Understanding Users’ Perceived Difficulty of Multi-Touch Gesture Articulation

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ABSTRACT

We show that users are consistent in their assessments of the articulation difficulty of multi-touch gestures, even under the many degrees of freedom afforded by multi-touch input, such as (1) various number of fingers touching the surface, (2) various number of strokes that structure the gesture shape, and (3) single-handed and bimanual input. To understand more about perceived difficulty, we characterize gesture articulations captured under these conditions with geometric and kinematic descriptors computed on a dataset of 7,200 samples of 30 distinct gesture types collected from 18 participants. We correlate the values of the objective descriptors with users’ subjective assessments of articulation difficulty and report path length, production time, and gesture size as the highest correlates (max Pearson’s \( r = .95 \)). We also report new findings about multi-touch gesture input, e.g., gestures produced with more fingers are larger in size and take more time to produce than single-touch gestures; bimanual articulations are not only faster than single-handed input, but they are also longer in path length, present more strokes, and result in gesture shapes that are deformed horizontally by 35% in average. We use our findings to outline a number of 14 guidelines to assist multi-touch gesture set design, recognizer development, and inform gesture-to-function mappings through the prism of the user-perceived difficulty of gesture articulation.

Categories and Subject Descriptors
H.5.2. [Information Interfaces and Presentation]: Information Interfaces and Presentation

Keywords
Multi-touch, articulation difficulty, ease of execution, user study, gesture articulation, number of fingers, number of strokes, number of hands, gesture structure, gesture geometry, gesture kinematics.

1. INTRODUCTION

Designing gesture sets can prove a challenging task because of users’ different preferences in terms of articulation patterns \([2,15,16]\) and gesture-to-function mappings \([22]\). The current practice of gesture interface design has outlined several guidelines to assist practitioners in this regard, according to which gesture shortcuts should be unambiguously recognized \([10]\), fast to articulate \([3]\), ergonomically easy to execute \([11,22]\), easy to learn and recall \([3,12,13]\), and well fit to application functions \([13,22]\). However, these guidelines are not straightforward to apply because of the little understanding of the factors acting behind them, e.g., what causes articulation difficulty and what triggers gesture recall? There is also a lack of methodology and models to reliably estimate these factors \textit{a priori}, which makes practitioners resort to involving users in time-consuming studies to identify good gesture designs \([5,11,12,22]\).

In this context, we argue that the user-perceived difficulty of gesture articulation is an important factor for gesture set design that has been little explored so far and, consequently, is little understood. While it is not straightforward to precisely define the notion of gesture articulation difficulty, we believe it captures many facets of gesture production, such as ergonomic difficulty to physically articulate the gesture path and cognitive difficulty required to learn and recall the geometry of the gesture shape and, conceivably, the specifics of its articulation (e.g., the number of fingers to employ and the gesture stroke structure). Although the notion of gesture articulation difficulty has been mentioned as design criteria by many works \([11,13,22]\), it has only been examined thoroughly for unistrokes \([20]\). However, opposed to unistrokes, multi-touch gestures present considerably more degrees of freedom afforded during articulation, such as employing various number of fingers, different stroke count and ordering, and single-handed and bimanual input \([15]\). In this work, we examine users’ perceived difficulty of multi-touch gesture articulation for symbolic gesture types \([3,15,19–21]\), such as those from Figure 1, and we provide the community the first understanding of this phenomenon as well as its potential implications in terms of gesture set design, multi-touch recognizer development, and gesture-to-function mappings.

Figure 1: The set of 30 gestures used for our experiment addressing the effect of the number of (a) fingers, (b) strokes, and (c) hands on perceived difficulty. The left 15 gestures (d) were designed to be familiar and the right 15 gestures (e) unfamiliar to our participants.
Our contributions are as follows: (1) we conduct the first investigation of the user-perceived difficulty of multi-touch gesture articulation, and deliver results in terms of gesture difficulty ratings and rankings; in doing so, we examine the effect of finger count, stroke count, and single-handed and bimanual articulation conditions on perceived articulation difficulty; (2) we report correlation results between users' subjective assessments of difficulty and objective gesture descriptors to enable a better understanding of the phenomena involved in the perception of articulation difficulty; as a practical result, we report gesture path length and production time as the highest correlates with users' perceived difficulty of gesture articulation; (3) we report novel findings on multi-touch gestures articulated under different conditions, e.g., bimanual articulations result in gesture shapes horizontally stretched by 35% than their single-handed counterparts; (4) finally, we use our large body of results to compile a set of 14 guidelines for multi-touch gesture set design and mapping gestures to functions by considering the ergonomics of multi-touch input through the prism of the user-perceived difficulty of gesture articulation. We hope our results will prove useful to designers and practitioners interested in maximizing the ease of execution of their multi-touch gesture set designs.

2. EXPERIMENT

We employ the methodology of Vatavu et al. [20] to collect users' self-reported difficulty assessments and apply it for multi-touch gestures. We use the methodology for a series of three experimental tasks designed to collect multi-touch gestures articulated under various conditions in terms of (1) number of fingers, (2) number of strokes, and (3) single-handed and bimanual input.

2.1 Participants

Eighteen (18) participants (four females) volunteered to take part in our experiment involving acquisition of multi-touch gestures. Participants’ ages varied between 22 and 35 years (mean age 27.4, SD=3.4 years). All participants, except one, were right-handed. Fourteen participants were regular users of smart phones and tablet devices with multi-touch screens, but none had previous experience with large-screen interactive tabletops.

2.2 Apparatus

Multi-touch gestures were collected on a 32 inch (81 cm) 3M™ multi-touch display (model C3266PW) that was set to work at a screen resolution of 1920×1080 pixels. The display supports detection of up to 40 simultaneous touches. The device was positioned horizontally on a table and connected to a computer running Windows and our custom data acquisition software. Participants entered gestures in an area of 1140×950 pixels (42×35 cm).

2.3 Procedure

We controlled the following conditions for multi-touch gesture articulation: (1) number of fingers, (2) number of strokes, and (3) number of hands and their sequential and synchronous use during articulation. In order to keep the overall duration of the data collection procedure manageable for our participants, the effect of each condition was tested as an individual experimental task.

Task #1: Effect of number of fingers. Each trial began by presenting participants with the gesture to articulate and the number of fingers to use during articulation: one (1F), two (2F), and three or more fingers (3+F). For the 3+F condition, participants were instructed to use their preferred number of fingers, as long as there were at least three fingers employed. Participants were instructed to enter gestures at normal speed, using their preferred hand, fingers, and number of strokes. The number of fingers was a fixed constraint during the entire articulation, but participants were allowed to use their preferred fingers. The order of trials was randomized. Each gesture type was articulated with five repetitions, with a total of 10 gestures × 3 finger conditions × 5 repetitions = 150 articulations produced by each participant. Our software application randomly presented the 150 articulations to our participants. This task took in average 30 minutes to complete.

Task #2: Effect of number of strokes. Each trial began by presenting participants with the gesture to articulate and the number of strokes to use: one (1S), two (2S), and three or more strokes (3+S). In the 3+S condition, participants were instructed to use their preferred number of strokes, as long as there were at least three strokes. Participants articulated gestures at normal speed and using their preferred hand, with 10 gestures × 3 stroke conditions × 5 repetitions = 150 articulations per participant. The 150 articulations were randomly presented to our participants. The task took in average 30 minutes.

Task #3: Effect of number of hands. Each trial began by presenting participants with the gesture to articulate and the number of hands to use during articulation. In the single-handed condition, all gesture strokes had to be entered one after the other. We also refer to this condition as sequential articulation (SEQ). For the bimanual condition, participants were instructed to articulate strokes in parallel (i.e., synchronous articulation, SYNC). The number of hands was a fixed constraint that had to be fulfilled during the entire articulation, but participants were given freedom with respect to the number of strokes and number of fingers to employ. Each gesture was executed for five times in each condition, with a total number of 10 gestures × 2 hand conditions × 5 repetitions = 100 articulations produced by each participant. The 100 articulations were randomly presented to our participants. This task took around 20 minutes to complete.

To minimize the influence of each experimental task over the others, task order was counter-balanced across participants.

Perceived articulation difficulty was collected after each experimental task using absolute RATING and relative RANKING measurements, similar to the methodology of Vatavu et al. [20]. RATING was collected using a 5-point Likert scale (see Table 1), which was presented to participants as a table with five columns, one column for each RATING value. Participants were asked to draw each gesture in the appropriate difficulty column, after having articulated it one more time on the multi-touch surface in order to re-enact the articulation experience and, consequently, perceived difficulty. Participants were allowed to change the ratings of previously rated gestures at any time as they moved along with the rating process until they were confident of the final classification of gesture types into difficulty classes. After rating each gesture under each condition, participants were asked to provide an ordered list of combined gesture types and articulation conditions in increasing order of perceived difficulty, which represents our RANKING measurement.

2.4 Gesture set

We employed 30 gesture types for our experiment, with 10 gestures per task (see Figure 1). All gestures for the stroke task were carefully chosen so that they could be articulated both as single and multi-strokes. All gestures selected for the number of hands task expose a symmetry axis, as it has been observed previously that only symmetric gestures can be conveniently parallelized during articulation [15]. In addition, half of the gesture shapes were selected to appear familiar to our participants, where we defined the familiarity of a shape as previous, frequent practice articulating that specific shape during everyday handwriting (e.g., familiarity...
relative R

2.5 Design

for multi-touch interaction (multi-touch gestures instead of standard gestures traditionally used and discussion from [20]). In this work, we investigate symbolic metrically complex, and the opposite is also true (e.g., see letter ‘g’ consequently, rated “easy to perform” by users although it is geo-

shape [20]. For instance, a gesture can be considered familiar and, practice [6,18,20]). Please also note that the familiarity of a gesture

rarity and practice affect human performance when articulating gestures from the gesture literature according to which shape familia-

rities were among the first sixteen gestures in ascending order of features were among the first sixteen gestures in ascending order of

features were among the first sixteen gestures in ascending order of
tions of the self-perceived difficulty when articulating multi-touch gestures (e.g., pan, zoom, rotate, etc.), because symbols are more versatile to generalize for other applications.

2.5 Design

Our experiment was a within-participants design with four inde-

ependent variables:

1. FINGER-COUNT, ordinal with 3 values corresponding to using one (1F), two (2F), and three or more fingers (3+F).
2. STROKE-COUNT, ordinal with 3 values corresponding to producing one (1S), two (2S), and three or more strokes (3+S).
3. SYNCHRONICITY, nominal with 2 values: one hand sequential input (SEQ) and bimanual synchronous input (SYNC).
4. GESTURE, nominal with 10 values per task, and 30 values for the entire experiment (see Figure 1).

The dependent variables were participants’ absolute RATING and relative RANKING of perceived articulation difficulty, which were collected during a post-experiment questionnaire:

1. RATING, ordinal variable, measures the absolute difficulty of articulating a multi-touch gesture into five levels, and was presented in the form of a Likert scale (see Table 1).
2. RANKING, ordinal variable, measures the relative difficulty of articulating multi-touch gestures. RANKING takes values in the set \{1, 2, ..., 30\} for the first two tasks (corresponding to 10 gesture types \times 3 conditions), and in the set \{1, 2, ..., 20\} for the third task (i.e., 10 gestures \times 2 conditions).

3. RESULTS #1: PERCEIVED DIFFICULTY

We are interested in this section in the level of agreement between participants in terms of their perceived difficulty of multi-touch gestures articulated under various conditions. To this end, we report and analyze 144 individual ratings of absolute difficulty and 54 rankings of relative difficulty collected from 18 participants.

Table 1: Likert questions employed to elicit absolute articulation difficulty of multi-touch gestures (i.e., RATINGs), similar to [20].

<table>
<thead>
<tr>
<th>Likert RATING (1–5)</th>
<th>Explanation provided to participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. very easy to execute</td>
<td>I executed these gestures immediately and effortlessly with absolutely no need to pay attention.</td>
</tr>
<tr>
<td>2. easy to execute</td>
<td>I executed these gestures easily, almost without paying attention.</td>
</tr>
<tr>
<td>3. moderate difficulty</td>
<td>I occasionally paid attention during execution. I paid special attention with each execution. I had to concentrate for each execution. There were times when I did not get the right shape from the first attempt.</td>
</tr>
<tr>
<td>4. difficult to execute</td>
<td>I had to concentrate for each execution. There were times when I did not get the right shape from the first attempt.</td>
</tr>
<tr>
<td>5. very difficult to execute</td>
<td>I had to concentrate for each execution. There were times when I did not get the right shape from the first attempt.</td>
</tr>
</tbody>
</table>

3.1 Assumption of gesture familiarity

Half of the gestures (15 gestures) were specifically selected to look familiar to participants (see our definition of familiarity in the previous section), while the other half were new gestures, specifically designed for our experimental tasks. In order to validate our initial assumptions about gesture familiarity, we asked participants to report at the end of each task which gestures looked familiar to them. In total, we counted 43 deviations from our gesture set assumed familiarity out of 540 total answers, which represents an error rate of less than 8%. Gestures such as “ball”, “butterfly”, “four curlicue”, and “square chain” were classified as familiar by some participants, although they witnessed no previous practice with these shapes. Under these circumstances, we can safely consider the assumptions of familiarity met for our gesture set.

3.2 Effect of finger count on difficulty

Figure 2 illustrates participants’ responses of the perceived difficulty of multi-touch gestures articulated with one (1F), two (2F), and three or more fingers (3+F). Overall, we found a high degree of agreement between participants’ responses, as reflected by Kendall’s coefficient of concordance \( W = .77, \chi^2(29) = 403.340, p < .001 \) for RATING, and \( W = .82, \chi^2(29) = 428.748, p < .001 \) for RANKING. The level of agreement between participants also stayed high (i.e., above .80 for RATING and above .85 for RANKING, \( p < .001 \)) when we ran the analysis for each value of the finger count condition individually (i.e., one, two, and three or more fingers). These findings indicate that the articulation difficulty of multi-touch gestures is perceived by people in a consistent manner, which justifies further investigation of the self-reported difficulty assessments.

We found a significant effect of the number of employed fingers on perceived articulation difficulty measured as both RATING (\( \chi^2(2) = 23.130, p < .001 \)) and RANKING (\( \chi^2(2) = 21.778, p < .001 \)), with more fingers causing an increase in the perceived difficulty of gesture articulation (see Figure 2, inner graphs). Post-hoc Wilcoxon signed-rank tests (Bonferroni corrected at \( p = .01/2 = .005 \)) confirmed a significant difference between two and three or more fingers with a medium to large effect (\( r = .51 \)), and a nonsignificant difference between one and two fingers conditions.

Familiar gestures were rated as less difficult to execute (median RATING=1 corresponding to “very easy to execute”) than unfamiliar gestures (median RATING=3 or “moderate difficulty”). These differences were significant, as confirmed by Wilcoxon signed-rank tests (\( z(N=18) = -3.782, p < .001, r = -.63 \)). The fifteen familiar gestures were among the first sixteen gestures in ascending order of RATING and RANKING (Figure 2), with 13/15=87% of familiar gestures being rated as “very easy to execute” (RATING=1). At the same time, 10/15=67% of the unfamiliar gesture articulations were rated from “moderate” to “very difficult to execute”. We also found participants less consistent when rating familiar than unfamiliar gestures (\( W = .28 \) versus .65 for RATING and \( W = .56 \) versus .72 for RANKING, all \( p < .001 \)), which suggests that people develop different preferences with practice for articulating gestures in terms of preferred number of fingers.

3.3 Effect of stroke count on difficulty

Figure 3 illustrates participants’ RATING and RANKING assessments of the self-perceived difficulty when articulating multi-touch gestures with one (1S), two (2S), and three or more strokes (3+S). This time, we found a lower degree of consensus between partici-

2. Kendall’s coefficient of concordance is a normalization of the statistic of the Friedman test used to assess continuity of judgement among multiple individuals. \( W \) takes values in \([0,1]\), where 0 denotes no agreement at all and 1 perfect agreement [9].
pants’ assessments of articulation difficulty, as opposed to the finger count task. However, Kendall’s coefficients stayed above .50, which shows large Cohen effect sizes (W = .58, χ²(29) = 308.816, p < .001 for RATING and W = .71, χ²(29) = 369.095, p < .001 for RANKING). When calculating agreement for each stroke condition, Kendall’s W coefficients stayed above .50 for RATING and above .60 for RANKING (p < .001). The lower degree of consensus compared to the previous finger count task suggests that STROKE-COUNT is a factor with a stronger influence on the self-perceived difficulty of articulated gestures than FINGER-COUNT.

We found a significant effect of the number of strokes on perceived difficulty for both RATING (χ²(2) = 23.049, p < .001) and RANKING measures (χ²(2) = 32.444, p < .001), with more strokes causing an increase in the self-perceived difficulty of gesture articulation (see Figure 3, inner graphs). In average, gestures articulated with one stroke were perceived as “very easy” and “easy to execute” (median RATING = 1.5), two-stroke gestures as “easy to execute” (median RATING = 2), and gestures articulated with three or more strokes having “moderate difficulty” (RATING = 3). Post-hoc Wilcoxon signed-rank tests confirmed significant differences (at p = .01/2 = .005) between the 1S and 2S conditions, as well as between 2S and 3+S with medium to large effect sizes (r > .50).

As in the previous experimental task, familiar gestures were rated less difficult to execute (median RATING = 2 corresponding to “easy to execute”) than unfamiliar gestures (median RATING = 3, “moderate difficulty”). These differences were significant, as confirmed by Wilcoxon signed-rank tests (z(N=18) = −3.535, p < .001, r = −.60). The fifteen familiar gestures were among the first twenty gestures in ascending order of RATING and RANKING (Figure 3), with 14/15 = 93% of familiar gestures being rated as “very easy” and “easy to execute” (RATING values 1 and 2). At the same time, 10/15 = 67% of the unfamiliar gesture articulations were rated from “moderate” (RATING = 3) to “difficult to execute” (RATING = 4). Again, we found participants less consistent when rating familiar than unfamiliar gestures (W = .40 versus .51 for RATING and W = .61 versus .57 for RANKING, all p < .001).

3. Kendall’s W coefficient is related to the average of n(n−1)/2 Spearman rank correlation coefficients between pairs of the n rankings [9] (p. 276). Therefore, we use Cohen’s suggested limits of .10, .30, and .50 for interpreting the magnitude of the effect size [8].
3.4 Effect of synchronicity on difficulty

Figure 4 illustrates participants’ assessments of difficulty in terms of RATING and RANKING for multi-touch gestures articulated with strokes in sequential order (i.e., one stroke at a time) and synchronously (i.e., strokes articulated in parallel). The degree of consensus between participants, when asked to rate and rank the difficulty of gestures articulated under sequential and bimanual conditions, stayed above .59 (W = .59, \( \chi^2(19) = 201.477 \), \( p < .001 \) for RATING and \( W = .75, \chi^2(19) = 257.921, p < .001 \) for RANKING). We found a higher degree of consensus among participants when rating gestures articulated with strokes in sequential order than in parallel (\( W = .73 \) versus .53 for RATING and \( W = .86 \) versus .70 for RANKING, all \( p < .001 \)). However, there was no significant effect of articulation type on self-perceived difficulty for either RATING (\( z_{(N=18)} = -1.363, n.s. \)) or RANKING (\( z_{(N=18)} = -1.244, n.s. \)).

As in the other experimental tasks, familiar gestures were rated less difficult to execute (median RATING=1, “very easy to execute”) than unfamiliar gestures (median RATING=2, “easy to execute”). These differences were significant, as confirmed by Wilcoxon signed-rank tests (\( z_{(N=18)} = -3.680, p < .001, r = -.61 \)). The ten familiar gestures were the first in ascending order of RATING and RANKING (Figure 4), with \( 90\% \) of familiar gestures rated “very easy”. Again, our participants showed less agreement when rating familiar than unfamiliar gestures (\( W = .26 \) versus .37 for RATING and \( W = .61 \) versus .39 for RANKING, \( p < .001 \)), which suggests again that people develop with practice different articulation preferences, this time in terms of bimanual input.

4. RESULTS #2: GESTURE ARTICULATION AND PERCEIVED DIFFICULTY

In this section, we accompany the results on participants’ self-reported assessments of gesture articulation difficulty with a quantitative analysis comprising geometric and kinematic gesture descriptors that we apply to our dataset composed of 7,200 multi-touch gesture samples of 30 distinct gesture types collected from 18 participants under various articulation conditions.

4.1 Gesture descriptors

We selected several gesture descriptors commonly employed in the gesture recognition and analysis literature [1,2,4,17,20,21] in order to characterize the articulation of gesture types belonging to different difficulty classes. In order not to overload our discussion with extensive numerical data, we limit our analysis to a subset of eleven representative descriptors that we believe adequate to characterize gesture articulations in terms of gesture structure, geometry and visual appearance, and kinematics.\(^4\). We characterize the structure of a multi-touch gesture by its number of points and number of strokes; gesture geometry is characterized by path length, bounding box size, and total absolute turning angle; and production time and speed are used to report the kinematics of multi-touch gesture articulation. As these descriptors are common and frequently used, we save paper space and do not define them here again. Instead, we refer the interested reader to previous works in which they are properly defined [1,2,4,17,20,21]. We are also interested in capturing subtle details specific only to multi-touch input. To this end, we proposed variations for computing some of the most used gesture features, and we denote these variations as actual number of strokes, actual path length, and actual total absolute turning angle. The term actual placed in front of a descriptor means the descriptor is computed using data points from all fingers touching the surface. For example, the actual path length is defined as the cumulative length produced by all fingers touching the surface, whereas (simple) path length produces a value independent of finger count (reflective of the path length irrespective of how it was articulated).

We computed Pearson correlations between all gesture descriptors and participants’ self-perceived articulation difficulty reported as absolute RATING and relative RANKING measures. Table 2 shows the correlation values for each experimental condition. The largest value in each column is highlighted as there are all the other values not significantly different from it. In the following, we discuss specific findings for each gesture descriptor category.

4.2 Gesture structure and difficulty

We characterize the structure of a multi-touch gesture by its number of points, number of strokes, and actual number of produced strokes, where the latter includes the effect of employing multiple fingers and also covers unintentional finger slips.

Clearly, more fingers touching the surface will generate more points sampled by the device for the gesture path, with an expected and uninteresting linear relationship between the number of employed fingers and the number of sampled points (Figure 5a). Simultaneously,

\(^4\) See Blagojevic et al. [4] for a comprehensive set of gesture features.
4.3 Gesture geometry and difficulty

We characterize gesture geometry in terms of path length (and corresponding actual path length), size of the bounding box area, total absolute turning angle (and the correspondent actual form), and aspect ratio measurements (Figures 5d—5i).

Overall, we found a significant effect of FINGER-COUNT on all gesture geometry descriptors. While this finding was expected for the actual descriptors due to the way they were defined to capture the effect of more fingers touching the surface, the finding is particularly interesting for the other descriptors. Specifically, participants produced gestures significantly longer in path length by 10−25% ($\chi^2(2)=902.11$, $p<.001$) and larger in area size by 10−29% ($\chi^2(2)=494.18$, $p<.001$) when more fingers were in touch with the surface (Figures 5d—5f). Another interesting effect was found for total absolute turning angle (Figures 5g—5i), with more fingers causing a decrease in gesture path smoothness ($\chi^2(2)=559.74$, $p<.001$). Friedman tests revealed a significant effect of STROKE-COUNT on path length ($\chi^2(2)=17.84$, $p<.001$), gesture size ($\chi^2(2)=19.10$, $p<.001$), and the actual total absolute turning angle ($\chi^2(2)=1058.45$, $p<.001$). Unlike gestures articulated with more fingers, gestures with more strokes presented smoother paths. Participants produced gestures that were longer yet smaller in area size during bimanual articulations when compared to sequential ones ($\chi^2(N=900)=17.06$, $p<.001$, $r=.40$ for path length and $\chi^2(N=900)=17.04$, $p<.001$, $r=.40$ for area size respectively). We also found an interesting effect of SYNCHRONICITY on the aspect ratios of gesture articulations: participants deformed gesture shapes more for bimanual articulations than for sequential ones ($\chi^2(N=900)=21.54$, $p<.001$, $r=.51$) by producing gestures narrower by 35% in average when two hands were used.

Familiar gestures were significantly shorter (≈1.8 times shorter) than unfamiliar gestures under all experimental conditions, as shown by Wilcoxon signed-rank tests (all $p<.001$, $r<.61$), and they were also smaller in area size ($p<.001$, effect sizes between $-0.60$ and $-4.4$). We found a significant effect of FAMILIARITY on the turning angle measures with familiar gestures presenting smoother paths ($p<.001$, effect sizes between $-0.61$ and $-5.5$).

Out of all geometric descriptors, path length presented the highest correlation with RATING and RANKING (average Pearson $r=.90$ and .86 respectively, $p<.005$, see Table 2).

5. DISCUSSION & DESIGN GUIDELINES

We found participants highly consistent when assessing the difficulty of articulating multi-touch gestures under various FINGER-COUNT, STROKE-COUNT, and SYNCHRONICITY conditions, as indicated by Kendall’s W coefficients of concordance between .58 and .82. At the same time, we found less consensus between participants’ ratings for familiar and unfamiliar gestures (average W = .31 and .51 respectively), which suggests that people develop different preferences with practice for articulating multi-touch gestures.

Overall, more fingers and more strokes were significantly related to more perceived difficulty during gesture articulation. More fingers touching the surface caused longer path lengths, larger gesture
sizes, longer production times, but also more strokes being produced, which all suggest more effort to articulate gestures. Articulating gestures with more strokes resulted in longer production times, which is explained by the transition times required to move fingers in air between consecutive strokes. Bimanual input resulted in more strokes, longer path lengths, and faster executions when compared to sequential input, and, interestingly, caused horizontal deformations in gesture shape by 35% in average. Familiar gestures were produced faster, with less strokes, and were shorter, smaller, and smoother than unfamiliar shapes. These results on multi-touch input add to the body of knowledge on gesture articulation difficulty by complementing the findings of Vatavu et al. that investigated unistrokes [20]. Informed by our findings, we are able to outline a number of 14 guidelines for designing multi-touch gesture interfaces that address (1) gesture ergonomics, (2) gesture recognizer development, and (3) principles of gesture set design. Note that some of these guidelines are common-sense, however we deliberately chose to state them explicitly, because they followed naturally from our study. Finally, our set of guidelines are in agreement with other recommendations available in the gesture literature [2,14,22], while they also open new opportunities for user interface practitioners to design easy-to-produce gestures from the users’ perspective.

- **Multi-touch gesture ergonomics guidelines.**

  (a) Single-touch unistrokes should be preferred to multi-finger gestures whenever possible (see also [2,14], p. 92 and p. 1133), as they are generally perceived easier to articulate. (Single-touch unistrokes are also produced faster than all other articulations.)

  (b) Two-finger gestures should be equally exploited, as they were perceived not more difficult to produce than single-finger articulations (as long as the choice of employed fingers is left to the user to decide). This guideline was suggested by our participants and later confirmed by our gesture descriptor analysis.

  (c) Where possible, privilege bimanual over sequential articulations, as they are faster and are perceived no more difficult to produce than sequential articulations. Note however that different users may produce different patterns during bimanual articulation. Also, avoid synchronous input for shapes that do not present easily identifiable axes of symmetry. For instance, we observed that our participants preferred gestures for which the geometrical shape presented a vertical axis of symmetry.

  (d) Design for flexible input by allowing users to employ their preferred choice for the number of strokes that structure a multi-stroke gesture. Otherwise, before designing the multi-stroke structure of a gesture shape, observe how users naturally decompose that shape into strokes. Our participants decomposed gestures into lines and curves with similar shape and orientation to maximize parallelization during bimanual input. We also observed that our participants decomposed directional gestures into multiple line segments whenever there was a direction change.

  (e) Prefer familiar to unfamiliar shapes (also see [2], p. 92), as they are produced faster, smoother and are perceived less difficult to articulate under all tested conditions (i.e., number of fingers, number of strokes and single-handed and bimanual input).

  (f) Gesture shapes with complex geometries (i.e., mixtures of lines and curves) should be designed so that (1) they are easy to articulate such that learning and memorization are facilitated (a recommendation suggested by our participants during their first trials) and (2) encourage bimanual (and, therefore, faster) articulations. Design such gesture shapes with an easily identifiable axis of symmetry to guide users during bimanual input (in this regard, also see our guideline (c) above).

  (g) Design articulation patterns (i.e., ways to produce gestures) that connect to users’ previous gesture practice whenever possible, e.g., our participants preferred to use one finger sequential strokes for letters and numbers as these symbols have always been produced with one contact point in pen writing.

  (h) Use objective gesture descriptors to inform gesture design by privileging shapes perceived by users less difficult to articulate. As informed by the results of our correlation analysis, gestures that take longer to produce, are longer in path length and larger in size were also perceived as more difficult to articulate (see Table 2).
Multi-touch gesture recognizers guidelines.

(i) Design flexible recognizers (e.g., [16]) that are invariant to users’ preferred articulation patterns, especially when these patterns are likely to be perceived equally difficult to articulate, such as employing one or two fingers.

(j) Train gesture recognizers with different articulation patterns in terms of finger count, stroke count, and single and bimanual input. Equivalently, this guideline suggests training recognizers in articulation-independent scenarios, which is a step further beyond the current practice of employing user-dependent and user-independent training procedures.

(k) Detect whether two hands are touching the surface simultaneously and make use of this knowledge to increase the tolerance of shape recognizers to horizontal deformations, as we found users horizontally stretching their gesture shapes by 35% during bimanual synchronous input.

(l) More fingers touching the surface produce longer path lengths, larger sizes, and larger production times. Consequently, employ with caution recognizers that rely on geometric and kinematic gesture descriptors, such as [17] (p. 335).

Strategies to map gestures to functions.

(m) Exploit the number of fingers as parameter to increase the expressiveness of gesture input (also see [22], p. 1091). For example, assign multi-finger gestures to more complex tasks to intuitively match users’ perceptions of articulation difficulty with task complexity. Or, associate the number of fingers with different parameter values by following a proportional mapping, e.g., more fingers employed cause the brush to paint thicker for a drawing application. For instance, our participants felt that they were drawing a thicker stroke when touching the surface with more fingers during single-handed input. Another example is to use more fingers to scroll faster when browsing a document. As the most simple scenario, privilege designs employing one and two finger gestures, as we found them being perceived as equally difficult to articulate.

(n) Use thoughtfully the number of strokes as parameter for gesture input, as we found our participants often expressing dissatisfaction when entering multiple strokes. When suitable, connect the number of strokes to the complexity of the task to execute, as we found that gestures with more strokes were perceived more difficult to articulate.

5.1 Gesture dataset availability

As a service to the community interested in replicating our results or in conducting further investigations on multi-touch difficulty, we make available our set of 7,200 samples of 30 gesture types from 18 users annotated with Rating and Ranking data.

6. CONCLUSION

We reported the first investigation of users’ perceived difficulty during the articulation of multi-touch gestures. By employing correlation analysis, we reported significant high correlations between the subjective perception of difficulty and commonly-employed descriptors that characterize gesture articulation. We hope that our results on the perception of articulation difficulty together with new findings on multi-touch input and our set of guidelines will prove useful to gesture interface designers, assisting them toward improved gesture set designs and gesture-to-function mappings that consider users’ perceived difficulty of gesture articulation.

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8. REFERENCES