisely, *Angle*, *Direction*, and *Diameter* allow us to cover objects of arbitrary orientation and size; *Position* allows us to cover a surface with different size and relative positions to the user.

Participants

Twenty-five participants were recruited with an age range of 22 to 29 (13 female, 12 male). All participants were right-handed, had normal or corrected-to-normal vision and no motor or cognitive disorders. The participants' hand span ranged from 142 to 209 mm with a mean of 176.9 mm.

Experimental Design

The experiment followed a within-subjects design with the following factors (illustrated in Figure 1):

- *Angle* (between starting points with respect to the long axis of the table): 0°, 60° and 120°;
- *Direction*: clockwise or anti-clockwise;
- *Diameter* (between fingers): 4, 5.5, 7 and 8.5 cm;
- *Position*: 4×3 grid (Figure 2). The position in the grid determines the center point of each rotation. The total area of 1018×573 mm was divided into grid sectors of 254×191 mm. By moving the tablet to different sectors, we could simulate the effects of a larger display space.

The number of levels for each factor was selected through a pilot experiment that obtained rotation durations for random locations, starting points, and finger distances within similar boundaries. A bandwidth analysis that maximized the prediction power of a simple model was used (inspired by GWR [2]) to provide optimum values.

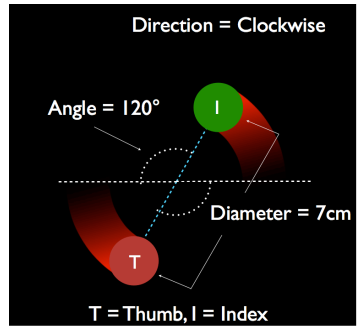

Figure 1: An example configuration of parameters: Angle, Diameter and Duration (Position is shown in figure below).

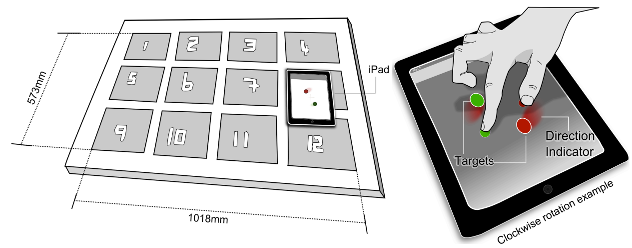

Figure 2: Experimental set-up: grid display with tablet in Position 8 (left) and participant performing a rotation (right).

Experimental Set-Up and Apparatus

The participants sat on a chair positioned so that the centre of the participant's navel was level with the centre of the grid surface and 5 cm away from the grid edge. All lateral and anterior movement of the participants' upper torso was restricted. All rotations were performed on a 24.13×18.57 cm Apple iPad 2 tablet. The experimental software recorded the time between the onset of movement and the loss of finger contact, along with the beginning positions and movement trajectories of the thumb and index finger.

Task and Procedure

The experiment made use of an aimed movement paradigm to systematically explore the design space. Two circles were shown on the display and the participants were asked to place their thumb and index finger of their dominant hand on the circles. The index finger was always placed to the right (for 0° and 60°) and up (for 120°). The task was to rotate the two circles 90° towards the target circles. The position of the target circles and rotation direction were determined according to the experiment parameters. The participants were asked to do each rotation three times as quickly and accurately as possible whilst ensuring that there was no loss of contact between the fingers and display. Overall there were 864 trials per participant.

If the participants were unsuccessful, they received audio feedback to alert them to their mistake. There were three types of mistakes: 1) wrong direction, 2) loss of contact, and 3) too many fingers on the display. The participants were given two chances to complete each trial correctly. If the trial proved to be too uncomfortable, the trial was skipped. After each successful rotation the participants were asked to touch a target marker, which was attached to the edge of the display. By returning their hand to a constant starting position, we could avoid issues with retrospective control [3]. In effect, users 'reset' their posture for each task.

RESULTS

Overall, we recorded 18468 trials. 39.7% of these trials were skipped or incomplete. Participants were allowed to skip rotations that were deemed "impossible"; we use these alongside trials in which there were contact losses as an index of the ergonomic failure rate. The average time per rotation was 2.71 seconds. Our analyses here focus on duration and ergonomic failure rate.

Duration

A repeated measures analysis of variance (ANOVA) of duration showed a significant main effect for *Angle* ($F_{(2,28)}$ = 4.5, p<.05), *Diameter* ($F_{(1.58,22.18)}$=176.9, p<.05) with Greenhouse-Geisser correction ,and *Direction* ($F_{(1,14)}$ = 13, p<.05). The analyses showed significant interactions between *Angle***Direction* ($F_{(1.25,17.5)}$=21.5, p<.05) with Greenhouse-Geisser correction , *Angle***Position* ($F_{(22,308)}$=2.3, p<.05), *Direction***Position* ($F_{(11,154)}$=12.7, p<.05), and *Angle***Direction***Position* ($F_{(22,308)}$=3.9, p<.05).

Ergonomic Failure

Examples of ergonomically difficult rotations encountered during the experiment are shown in Figure 3. A repeated measures ANOVA on failure rate showed a significant main effect for *Diameter* ($F_{(1.6,30.6)}$=7.6, p<.05) with Greenhouse-Geisser correction , *Direction* ($F_{(1,19)}$=23.8, p<.05), and *Position* ($F_{(11,209)}$=7.3, p<.05). There were also many significant interactions between *Angle***Direction* ($F_{(1.3,25.2)}$=31.2, p<.05), *Diameter***Direction* ($F_{(3,57)}$ = 3.8, p<.05), *Angle***Diameter***Direction* ($F_{(6,114)}$=5.8, p<.05), *Angle***Position* ($F_{(22,418)}$=4.5, p<.05), *Direction***Position* ($F_{(11,209)}$ = 9, p<.05), *Angle***Direction***Position* ($F_{(22,418)}$=7.7, p<.05), and *Direction***Diameter***Position* ($F_{(33,627)}$=2.2, p<.05).

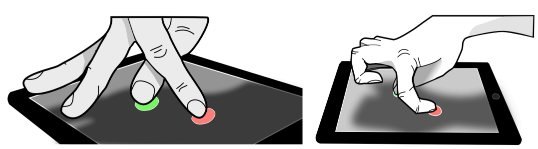

Figure 3: Ergonomically uncomfortable rotations encountered by participants during the experiment.

Angle and Direction

Bonferroni adjusted post hoc tests showed that rotations with a trial *Angle* of 0° were significantly faster than 60° or 120° (p<.05). *Angle* also had an interaction effect with *Direction*. In particular, a crossover between clockwise and anti-clockwise directions was observed for the 120° rotations, as can be seen in Figure 4. This interaction effect was present in both failure rate and duration analyses.

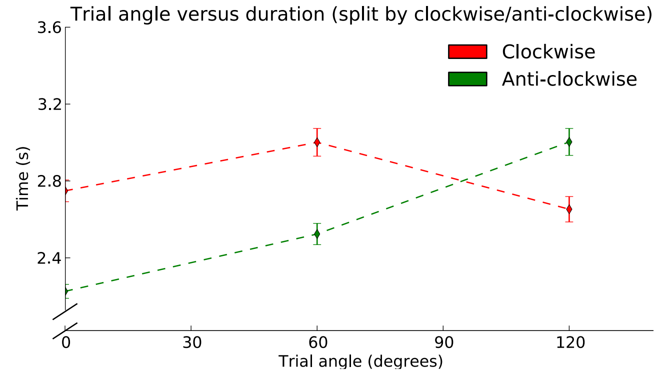

Figure 4: Mean rotation duration (in seconds), for each angle, separated by direction (error bars = 95% CI).

Figure 5 shows the *primary angle* of the finger trajectory versus duration. The primary angle is the slope of a line drawn from the starting finger targets to the end finger targets (measured with respect to the table *x*-axis, so that zero means a horizontal line). This models the gesture as if the movement was performed as a straight line and not an arc section. It is apparent that rotations are slowest when the primary angle is close to 180° (horizontal finger movement) and that increasing finger distance consistently slows movements.

Direction and Diameter

The effect of *Diameter* on Duration was statistically significant. Bonferroni adjusted post hoc tests showed that larger rotations took longer to perform and had a larger failure rate (p<.05). The effect of *Direction* on Duration was also statistically significant. Clockwise rotations took longer to complete than anti-clockwise. This could be related to the fact that clockwise rotations by right-handed users are known to generate higher wrist extensor and dominant deltoid muscle activity than anti-clockwise rotations [3].

There was a significant interaction effect for *Direction* and *Position* on Duration. A Bonferonni adjusted post hoc test (p<.05) showed that contra-lateral (the opposite side of the body) to the dominant hand, anti-clockwise rotations are significantly slower than clockwise rotations, whereas ipsilateral (the same side of the body) clockwise rotations are significantly slower than anti-clockwise rotations (see Figure 6).

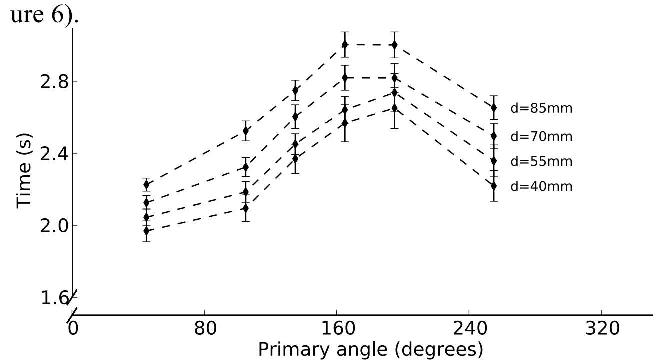

Figure 5: Primary angle and diameter versus mean duration

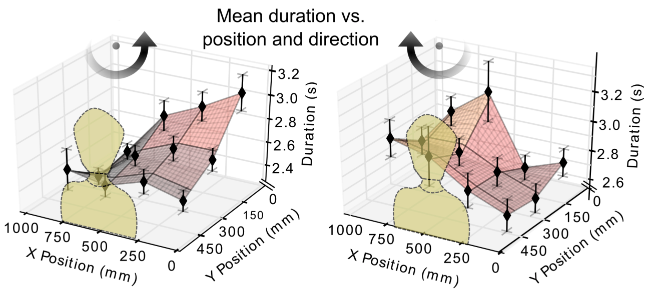

Figure 6: Mean duration (s) for clockwise and anti-clockwise rotations in each grid sector. Error bars show 95% CI.

CONCLUSION

This paper has presented a novel empirical data charting user performance in the rotation design space, in particular the effects of within-gesture differences such as angle, direction, diameter and position. The results show that:

- As the rotation diameter increases, so does the duration and ergonomic failure rate;
- Rotations with a trial angle of 0° are significantly faster than 60° or 120°;
- Clockwise rotations take longer to complete and produce more ergonomic failures than anti-clockwise rotations until the angle reaches 120°, at which point the effect is reversed;
- Contra-lateral anti-clockwise rotations are slower with more ergonomic failures than clockwise rotations, and vice versa for ipsilateral rotations;
- Rotations are slowest when fingers move horizontally.

The results we provide are useful as heuristics aids in design. For instance, the data suggest that rotations with a large diameter over 70 mm should be avoided, as they are slow and cause a larger failure rate. The angle of rotation is another factor to consider. 120° clockwise rotations are easy to perform, but in anti-clockwise direction they are much more challenging: 48% of these rotations could not be completed. We also observed that anti-clockwise rotations in the contra-lateral side are particularly hard to perform compared to clockwise rotations (e.g. Figure 6).

Besides the heuristics, the main conclusion of the study is that there is no universal rotation gesture. We learned that many of the within-gesture variables we manipulated had a statistically significant effect on both movement time and failure to complete the rotation, and we saw strong interactions among the variables. Thus, when one talks about "the rotation gesture," one is in fact referring to whole categories of movements involving a range of motor patterns. These gestures have a common terminal trajectory as measured at the interaction surface but are generated in distinct ways involving different muscle and joint groups, and have characteristic performance and ergonomic features. Future work should differentiate these classes to inform efforts in interaction design, and predictive modeling of user performance.

We believe that the novel experimental design we used to explore the design space of rotations will be useful in further studies of multi-touch gestures. Although it might miss the finer variations among movements, it captures the most critical factors in an economic study design. The scope of our study was limited to 90° rotations on a tabletop set-up. Further investigations will be necessary to examine the effects of unconstrained rotation angles. Future work will also need to address the other popular multi-touch gestures, for example, pinching and translating, and extend the work from horizontal surfaces to cover vertically positioned displays and mobile terminals where the supporting hand can change the relative position and angle of the display.

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