Perceptual Dimensionality of Manual Key Clicks*

Quan Liu, Hong Z. Tan, Liang Jiang, and Yulei Zhang

Abstract—**The present study investigated the perceptual dimensions associated with manual key clicks, with the goal of developing realistic haptic key-click feedback signals for virtual keys. We first harvested eight adjective pairs for describing the haptic feel of button and key presses from native English speakers. We then conducted the main experiment where participants provided adjective ratings and grouping data for twenty-three buttons and keys. An MDS analysis of the grouping data led to either a 2-D or 3-D solution. By projecting adjective ratings onto the MDS solution spaces, we found the 2-D perceptual space to be an adequate representation of human perception of manual key clicks. The two perceptual dimensions are determined to be *shallow-deep* and *rough-smooth*. Future work will explore the physical parameters corresponding to the perceptual dimensions and ways to simulate realistic key clicks by designing feedback signals using the relevant parameters.**

I. INTRODUCTION

Since perhaps the first publication to use vibrotactile feedback for key-click feedback [1] in 2001, and the first commercial product to employ virtual keys in Motorola ROKR E8 music phone, research on this topic has been increasing steadily. Many of today's mobile devices, such as cellphones, are more structurally streamlined compared to their predecessors due to the removal of physical keys. Users type out messages with an onscreen virtual keyboard. This is however difficult as the lack of feedback on the fingertips forces users to rely on visual feedback to ascertain the acceptance of a key press, not to mention that individuals with severe visual impairments must seek other means of feedback in order to operate a virtual keyboard. To overcome this loss of tactile feedback due to non-moving keys, tactile key-click feedback has been widely implemented in the latest generation of mobile devices. For example, many Android devices use customizable haptic feedback that allows users to feel light vibrations on the fingertips when typing. Apple's iPhone 7 has a virtual Home button that provides button-press feedback with its vibrotactile Taptic Engine. It remains arguable whether vibrotactile key-click feedback can satisfactorily replicate the feel of pressing a physical key.

Many studies on simulated key clicks or button presses focused on the perceived quality of virtual keys and the physical parameters affecting it. Kaaresoja et al. investigated the effect of temporal properties of tactile feedback on mobile devices and provided guidelines in terms of duration and latency for designing tactile feedback signals [2], [3]. Some researchers designed and evaluated distinctive key-click feedback signals for mobile devices. Chen et al. [4] reported four experiments using a piezoelectric actuator and concluded that up to 5 to 6 key-click feedback signals varying in frequency, amplitude and number of waveform cycles can be perfectly identified on a mobile phone prototype. A large collection of distinct vibrotactile feedback signals, referred to as vibrotactile icons or "tactons," have been developed [5], [6], [7]. A variety of vibrotactile icons are now accessible from pre-built libraries [8], while others are customizable [9]. These carefully crafted vibrotactile signals are expected to permeate future virtual key-click applications to enrich user experience.

There is no standard way of classifying keys, buttons and switches. A typical way of characterizing a keyboard key is by its force vs. displacement profile as specified by the ISO standard TS 9241-411:2012 [10]. Some introduced the term "tactility" to evaluate the soft or light touch of keyboards [11]. Empirically, ergonomic keyboards with satisfying typing experience produce a keystroke travel of approximately 3.5 to 4 mm with a typical actuation point at around 2 mm. Driven by compactness, modern keyboards have shortened key travel by innovating new key-press mechanisms. For example, the 12-inch MacBook Retina 2015 debuted its patented butterfly mechanism that replaced the traditional scissors mechanism to drastically reduce key travel to around 1 mm while improving stability [12]. Driven by the desire to characterize switches and keys with physical parameters that matter to perception, Weir et al. proposed the idea of a "haptic profile" to capture the feel of three switches that felt "clicky", "smooth" and "mushy" [13]. In addition to the usual force *vs.* position plot, they also used the force *vs.* velocity and position *vs.* velocity plots to demonstrate the differences among the switches they studied. Tan et al. further demonstrated that humans are able to perceive the invariant spatial properties of a switch despite temporal variations in the proximal stimuli felt by the hand during an active turning of the switch [14]. Tashiro et al. discussed the different force *vs.* stroke changes due to a finger pushing a button and the buckling and rapid restitution of the dome top of the button, but did not go as far as categorizing buttons based on these characteristics [15]. With actual displacement diminishing or disappearing in virtual keys and buttons, the ISO standards and any displacement-based physical characterization of key presses need to be updated and revised.

We ask the question of what makes a key press feel real, and to what extent virtual keys can be made to feel real. The present study is the first step towards mapping physical parameters to perceptual dimensions with the goal to deliver distinct haptic key-click feedback signals that feel as realistic as possible. We approach the problem by first studying the perceptual dimensionality of manual key clicks using multidimensional scaling (MDS). The MDS method has been

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*This work was supported in part by AAC Technologies.

Quan Liu and Hong Z. Tan are with the Haptic Interface Research Laboratory, School of Electrical and Computer Engineering at Purdue University, 465 Northwestern Ave, West Lafayette, IN 47907 USA (e-mail: {liu2029, hongtan} @purdue.edu).

Liang Jiang and Yulei Zhang are with AAC Acoustic Technologies (Shanghai) Co., Ltd., Room 804, Bldg. B, Venture International Park, No. 2679 Hechuan Road, Minhang District, Shanghai, PRC (e-mail: {JiangLiang, ZhangYuLei}@aactechnologies.com).

used in the past along with adjective rating to explore the perceptual dimensions associated with textures and other material properties [16], [17], [18], vibratory signals [19] and other aspects of haptic interactions [20], [21], [22]. Our study employs mostly real buttons and keys except for the virtual Home button on an iPhone 7 [23]. Our objectives are to discover the perceptual dimensions associated with manual key presses, and eventually map them to the physical characteristics of real or virtual keys and buttons.

In the rest of the paper, we first present our methodology that is slightly modified from that used in most MDS studies, and then show our results and discuss their implications for future research.

II. METHODS

Our study consisted of a pilot study and a main experiment involving Adjective Rating and Similarity Judgment. The purpose of Adjective Rating was to collect data along adjective pairs relevant to key presses, to assist with the interpretation of the dimensions from MDS analysis. The adjective pairs used in Adjective Rating was determined through the pilot study. We chose to perform Adjective Rating prior to Similarity Judgment using the same participants in order to “condition” the participants to judge similarity along these perceived qualities (personal communication with Mark Hollins, 2017). The purpose of Similarity Judgment was to collect perceived dissimilarity scores for each pair of the keys and buttons in the stimulus set. We applied the standard MDS analysis procedure to the dissimilarity matrix from Similarity Judgment, and mapped Adjective Rating results onto the MDS solution space to seek insight into the meaning of the recovered dimensions. This section presents our methodology and the pilot study.

A. Participants

Twelve participants (6 males and 6 females; 20-30 years old, average 23.2±3.2 years) took part in the main experiment. All but one participant were right-handed by self-report. All participants gave informed consent on an IRB approved form. They were compensated for their time.

B. Apparatus

We developed a semi-automated system consisting of a customized linear motorized stage (V-Slot® Mini V Linear Actuator from OpenBuilds Part Store) for positioning stimulus alternatives, a PC laptop running a MATLAB GUI, a customized unit interfacing the PC laptop and the motorized stage, and an arm and finger rest (Fig. 1). The keys and buttons were visually hidden from all participants prior to the experiments, and a large cardboard prevented the participants from seeing the stimulus presented during the experiment.

Fig. 1: Experimental Setup with the view from the participant (left) and the experimenter (right). The inset on the right shows the finger rest.

TABLE I. THE 23 STIMULI USED IN THE PRESENT STUDY

Sample #	Description
1	Tactile Switch (SN 94) – Tall Blue [a]
2	Tactile Switch (SN 95) – Tall Black [a]
3	Cherry MX – Clear [b]
4	Cherry MX – Gray [b]
5	Cherry MX – Brown [b]
6	Cherry MX – Red [b]
7	Tactile Switch (SN 71) – mini Yellow [a]
8	Tactile Switch (SN 91) – Short Blue [a]
9	Tactile Switch (SN 48) – mini Red [a]
10	Tactile Switch (SN 60) – mini Green [a]
11	Tactile Switch (SN 96) – Tall Yellow [a]
12	Cherry MX – Black [b]
13	Cherry MX – Green [b]
14	Cherry MX – Blue [b]
15	Cherry MX – White [b]
16	iPhone 7 Home Button [c]
17	iPhone 7 Power/Volume Button [c]
18	iPhone 6 Home Button [d]
19	iPhone 4s Home Button [e]
20	iPhone 4s Volume Button [e]
21	iPhone 4s Power Button [e]
22	Surface Pro Type Cover - Trackpad [f]
23	Surface Pro Type Cover - Shift Key [f]

a. https://item.taobao.com/item.htm?spm=a1z09.2.0.0.761a8f61JlqrvU&id=541223760534&_u=d3522a2e6db
b. http://www.maxkeyboard.com/max-keyboard-keycap-cherry-mx-switch-o-ring-pro-sampler-tester-kit.html
c. https://www.apple.com/shop/buy-iphone/iphone-7
d. https://www.amazon.com/iPhone-6-Plus/b?ie=UTF8&node=12522859011
e. https://www.amazon.com/Apple-iPhone-4S-16-White/dp/B005SSB0YO
f. https://www.microsoft.com/en-us/surface/accessories/browse

C. Stimuli

TABLE I lists the 22 physical buttons and keys and 1 virtual button (#16 in TABLE I) used in the present study. The stimuli included buttons on several iPhone models (since we are interested in emulating them later), keyboard keys (because they are representative of typical keys used by most people), Cherry MX mechanical switches (because they are highly sought after by some people) and tactile switches used by hobbyists (because they are very similar to the smaller buttons on the side of phones). Within each category, several keys with varying properties are included. Since the results of MDS analysis are highly dependent on the variety of the stimuli, one virtual button was also selected in order to examine whether physical and virtual buttons occupy a similar space in the MDS solution. Therefore, the 23 stimuli produce a wide range of tactile sensations when manually pressed and cover a reasonable range of physical key clicks. Samples #1-15 were mounted securely on the motorized stage, while the rest of the samples were presented manually by the experimenter due to their larger form factors.

D. Procedure

The participant sat in front of a long table with the MATLAB program running. The participant rested the dominant arm on the arm-rest with the palm facing down and the index finger in a finger rest (see Fig. 1). The participant operated the program with the non-dominant hand and completed the following two tasks in the order given: Adjective Rating and Similarity Judgment. A noise-reduction headset (Peltor, with a noise reduction rating of 30 dB) was worn by the participants throughout the experiment to eliminate any audio cues of button/key pressing. On the computer screen, the 23 stimuli were represented by 23 gray buttons labeled with numbers #1 to #23. The participant could click on any of the gray buttons onscreen in order to press on the corresponding stimulus. Participants could feel each stimulus as many times as they wanted. As mentioned earlier, the participants could not see the stimuli being pressed. Furthermore, the mapping of the 23 stimuli to the 23 onscreen buttons was randomized for each participant, so that the data collected would not be confounded by the order in which the stimuli were operated in case all participants chose to experience the 23 stimuli from #1 to #23. On average, the experiment took 40 minutes per participant. The participants could take a break at any time during the experiment.

For Adjective Rating, the participants were asked to rate each of the 23 stimuli along eight adjective pairs determined from the *Pilot Study* described later in this section. The pairs were: *shallow-deep, wobbly-stable, hard-soft, rough-smooth, unresponsive-responsive, displeasing-pleasing, virtual-real,* and *uncomfortable-comfortable*. The first adjective of each pair was on the left end of the scale, and its antonym adjective on the right end (see Fig. 2). The participants first picked a stimulus to be presented, waited until an onscreen message signaling that the stimulus was ready, and then pressed on the button or key with the dominant index finger. The participants were instructed to focus on the tactile feel of the buttons and keys when rating the sensations along the adjective pairs listed. They provided ratings by moving the slide bars from the default center positions towards either adjective. They were allowed to pick the stimuli in any order or revisit previously rated stimuli. They continued until all 23 stimuli had been rated. After all the Adjective Ratings results were submitted, the participant was prompted to move to the next task. Overall, the ratings from the 12 participants appeared to be consistent. The standard deviations for each adjective pair varied from 9 to 33 and the average standard deviation was 21.0 ± 4.7.

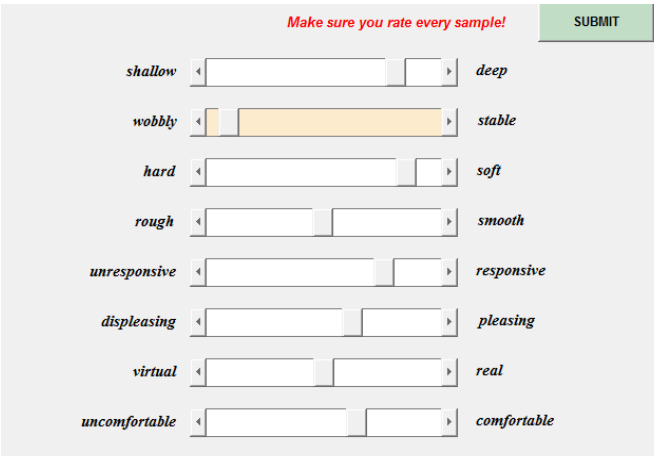
Make sure you rate every sample!

Fig. 2: Adjective Rating interface with a 0-100 scale from the left to right

For Similarity Judgment, the participant pressed on stimuli 1 through 23 again. This time, the goal was to place stimuli with similar sensations during pressing into the same group. At the end of this task, a minimum of 3 and a maximum of 7 groups must be generated. The participant was allowed to and often needed to revisit previous stimuli. The participant was also strongly encouraged to double-check the grouping before submitting the results (Fig. 3). On average, the 12 participants used 5.4 ± 1.2 groups.

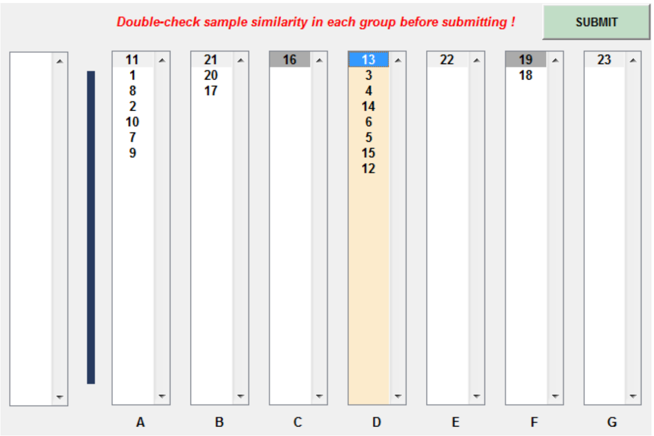
Double-check sample similarity in each group before submitting !

Fig. 3: Similarity Judgment interface showing subjectively similar stimuli placed in the same group

E. Data Analysis

For Adjective Rating, the positions of the slider bars were linearly mapped to scores between 0 and 100. The scores from the 12 participants were averaged, resulting in a 23-by-8 table of adjective scores for the 23 stimuli and 8 adjective pairs.

Data obtained from Similarity Judgment were used to form a similarity matrix for all stimulus pairs. The similarity value for each pair was the number of participants who placed the two stimuli in the same group divided by the total number of participants (12). Next, the similarity values were subtracted from 1.0 to form a dissimilarity matrix, whose values were analyzed using the MDS procedure in SAS 9.4. The output of the procedure included a Kruskal's stress plot, based on which the optimal number of dimensions for the solution space was selected. The stress value ranges from 0 with 1, with lower values indicating a better goodness of fit. Stress decreases as dimension of the MDS solution space increases, and plateaus after a certain dimension. The number of dimensions at the "elbow" point suggests a dimensionality solution that accounts for the MDS data in an optimal way. For each dimensionality solution, the coordinates for all 23 stimuli in the perceptual space were available from the MDS procedure. After the best MDS model dimensionality was selected, the 23 data points representing the 23 stimuli were then plotted in the solution space. A cluster of stimuli indicated similarity in the way the buttons and keys felt when they were pressed, while a large distance between any two stimuli meant that they felt different.

To project adjective ratings onto the MDS solution space, we ran a multiple linear regression in SAS 9.4 with stimulus coordinates being the independent variables and the adjective ratings for each adjective pair as the dependent variables. We chose the option of outputting standardized regression coefficients. The coefficients were treated as the vector components for a particular adjective rating scale. For example, for the *shallow-deep* scale in the 2-D space, we obtained standardized regression coefficients a and b. Therefore, the direction of the scale was represented by the vector (a, b). This adjective rating vector was then normalized and scaled by the coefficient of determination (R^2), a measure of how close the data are to the fitted regression line. An R^2 of 1.0 indicates that the regression line fits the data perfectly. In the end, an adjective scale with specified direction and magnitude was projected onto the MDS space. The same procedure was applied to all 8 adjective rating scales, for both 2-D and 3-D MDS solution spaces. All adjective rating vectors were later scaled in magnitude for better viewing purposes. We then looked for pairs of adjective rating scales with relatively high R^2 values and are almost orthogonal to each other. These adjective pairs are then deemed to be likely the perceptual dimensions for manual key clicks.

F. Pilot Study on Adjective Harvesting

The purpose of the pilot study was to explore and collect the adjectives people use to describe the tactile sensations arising from pressing on keys and buttons. The resulting adjective pairs were then used for Adjective Rating during the main experiment. Five native speakers of English (2 males and 3 females; 19-21 years old; all right-handed) took part in the study. Before the study, the participants were advised to focus on the tactile sensation associated with the vertical travel of the buttons and keys, and ignore the shape and size of the contact surfaces to the best of their abilities. The participant was blindfolded and wore the Peltor noise-reduction headset to eliminate any visual or audio cues. The participant used the index finger of the dominant hand to interact with the keys and buttons. The experimenter presented one key or button at a time in a random order. The participant pressed on the key or button, and responded with as many adjectives as they could think of. The experimenter recorded all the adjectives on a laptop. The participants could take a break whenever they needed it.

Adjectives with similar meanings were combined. This resulted in nine distinct categories: *Perceived Distance, Stability, Pressing Resistance, Evenness, Responsiveness, Perceived Shape, Emotion, Comfort* and *Realness*. The category of *Perceived Shape* was removed as we did not want to call attention to this physical feature. Within each category, the adjective that captured the essence of the meaning best (Personal Communication with Joanne Lax, Communications Specialist at the College of Engineering at Purdue University) was selected to represent the category. Afterward, its antonym was chosen to form an adjective pair. In the end, the eight pairs of adjectives shown in Fig. 2 were selected.

III. RESULTS

First, we attempted to find the optimal MDS solution dimensionality. By running a standard MDS procedure on our dissimilarity matrix dataset with increasing dimensionality, we were able to plot the Kruskal's stress values as a function of number of dimensions (Fig. 4). A visual inspection showed an "elbow" point at 2 or 3 dimensions. The stress values are 0.1048 and 0.0583 for the 2-D and 3-D solutions, respectively. We examine both the 2-D and 3-D MDS solutions in order to gain insight into the perceptual dimensions associated with manual pressing of buttons and keys.

A scatter plot of all 23 stimuli on the 2-D solution space is shown in Fig. 5. The stimuli are color coded as follows: green for tactile switches (see TABLE I), blue for phone buttons, yellow for Cherry MX keys, and red for Surface Pro keyboard keys. Cherry MX keys (yellow) are well clustered on the right side of the space and well separated from other stimuli, demonstrating their distinct key-click sensations. Tactile switches (green) are also relatively well clustered on the upper-left corner despite the differences in their shapes and structures. The phone buttons (blue) are more spread out on the left side of the 2D space. Interestingly, the volume/power buttons of different phones (#17, #20 and #21 in TABLE I) are located closer to the tactile switches above them, indicating that the volume and power buttons on iPhones feel similar to other switch buttons. The three home buttons (#16, #18 and #19) form their own cluster that is further away from the tactile switches. The two stimuli from the Surface Pro Type Cover (#22 for trackpad and #23 for shift key) are expectedly separated from each other as the trackpad feels stiffer on the finger than the shift key on the keyboard. Note that the Home button of iPhone 7 (#16), the only virtual button, was perceived to be very similar to the trackpad of Surface Pro Type Cover (#22). The two share the common characteristic of minimal vertical travel, with the virtual Home button technically having zero vertical travel. It is worth mentioning that during the pilot study, participants had difficulty coming up with adjectives to describe the feeling of pressing the (virtual) Home button on iPhone 7. The participants without any prior experience with iPhone 7 expressed mostly negative emotions such as "frustrating," "difficult," "awful" and "nonresponsive," while the one participant who guessed it to be an iPhone 7 used more neutral adjectives like "hard" and "very shallow." Overall, the distribution of the stimuli in the 2-D solution space is consistent with the characteristics of the 23 stimuli used in the present study.

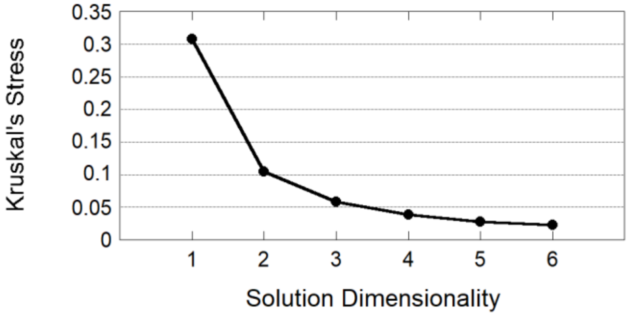

Fig. 4: Kruskal's stress plot showing the residual errors between the dissimilarity matrix and the MDS solutions for increasing number of dimensions

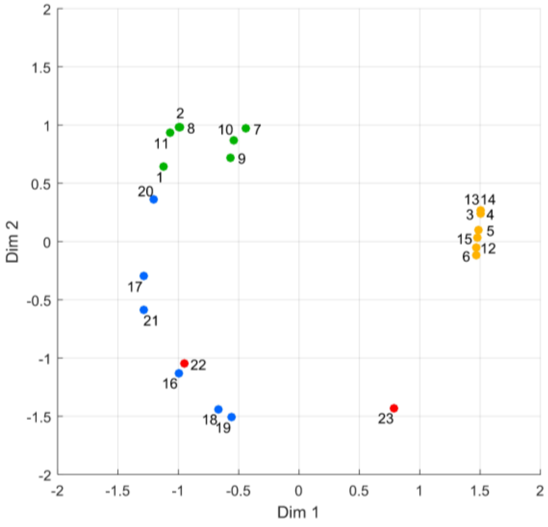

Fig. 5: 2-D MDS solution scatter plot (green: tactile switches; blue: phone buttons; yellow: Cherry MX keys; red: Surface Pro Type Cover keys)

The 3-D scatter plot of the stimuli (Fig. 6) show similar clustering as in the 2-D plot. It appears that the Surface Pro Shift Key (#23) lay closer to the Cherry MX key cluster (yellow) in this case. However, a closer examination of the coordinates of #23 verified that the absolute distance between stimulus #23 and the Cherry MX key cluster was still substantial and similar to that shown in the 2-D solution plot (Fig. 5). In other words, stimulus #23 is located in front of the Cherry MX cluster in the 3-D space (Fig. 6).

Next, we proceeded to project the average rating of each adjective pair to the 2-D and 3-D MDS solution spaces using the multiple linear regression method described earlier in *Sec. II.E. Data Analysis*. From the 2-D plot (Fig. 7), it can be seen that the shallow-deep (red) and stable-wobbly (black) adjective pairs nearly overlap completely, the rough-smooth pair (green) is roughly perpendicular to shallow-deep, and the hard-soft pair (blue) is about 45° from the shallow-deep and rough-smooth pairs, respectively. Recall that we look for two almost-perpendicular adjective ratings with high R^2 values as the interpretation of the two dimensions recovered in the 2-D MDS solution. Since the MDS solutions are rotation- and translation-invariant as they model only the relative distances between stimulus pairs, one can easily rotate the MDS solution space so that the axes align with the projected lines of the major adjective pairs. In this case, it appears that the adjective pairs shallow-deep (or stable-wobbly) and rough-smooth may well represent the 2-D perceptual space shown in Fig. 7.

It's worth mentioning that there exists no threshold for R^2 value when judging the importance of an adjective pair. Hollins *et al.* called adjective scales with R^2 value of 0.712 to be "substantial" [16]. In our case, the R^2 values for *shallow-deep*, *stable-wobbly*, *hard-soft* and *rough-smooth* turned out to be higher than 0.7. Therefore, they are regarded as important and shown in solid lines in Fig. 7. The other four adjective pairs are plotted in dashed lines. In choosing the two adjective pairs representing the perceptual dimensions in the 2-D MDS solution, we first chose the longest line *shallow-deep* to be the first dimension, and then *rough-smooth* that was most perpendicular to *shallow-deep* (99.6°; see Table II). We did not consider *uncomfortable-comfortable* or *displeasing-pleasing* due to their relatively low R^2 values even though they also appear to be roughly perpendicular to *shallow-deep*.

To investigate whether there might be a third perceptual dimension in the perception of manual key clicks, we plotted the adjective rating scales in the 3-D MDS solution space (Fig. 8). Table III shows the relative angles between each pair of adjective ratings with angles close to 90° shown in bold font. Ideally, if the third perceptual dimension did exist, then it would be relatively orthogonal to both the first and second dimensions determined previously. From Table III, there was again a high orthogonality of 98.7° between *shallow-deep* and *rough-smooth*. Although *uncomfortable-comfortable* or *displeasing-pleasing* was also orthogonal to *shallow-deep,* neither was close to being orthogonal to *rough-smooth* (roughly 30°). Furthermore, *unresponsive-responsive* had a relatively low R^2 value of 0.366. In short, we were unable to find three adjective pairs that are nearly orthogonal to each other.

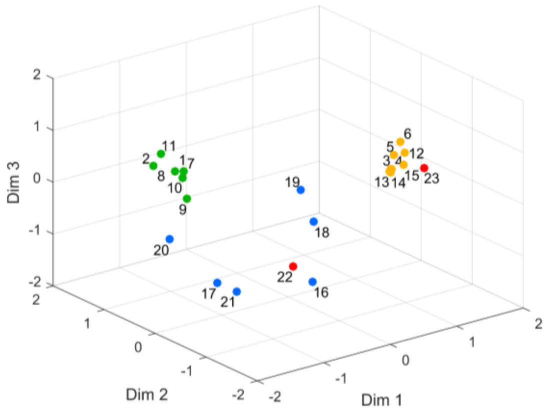

Fig. 6: 3-D MDS solution scatter plot (green: tactile switches; blue: phone buttons; yellow: Cherry MX keys; red: Surface Pro Type Cover keys)

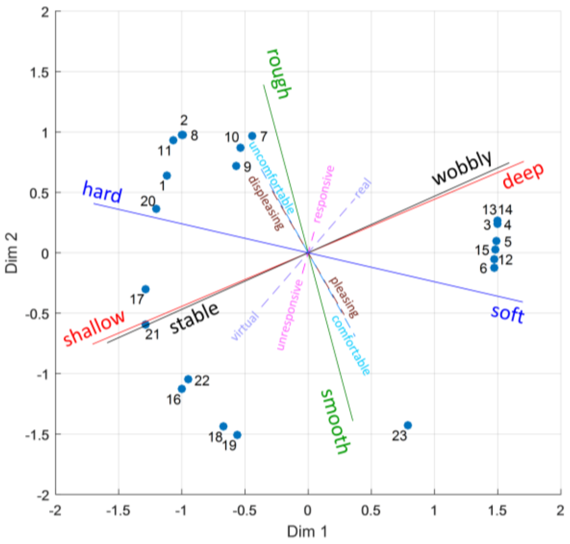

Fig. 7: Adjective Rating scales regressed onto the 2-D MDS solution space. The R^2 values for the shallow-deep, stable-wobbly, hard-soft and rough-smooth adjective pairs were 0.9335, 0.8783, 0.8734 and 0.7177, respectively, and much smaller for the remaining 4 adjective pairs. The length of each line in the plot is the R^2 value scaled by 4 (for better viewing).

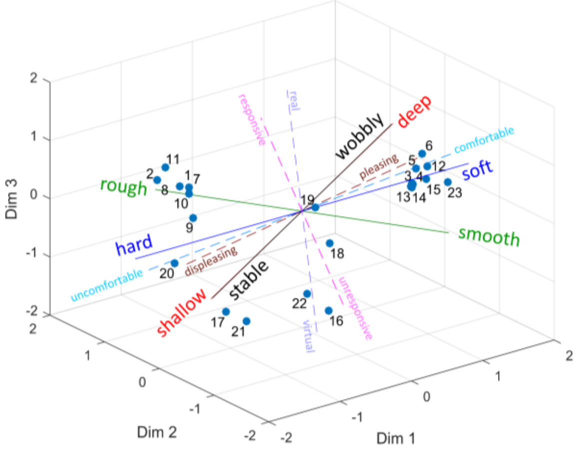

Fig. 8: Adjective Rating scales regressed onto the 3-D perceptual space. The R^2 values for the shallow-deep, stable-wobbly, hard-soft and rough-smooth adjective pairs were 0.9403, 0.8862, 0.8733 and 0.7387, respectively, and much smaller for the remaining 4 adjective pairs. The length of each scale is represented by R^2 scaled by 8 (for better viewing).

IV. DISCUSSION AND CONCLUSIONS

The present study investigated the perceptual dimensions associated with manual key clicks, with the goal of developing realistic haptic key-click feedback signals for virtual keys. We first harvested eight adjective pairs for describing the haptic feel of button and key presses from native English speakers. We then conducted the experiment where participants provided adjective ratings and grouping data for 23 buttons and keys. An MDS analysis of the grouping data led to either a 2-D or 3-D solution. By projecting adjective ratings onto the MDS solution spaces, we found the 2-D perceptual space to be an adequate representation of human perception of manual key clicks. The two perceptual dimensions are determined to be *shallow-deep* and *rough-smooth*.

Our finding of *shallow-deep* being a perceptual dimension for manual key clicks is consistent with the current industry design standard as the vertical travel distance of keys and buttons is often considered a crucial factor in determining user experience. The stimulus set used in the present study included keys and buttons with a wide range of vertical travel, from Cherry MX keys with 3.8-mm travel to the iPhone 7 Home button with zero travel. It appears obvious that a virtual button can never achieve the same haptic feel as, say, a Cherry MX key. However, it might still be possible to emulate the feel of a button or key with 1-2 mm travel (e.g., those on the 12-inch MacBook Retina 2015 keyboard). Tan *et al.* estimated human fingertip position resolution to be 2.2 mm during active free movements from a series of finger joint-angle discrimination thresholds (p.12, third paragraph [24]). This is a lucky result for designers of virtual buttons for the following reason. When the index finger presses on a solid surface, the fingertip tissues can yield up to about 2 mm. Since humans cannot sense such a position change at the fingertip during active moments in free space, it might be possible to create the illusion of a virtual key yielding 1-2 mm under the fingertip instead of the fingertip being compressed by the same amount. Therefore, we conclude that the total vertical displacement is an important perceptual cue for sensing manual key clicks, and it remains to be shown whether the feel of a virtual key can approximate that of a real key with a moderate travel (1-2 mm).

TABLE II. RELATIVE ANGLES BETWEEN THE FOUR MOST IMPORTANT ADJECTIVE RATING SCALES IN THE 2-D MDS SOLUTION SPACE

	shallow-deep	wobbly-stable	hard-soft	rough-smooth
shallow-deep	–			
wobbly-stable	178.8°	–		
hard-soft	37.4°	141.4°	–	
rough-smooth	**99.6°**	79.2°	62.3°	–

An additional note on this perception dimension is that *shallow-deep* and *stable-wobbly* are highly correlated in perception in that shallower keys tend to feel more stable. For example, Apple highlighted the improved stability of its thinner keyboard design for the 12-inch MacBook Retina 2015.

Another perceptual dimension found in the present study is *rough-smooth* due to its high R^2 value and approximate orthogonality with *shallow-deep*. While the *shallow-deep* dimension separates the Cherry MX keys from the rest of the stimuli (Fig. 7), the *rough-smooth* dimension nicely captures the variations in feel within the Cherry MX keys, the tactile switches and the phone buttons. Our future work will focus on the investigation of this perceptual dimension. Physical measurements taken with the stimuli used in the present study will be correlated with the ratings of the *rough-smooth* adjective pair. The parameters that are highly correlated with the adjective ratings will be extracted and used as signal specifications for simulating virtual keys using a high-performance actuator. Psychophysical experiments will be conducted to assess the distinctiveness of the resulting haptic key-click feedback signals and their resemblance to the sensations felt during the pressing of real keys and buttons.

ACKNOWLEDGMENT

The authors thank Mark Hollins for discussions on the MDS methodology and Richard Faldowski, Inwook Hwang, Waseem Hassan, Junji Watanabe, Zhiyu Shao and Miao Wu for sharing their approaches on visualizing adjective rating scales in the MDS solution space. We appreciate the constructive comments from the anonymous reviewers.

TABLE III. RELATIVE ANGLES BETWEEN PAIRS OF ADJECTIVE RATING SCALES IN THE 3-D MDS SOLUTION SPACE

	shallow-deep	wobbly-stable	hard-soft	rough-smooth	unresponsive-responsive	displeasing-pleasing	virtual-real	uncomfortable-comfortable
shallow-deep	–							
wobbly-stable	179.2°	–						
hard-soft	37.2°	142.3°	–					
rough-smooth	**98.7°**	**80.7°**	62.0°	–				
unresponsive-responsive	66.9°	112.8°	**87.9°**	111.8°	–			
displeasing-pleasing	**83.5°**	**95.7°**	56.3°	33.3°	**78.6°**	–		
virtual-real	41.8°	138.0°	69.8°	115.3°	26.0°	**84.4°**	–	
uncomfortable-comfortable	**84.4°**	**94.8°**	55.6°	30.0°	**82.0°**	3.4°	**87.3°**	–

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