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# Evaluating Differences Between Bare-Handed and Tool-based Interaction in Perceptual Space

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*Abstract*— **In this paper, we examine the perceptual difference between bare-handed and tool-based interaction by identifying dissimilarities between two perceptual spaces constructed for the two interaction modes. For each interaction mode, four dimensional perceptual spaces are constructed using cluster sorting-based multidimensional scaling with 31 real textured surfaces. In addition, an adjective rating experiment was conducted to understand the meaning of the difference. Distinctive trends and differences of the perceptual spaces were identified. It was seen that familiarity with textured surfaces seemed to decrease the precision of bare-handed interaction, while at the same time it increased classification speed. Furthermore, likely evidence of pre-judgment in tool-based interaction was seen.**

**Keywords: Perceptual space, multi-dimensional scaling, adjective rating**

## I. INTRODUCTION

In our daily life we often encounter situations where direct contact using a finger or hand is not applicable. Usually, we use a rigid tool for interaction in such circumstances. For example, when we write with pencil on a rough paper or touch a pan while cooking, we can judge the nature of the surface. Despite of the tool-based interaction, people perceive a rich haptic feedback [1]. Similarly, in medical surgery (laparoscopy), the doctor is not in direct contact with the intended organ. Instead, different tools are used for interaction. Such examples emphasize the importance of tool-based haptic interaction.

Although the perception of textures remain undefiled through a tool, its relation with bare-handed perception remains mostly unanswered. Therefore, it is of utmost importance to study the differences between tool-based and bare-handed interaction. The two modes of interaction, i.e. tool-based and bare-handed interaction, have individually received a lot of attention from the research community. Researchers have focused on finding the underlying factors or perceptual dimensions that make up the overall perception of texture mainly for bare-handed interaction. Pioneering work in finding the dimensions of haptic texture for bare-handed interaction was done by Yoshida et. al. [2]. They found out that the main dimensions of haptic textures were hard-soft, heavy-light, cold-warm and rough-smooth. Subsequently, the authors in [3] used bipolar adjective scales to identify the basic dimensions in the perceptual space. They reported smooth-rough and soft-hard as the main dimensions. As summarized in [4], many researches (e.g. [5], [6]) have identified three basic dimensions, i.e. rough-smooth, hard-soft and cold-warm. The rough-smooth dimension can be further divided into macro and micro roughness, while friction could also be included to account for the stickiness-slipperiness of the textured surfaces.

On the other hand, for tool-based interaction, Lamotte in [7] showed that texture perception varies along the hard-soft dimension. It was concluded that participants were better at discriminating the differences in softness when they used active tapping. Other studies such as [8], [9] found that the textural perception mainly varies along the rough-smooth dimension.

The comparison between the two modes of interaction has received little interest from the researchers. Recently in [10], the authors have proposed that the neural mechanisms involved in texture perception vary across bare-handed and tool-based interaction. First, they carried out a pairwise comparison of 16 daily life surfaces (e.g. cloth, paper, rubber, etc.) to establish a 3D perceptual space using multi-dimensional scaling. The authors found out that roughness scores for the two modes showed similarity. However, some variations were found across the hardness and stickiness dimension. They also analyzed the effect of physical quantities (like the compliance, vibrations and friction) on the dissimilarities between different textures.

Although they defined the overall trends in the two perceptual spaces, they did not go into the details of inter-texture dissimilarities. Moreover, due to the pairwise comparison procedure, the number of textures was limited to 16 only. The range of these 16 textures could not cover the whole perceptual space due to small number and inability to be generalized for arbitrary texture. Furthermore, the tip of the tool that was used during their study had a diameter of 3 mm. In [11], the authors have shown that the size of tip affects the perception of roughness, which is one of the most important aspects of texture perception. According to them, the tip size that showed close resemblance to bare-handed interaction was 8 mm.

The aim of this research is to explain and evaluate the differences between bare-handed and tool-based interaction. For this purpose, perceptual spaces were established for bare-handed and tool-based interaction. A cluster sorting experiment was carried out to obtain the differences in the 31 real life textured surfaces shown in Fig. 1. This dissimilarity matrix was later used to establish the perceptual space using Multi-dimensional Scaling (MDS). The reason for selecting MDS was because it provides an overall view of the differences among all the surface textures. The process was repeated for both modes of interaction. Afterwards, results

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for bare-handed and tool-based interaction were compared in the perceptual space. The comparison was quantified and explained using the data that were collected during the cluster sorting experiment and an adjective rating experiment. The adjective rating quantifies the trends shown in the MDS scatter plot.

The main contribution of this paper is that a more dynamic range of textured surfaces is analyzed. The textured surfaces analyzed in this study cover a variety of materials used in daily life. Complete details of all the textures are provided in section II. Additionally, we explain the nature of individual perceptual spaces. We also provide detailed explanation for the changes in inter-surface distance across the two perceptual spaces. Besides, a physical proof of the masking of spatial deformity information in tool-based interaction is also provided.

This paper is organized as follows. In Section II, first we explain the experimental setup and the procedure to carry out the experiment. In Section III, the experimental results are presented along with a brief description of the nature of data. The discussion, based on the results, is given in Section IV. Finally, we conclude the paper in Section V

## II. EXPERIMENT

Two different experiments were conducted to evaluate the differences between the perception of real life textures in bare-handed and tool based interaction. The aim of the first experiment was to establish a perceptual space. The second experiment was an adjective rating experiment. It was carried out to evaluate the perceptual characteristics of all the textured surfaces.

### A. *Establishing Perceptual Space*

In order to find the exact dissimilarities between any two textures, a pairwise comparison is always preferable. But as the size of the data set increases, the number of pairwise comparisons increase dramatically. For, example for a data set of 20 samples, the total pairwise comparisons are 190 but for 30 samples it goes upto 435. This causes fatigue in the participants and runs the risk of the participants forgetting the scale. In order to avoid such kind of issues, the cluster sorting method was preferred. Additionally, in [12] the authors show that it is a robust representation of the dissimilarity matrix. Therefore, a cluster sorting experiment was conducted to establish the perceptual spaces.

*1) Participants:* A total of six participants took part in the experiment. All participants were paid for their participation. Ages of the participants range from 23 to 30 years. One participant was female. They reported no disabilities.

*2) Stimuli:* The stimuli were 31 real life textured surfaces. These 31 textured surfaces were selected from a set of 100 textured surfaces which we are using for another study. Those 100 surfaces were chosen from a wide range of natural surfaces to cover the full range of daily life haptic interactions. In the current setup, it was not feasible to use 100 surfaces because the experimental time would increase and the participants might forget the groupings. Therefore, the 31 surfaces were subjectively chosen in such a way that all kinds of different textures and materials, in the set of 100, were equally represented. Additionally, the MDS scatter plot for the 31 samples was similar to that for 100 samples, which showed that the range of the 31 samples is almost the same as that of 100 samples. Each surface was glued to an acryl plate of size 100×100×5 mm using spray on glue. The textured surfaces will be referred to as ‘samples’ henceforth for convenience. The details of all the 31 samples can be found in Fig. 1.

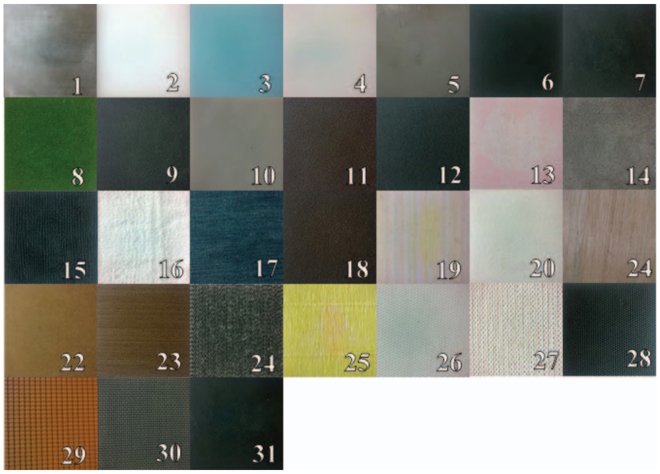

Fig. 1. Textures Samples used in this study. 1-Aluminum, 2-Acryl, 3-Sandpaper (1 $\mu$m)*, 4-Glossy paper, 5-Thin rubber 1, 6-Cloth like rubber, 7-Thin rubber 2, 8-Artificial grass, 9-Sandpaper (36 $\mu$m)* , 10-Sandpaper (6.5 $\mu$m), 11-Sandpaper (192 $\mu$m)*, 12-Plywood, 13-Textured Cloth, 14-Contoured cloth, 15-Thick cloth, 16-Towel, 17-Jeans, 18-Rough cloth 1, 19-Rough cloth 2, 20-Wet tissue, 21-Lined Wood, 22-Hard board, 23-Lined Wood 2, 24-Thread mesh , 25-Lined Kite paper, 26-Textured shoe pad, 27-Textured rubber, 28-Textured hard rubber, 29-Model Roof tile, 30-Steel-mesh, 31-Thick-rubber. **The average particle size of the sandpapers*

*3) Procedure:* The participants were seated on a chair with a desk in front of them. An engraved aluminum plate was placed on the table to hold the samples from slipping during interaction. In the beginning of the experiment there was no sample placed in the engraved aluminum plate. The participants were given a printed paper containing the instructions for the experiment. After reading the instructions, the participants were encouraged to ask any questions. The participants were blindfolded during the experiment to restrict visual cues. Additionally, they also wore headphone playing white noise. The volume of white noise was set such that it masked the sound of interaction with the surfaces but did not hamper normal conversation. The experimental environment is shown in Fig. 2

The experiment was a cluster sorting task similar to the one carried out in [12], [13]. Participants were required to classify the given 31 samples into predefined number of groups. The experiment consisted of three trials for both bare-handed and tool-based interaction. The number of groups in each trial, due to the limited number of samples, were 3, 6 and 9, respectively. The variable number of groups ensured the sub-classification of samples. One sample was presented at a time and the participants were asked to assign

Fig. 2. The upper picture shows tool-handed interaction. Lower picture shows the bare-based interaction

it to a group based on the perceived differences. Similarly perceived samples were assigned to the same group. The participants were free to explore the surface as long as they wanted using active touch. After the assignment of all samples into the given number of groups, the participants were given another chance to check all the groups for any error in assignment. In case of an error, they were allowed to re-assign the sample into another group.

The experiment was carried out with two different modes of interaction. In one part, participants were only allowed to use the index finger of their dominant hand. While in the other part they used a pen-like rigid aluminum rod with a solid plastic tip, as shown in Fig. 3, for interaction with the surfaces. The diameter of the tip was 7 mm while length of the tool was 14 cm. The order of bare-handed and tool-based interaction was altered from participant to participant to avoid ordering bias.

Fig. 3. Tool used for tool-based interaction.

*4) Data Analysis:* In order to evaluate the differences between bare-handed and tool-based interaction, we calculated a similarity matrix from the cluster sorting experiment after averaging the data across all the participants. Unlike pairwise comparison tasks where each sample is evaluated against each other sample, the dissimilarity matrix from cluster sorting is calculated in a different manner. Score to a pair of samples was assigned based on the number of times they were grouped together across different trials. If a pair of samples was grouped together in any given trial, then the score received by that pair was equal to the total number of groups in that trial. Thus, the score of a pair of samples which were always grouped together would be 18 (3 + 6 + 9). Afterwards, the similarity matrix was converted into a dissimilarity matrix and scaled from zero to one thousand. A score of zero meant that the pair of samples was always assigned to the same group, while a score of 1000 meant that they were never grouped together.

Additionally, scanning motion of hand was tracked using OptiTrack V:120 Trio$^{\text{TM}}$. Velocity of scanning (finger in case of bare-handed interaction and tool in case of tool based interaction) was calculated from the position tracking data. The participnts were free to use any scanning strategy.

### *B. Adjective Rating*

The aim of this experiment was to find out different adjectives that can describe the textural properties of all the textures used in the cluster sorting experiment. In the method of adjective rating, the participants rate the similarity between the feel of the surface during exploration with an adjective pair.

*1) Participants And Stimuli:* The same six participants took part in this experiment. Furthermore, the experimental environment was the same as the first experiment.

*2) Procedure:* This experiment was divided into two sub parts. In the first part, different adjectives were collected, which could describe the feelings associated with the given textures. All the texture samples were placed in a box with an opening for one hand. The participants were provided with a list of 25 adjectives. And they were asked to feel all the surfaces and choose the relevant adjectives from the list that can describe the feelings associated with the surfaces. The adjectives that were not selected by any participant were discarded. The adjectives that had a corresponding adjective with an opposite meaning in the list, were selected to form an adjective pair. As a result, five adjective pairs, as shown in Table I, were selected for the next part of the experiment.

In the second part of the experiment, a GUI (Graphical User Interface) was made for data collection. It contained the adjective pairs on the opposite sides of a slider. There was no scale marked on the slider while its length was set to 127mm [14] on the screen. Each sample was rated against the five adjective pairs. The slider values were mapped to a scale of zero to hundred. Subsequently, the scores across all participants were averaged.

## III. RESULTS

The Kruskal stress [15] for the perceptual spaces (i.e. for bare-handed and tool based interaction) is shown in Fig. 4. Although a distinct 'elbow' is not visible, but the stress values at four dimensions for bare-hand and tool based are 0.12 and 0.15, respectively. According to [16], these stress values are considered as fair. Therefore, a 4D MDS was applied to the dissimilarity matrix calculated from the cluster sorting experiment. Fig. 5 shows dimension one and two of the MDS (bare-handed and tool based combined).

While, Fig.e 6 shows dimension three and four of the MDS. As the orientation of axes of the plots generated by MDS are irrelevant, so the plots were rotated around for better visualization and ease of understanding. The two perceptual spaces can be combined in a single graph since they were scaled by the same amount as shown in Section II. Combining the graphs provides an easier analysis and shows the overall scheme of things.

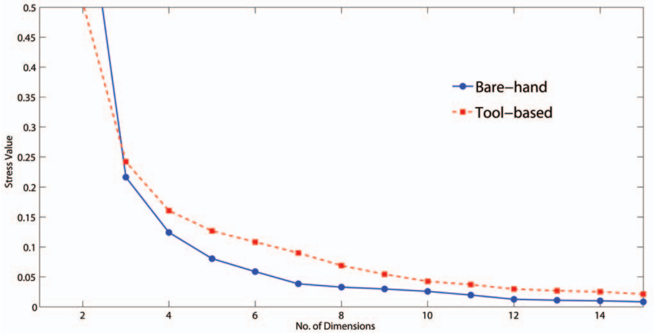

Fig. 4. Kruskal stress for bare-handed and tool based MDS.

First, we analyze the first and second dimension of the bare-handed interaction. In Fig. 5 the perceptual space for bare-handed interaction (see blue circles) shows three distinct clusters. All the smooth surfaces are located on the right side of the plot. The rough and hard surfaces are located on the upper side. Meanwhile, the cloth based and wooden textures are placed in the left half of the space. This distinct grouping shows that all the three clusters can be easily differentiated by the bare-hand.

Second, the first and second dimensions of the tool-based interaction are discussed. The samples, in the first and second dimension of perceptual space for tool-based interaction (see red stars in Fig. 5), exhibit a relatively diffused nature. Although, the overall scattering pattern shown by the samples is similar to that of bare-handed interaction, i.e. the right side of the space contains the smoother samples. The left side is occupied by the cloth and wooden samples. And the rough and hard samples lay atop of the space. This shows that classifying the samples into major textural groups was equally easy in both modes of interaction in the first and second dimension. But the diffused nature of the tool-based perceptual space indicated that participants could readily discriminate the perceptually closer samples as well.

Third, we analyze the third and fourth dimensions of the perceptual space for bare-handed interaction. In Fig. 6 the bare-handed perceptual space (see blue circles) shows a trend along dimension three. The samples are scattered along a continuum along the third dimension. It starts from the wooden samples, on the left side of the plot, goes through the plastic samples (smooth and rough both) and finishes with the cloth like samples, towards the right side of the plot. But, if we look at the fourth dimension (see blue circles in Fig. 6) of the bare-handed perceptual space, we find that most of the samples are stacked very closely except a few. There is no well defined trend.

TABLE I

CORRELATION OF ADJECTIVE PAIRS WITH PERCEPTUAL SPACE.

*values higher then 0.5 are shown in bold*

| Adjective Pair | Bare-Handed | | | |
|---|---|---|---|---|
| | Dim 1 | Dim 2 | Dim 3 | Dim 4 |
| Rough - Smooth | 0.36 | **-0.78** | 0.13 | -0.27 |
| Flat - Bumpy | -0.27 | **0.88** | -0.11 | -0.01 |
| Sticky - Slippery | 0.04 | **-0.58** | 0.13 | -0.21 |
| Hard- Soft | **-0.57** | 0.26 | 0.27 | -0.35 |
| Irritating - Pleasant | 0.05 | -0.51 | 0.33 | -0.41 |
| | Tool-Based | | | |
| Rough - Smooth | 0.46 | **-0.76** | 0.12 | -0.17 |
| Flat - Bumpy | -0.48 | **0.73** | 0.03 | -0.02 |
| Sticky - Slippery | 0.15 | **-0.61** | -0.3 | 0.06 |
| Hard- Soft | -0.49 | -0.06 | **0.57** | -0.25 |
| Irritating - Pleasant | 0.19 | -0.74 | -0.01 | -0.02 |

Last, we look at the third and fourth dimension of the perceptual space for tool-based interaction(see red stars in Fig. 6). The tool-based perceptual space shows a clear scattering of samples along the third and fourth dimension. But, the trends cannot be quantified easily. The vast difference between the third and fourth dimension for bare-handed and tool-based perceptual spaces means that participants used totally different classifying strategies in these dimensions.

The adjective rating experiment provided the qualitative properties of all the samples in the form of scores. In order to check the validity of the adjective rating scores, the correlation between every adjective pair and the perceptual space was calculated. Table I shows the correlation coefficients for all the adjective pairs. It can be seen that the correlation for the adjective pairs of Rough-Smooth and Flat-Bumpy is very high for the second dimension (for both bare-handed and tool based interaction). Meanwhile, the adjective pair of sticky-slippery also shows a considerable correlation for the second dimension. The fact, that correlations for the third and fourth dimensions are very low, means that participants used different properties or a combination of the ones we used in the experiment to classify samples.

To find out the relationship between adjective pairs and the dissimilarity scores, multi-linear regression was performed. The predictor variable was the adjective score, while the location coordinates of samples in perceptual space was the response variable. Fig. 5 and Fig. 6 show the linearly regressed adjective pairs in the form of lines, for dimension one-two and dimension three-four, respectively. The length of the regressed line indicates the mean squared error of the adjective pair. A longer line means that the adjective pair has high correlation. The average scores for the Rough-Smooth and Flat-Bumpy, the adjective pairs with high correlation, can be seen in Fig. 7 and Fig. 8, respectively.

## IV. DISCUSSION

The perceptual spaces showed at least four distinct dimensions, as evident from the stress function. This was mostly due to the dynamic range of the samples used in this study. In [10], the authors could not find more then three dimensions because either the sample set was too small or the samples were similar in nature. Still, there is room

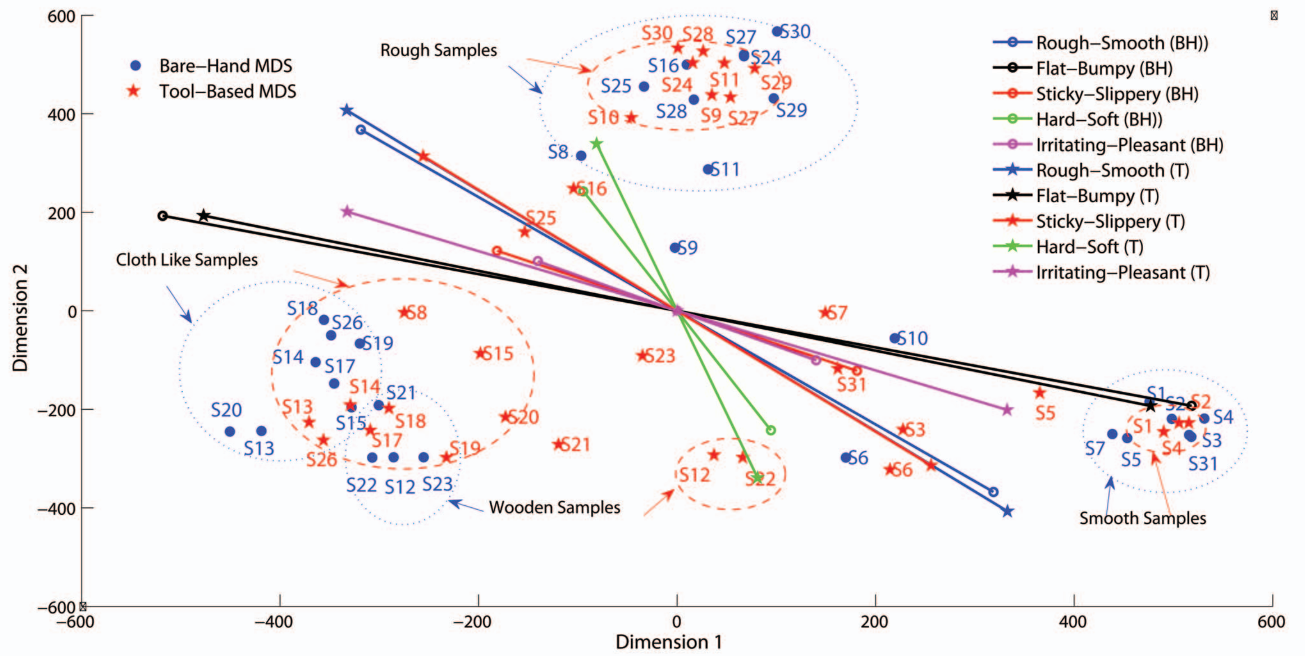

Fig. 5. MDS scatter graph for Bare-Handed and Tool-Based Interaction (Dimension 1 - 2)

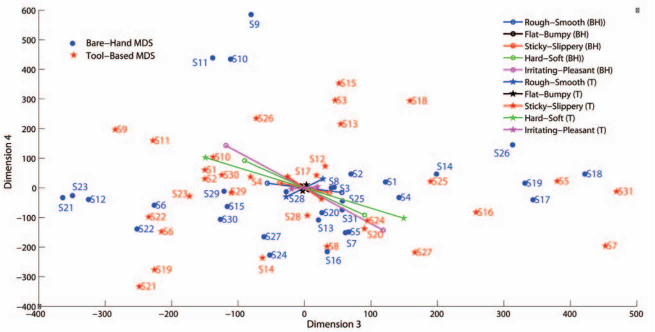

Fig. 6. MDS scatter graph for Bare-Handed and Tool-Based Interaction (Dimension 3 - 4)

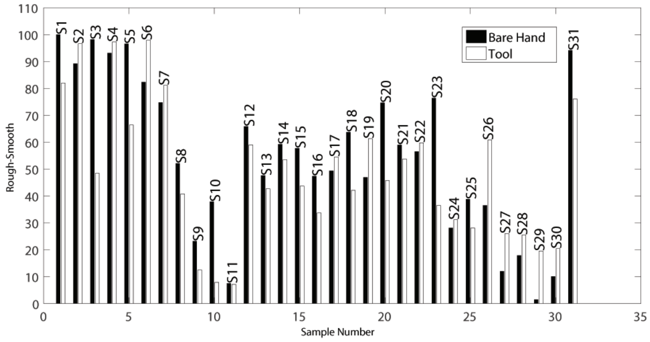

Fig. 7. Scores for the adjective pair Rough - Smooth

for completely different samples, i.e. oily or wet surfaces, organic samples etc. Even more dimensions might appear if we add such samples.

As for the differences between the perceptual spaces for bare-handed and tool based interaction, they can be explained with the help of scanning velocity during interaction and the differences in adjective rating scores for the adjective pairs. First, we discuss dimension one and two of the perceptual spaces. These dimensions will mostly remain the focus of our discussion as they showed high correlation with the adjective pairs.

Using bare-hand for identifying or classifying different samples come to us from daily experience. As we are familiar with the feeling of the surfaces, we need little time to identify them. In the experiment, initially participants required almost the same time (4-5 seconds) for both types of interactions (i.e. bare-handed and tool-based). However, in subsequent trials the scanning time for bare-handed interaction kept on reducing (1-2 seconds), because the range of information perceived in bare-handed interaction is very wide. It became easier to judge samples quickly. This showed that participants used familiarity and pre-judgment for classification using bare-hands. On the other hand, in tool based interaction participants were unable to use their experience and relied more on the information from interaction. Since the information from tool based interaction is limited as compared to bare-handed interaction, the time for tool-based interaction almost remained constant (4-5 seconds). Based on this evidence it can be assumed that for time critical tasks bare-handed interaction is better. Whereas the precision of bare-handed interaction was lowered due to pre-judgment. In order to increase the precision, participants can be advised to avoid the use of pre-judgment.

The evidence of pre-judgment can be explained with an example from the perceptual space. As shown in Fig. 5, the perceptual space for bare-handed interaction (see blue

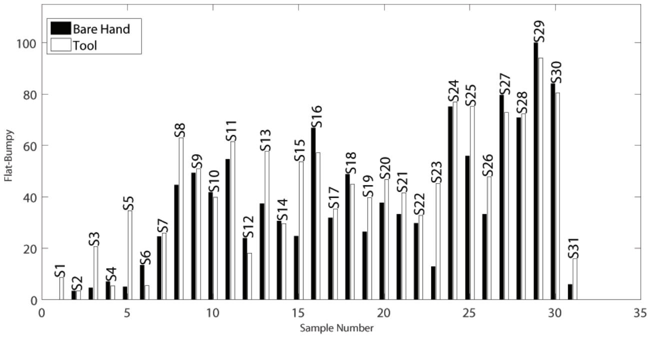

Fig. 8. Scores for the adjective pair Flat - Bumpy

circles) showed distinct clusters while that for tool-based interaction (see red stars) showed a rather diffused scattering. For example, in the bare-handed perceptual space, all types of smooth surfaces were tightly grouped together, regardless of the difference in texture within the group. On the other hand, in case of tool-based interaction, although three groups could be seen, the intra-cluster differences were escalated. A similar trend was seen for the groups with rough and cloth like surfaces. As participants grew familiar with the samples in bare-handed interaction, the basis for classification changed from textural differences to pre-judgment and experience. Whereas, the samples in the perceptual space for tool-based interaction were stretched apart based on the minor differences in textures. It was speculated that the participants used the actual textural differences for clustering since they did not have prior experience of differentiating samples through a tool.

Similarly, it was seen that after a few trials when a wooden sample was placed in front of a participant, the participant would immediately assign it to a group where all sample were made of wood. The four wooden samples (S12, S21, S22 and S23) are located together in the lower left portion of the bare-handed perceptual space. However, in the tool-based perceptual space, only samples S12 and S22, which are very similar, are in close proximity. The participants, when devoid of the direct knowledge about the nature of material, used the textures to differentiate.

The smooth samples (S1-S5) are located very close to each other in the bare-handed perceptual space. While in the tool-based perceptual space, they are far apart. If we compare the adjective rating scores for the rough-smooth adjective pair, we see a peculiar trend. The adjective scores for bare-handed interaction are very similar for smooth samples (S1-S5), thus the closely packed nature in the perceptual space. On the other hand, the adjective scores for tool-based interaction for the very smooth samples (S1,S2 and S4) are similar to each other, and different from the other smooth samples (S3 and S5), which are much lower, resulting in the dispersion that was seen in the perceptual space for tool based interaction. Further evidence that in tool-based interaction participants relied on the information received through tool can be seen if we analyze samples S7 and S31. These samples are in close proximity of the smooth samples (S1-S5) in the bare-handed perceptual space, but have moved farther away in the tool-based perceptual space. Since, these samples (S7 and S31) were rubber based smooth samples, the tool encountered friction, and the participants perceived them differently from the very smooth samples.

Conversely, traces of pre-judgment were evident in the tool-based interaction as well. For example, the sandpaper samples (S9, S10 and S11), except sample S3 (which is extremely fine), are far apart in the perceptual space (see blue circles in Fig. 5) for bare-hand. Whereas in the perceptual space for tool-based interaction (see red stars in Fig. 5) they are relatively close. This is due to difference in the rough-smooth scores perceived by the participants. The rough-smooth scores, for tool-based interaction, of the these three samples are almost the same. Since sandpapers have a very different texture as compared to most other surfaces, they can be readily discriminated even with a tool. Stroking a tool across a sandpaper is an irritating feeling. Hence, as soon as the participants came across a sandpaper, it was assigned to the same group as other sandpapers without taking the texture into account.

We get cutaneous cues through the deformation of skin at the point of contact. But in tool based interaction this information is transformed, instead the deformation is relative to the shape of the tool and the transfer of information occurs through vibrations. However, in some cases this information can be masked. For example, in the perceptual space for tool-based interaction (see red stars in Fig. 5), sample S16 (towel) and sample S8 (grass) are further out from the rough cluster. Although these are quite rough surfaces, but due to the soft nature of the macro bumps, they were perceived as smoother then they actually were.

The cloth like samples exhibited very similar characteristics in both bare-handed and tool-based perceptual spaces. They are clustered together and show almost the same level of scattering. It is assumed that in bare-handed interaction the participants classified these samples using familiarity, while in the tool based interaction, all the cloths were perceived as similar because the variations in textures were masked by the rigidity of the tool tip. Therefore, there is no major difference in the scatter of the cloth cluster across the two modes of interaction in the first two dimensions.

Considering the third and fourth dimensions of the perceptual spaces. We can see that the third dimension of the perceptual space for bare-handed interaction (see blue circles in Fig. 6) shows some semblance of grouping. Although none of the adjective pairs show high correlation, we can see some trends. We can see the wooden samples, the rougher sand papers and the fabrics etc. grouped together. This means that the participants used some criteria other then the adjectives used in this study to classify the samples into groups. But, if we have a look at the fourth dimension of perceptual space for bare-handed interaction (see blue circles in Fig. 6), it shows very little difference across all the samples. Just a group of the sandpapers is located in separation along this dimension, while the rest of the samples are jumbled together. Therefore, it is not easy to define a trend along this dimension. On the contrary, both the third and fourth dimensions of the perceptual space for the tool based interaction (see red stars in Fig. 6) show a distinct spread of the samples. Yet, the meaning of this spread is unclear. The trends are not in conformity with the adjectives that were used in the second experiment. In fact, the trends might be a very complicated and sophisticated mixture of different feelings across which the samples were classified.

Overall, the classification using bare-handed and tool-based interaction was very similar. The correlation between corresponding adjective pairs of bare-handed and tool-based interaction are 0.79 for rough-smooth, 0.9 for flat-bumpy, 0.78 for sticky-slippery, 0.79 for hard-soft and 0.84 for irritating pleasant. This clearly shows that similarities were present in perception through the two methods, as evident from the first two dimensions of perceptual space, but it was not exactly the same.

## V. CONCLUSION

In this study, we provide an analysis of the differences among bare-handed and tool-based interaction. The factors that contribute to the differences in the perception were highlighted and explained. It is likely that the precision in perception of bare-handed interaction was affected by pre-judgment. Additionally, possible evidence of pre-judgment in tool-based interaction was also highlighted. From the experimental results it can be assumed that tool based interaction showed more precision while bare-handed interaction required less time for classification.

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