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Augmenting Pinch Selection Using Smart Ring Vibration Feedback for Extended Reality Interaction: Perceptual Analysis and Guidelines

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Abstract*—The rise of extended reality technologies has elevated the importance of seamless and natural haptic feedback, particularly for bare-hand interactions. To this end, a ring-type form factor can offer an effective solution. In this paper, we investigate the perceptual space and key perceptual dimensions of vibrotactile feedback applied on the palmar side of the proximal phalanx of the index finger using a ring-shaped device during a two-finger pinch selection task—a widely used interaction technique in XR. A total of 37 feedback conditions were designed, comprising 36 vibration patterns that varied in frequency, amplitude, envelope shape, and duration and a no-feedback baseline condition. Two perceptual experiments were conducted. In Experiment 1, a perceptual space was constructed to visualize the relationships between different feedback sensations. The estimated space had two dimensions, and the sensations were differentiated mostly by the frequency and perceived intensity. In Experiment 2, we identified perceptual dimensions within the perceptual space constructed in Experiment 1 by evaluating the sensations using seven bipolar adjective pairs. The space was best explained using *trivial-consequential* and *dull-crisp* dimensions. Our findings contribute to understanding how vibrotactile feedback augments pinching sensations and provide design guidelines for smart ring vibrotactile feedback.

***Index Terms*—Pinch gesture, smart ring, haptic feedback, vibrotactile, extended reality, perceptual space, adjective rating**

I. Introduction

Haptic feedback is pivotal in enhancing the overall user experience by establishing a tangible connection between the user and the computer. Not only does it provide confirmation feedback for user input [1], it also provides specific tactile sensations [2], enabling intuitive and engaging interactions. Due to its significant potential, extensive research has been conducted to develop compelling haptic feedback that enhances human-computer interaction (HCI). For example, Brewster et al. discussed the importance and effectiveness of tactile feedback in mobile interactions, exploring how tactile sensations can improve user experience and usability [1]. Dube et al. reported that augmented ultrasonic haptic feedback improved speed, accuracy, and comfort for gesture selection methods [3]. In particular, extensive research has been devoted to designing effective haptic feedback for virtual buttons on touchscreens [1], [4]–[6].

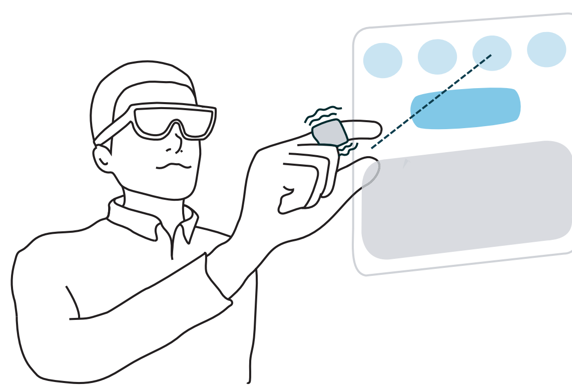

Fig. 1. Pinch gesture for bare-hand interaction in XR and haptic feedback for confirmation provided by a smart ring.

These approaches add a tactile dimension to HCI, making them more engaging and realistic. Furthermore, the recent advent of extended reality (XR) has expanded the user's workspace beyond a small, confined physical space to nearly unlimited virtual environments. For interaction in such spaces, leading companies widely adopt bare-hand methods, such as META's Orion [7], Apple's VisionPro [8], and Microsoft's HoloLens [9], to support natural and efficient transitions between physical, augmented, and/or virtual environments. Here, a natural transition refers to the ability to elicit haptic feedback without additional preparation when switching between the physical and virtual realms, anytime and anywhere it is desired. These new technologies necessitate haptic feedback devices that are portable and unobtrusive to hand movements. Traditional XR controllers, while they are effective for specific tasks, are not ideal for addressing those emerging needs.

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A promising form factor for seamless bare-hand interaction in XR with haptic feedback is a *smart ring*, which is wearable and convenient while minimizing interference between the user's hands and fingers. Wearable ring devices have been explored in many studies [10]–[18], and recent commercial smart rings offer the ability to measure human motion and deliver haptic feedback [19]–[23]. This ring configuration works well in most situations of haptic feedback; only possible exceptions are those requiring power grasp. Despite this significant progress, the effects of haptic feedback provided by ring-shaped devices on user perception remain relatively underexplored. We need to elucidate the relationship between haptic stimuli and human perception in order to diversify the feedback and provide richer interaction experiences.

In this paper, we explore adequate methods to provide haptic feedback for the *pinch selection* task using a smart ring (Figure 1). Pinch selection is a common interaction technique for bare-hand interaction in XR. For example, industry leaders, such as META Quest [24] and Apple VisionPro [8], widely adopt this gesture for selection tasks while wearing their XR headsets. We imagine a use scenario in which a user who wears a smart ring on the index finger makes a pinch gesture for XR interaction, and the ring presents a vibrotactile stimulus for confirmation feedback. Here, the natural touch sensation generated by the physical contact between the thumb and index fingertip is augmented by an additional vibration stimulating the proximal phalange of the index finger; so, it can be regarded as one scenario for haptic augmented reality [25], [26]. It should be noted that the real contact and vibration stimulation points are quite close spatially but do not exactly coincide. We postulated that this configuration would still provide naturalistic experiences to users for XR interaction.

We designed 36 vibration patterns of three frequencies (50, 150, and 250 Hz), two amplitudes (weak and strong), two envelope shapes (rectangular and linearly decaying), and three durations (70, 120, and 250 ms) to provide at pinch selection. Then, we investigated the perceptual effects of those vibration stimuli and one more without vibrotactile feedback (37 feedback in total) by performing two experiments. Experiment 1 estimated the perceptual space of the 37 pinch selection sensations, thereby visualizing the perceptual structure of the vibrotactile stimuli. In Experiment 2, participants rated the augmented pinch sensations with seven pairs of bipolar adjectives. These results were projected into the perceptual space obtained in Experiment 1 to find meaningful perceptual dimensions. To our knowledge, this study is among the first to explore the perceptual structure and dimensions of vibrotactile feedback for pinch selection using a smart ring.

The remainder of this paper is structured as follows. We first review related work in Section II. It is followed by Section III, which describes the general methods used in both Experiments 1 and 2. Sections IV and V present the specific methods, results, and discussions for each experiment. Then, Section VI summarizes the main findings to provide design guidelines, which can facilitate actual application development. Finally, we conclude the paper in Section VII.

II. Related Work

A. Haptic Ring

Several haptic devices in ring-type wearables have been proposed in recent years. For example, Sun et al. introduced the ATH-Ring, which combined tactile and temperature sensing with vibro-thermal feedback to enhance immersive interactions in virtual environments [10], [11]. Lin et al. developed a theoretic design scheme for a compact wearable ring, optimizing the mass-spring-damper system within the ring structure to maximize vibration generation performance [12]. Talhan et al. designed a finger-worn actuator that produced static pressure, high-frequency vibration, and impact [15]. Nunez et al. presented a wireless haptic ring, HapRing, designed for spatial interaction [16]. Lastly, a haptic ring capable of delivering touch/pressure and shearing force to the user's fingerpad was proposed [14].

In addition to the device design, several studies explored interaction methods for haptic rings. For example, Han et al. proposed passive kinesthetic force feedback as a novel output method for rotational input on smart rings [13]. Aoki et al. introduced a new symmetrical haptic interaction system, enabling bidirectional force exchange between the user and virtual creatures in mixed reality [18]. Friesen et al. suggested haptic texture rendering via frequency and amplitude modulation using a wearable vibrotactile ring [27]. Normand et al. compared visuo-haptic rendering techniques on the four spatially distinct stimulation sites, including the proximal phalanx of the fingers [28].

Despite these progresses, the literature lacks in-depth research on the perceptual characteristics of haptic feedback provided by smart rings when users interact with virtual elements using hand-finger gestures.

B. Perceptual Space

Perceptual space is an n-dimensional mathematical representation that visualizes perceptual relationships between stimuli based on dissimilarity judgments [29]. It is a powerful tool in perception research, allowing the discovery of underlying perceptual structures. Furthermore, perceptual spaces can be interpreted more precisely by assigning dimensions with qualitative meanings. It can be achieved through adjective rating, where the perceptual quality of stimuli is evaluated based on adjective pairs consisting of opposing extremes. The resultant dimensions are then mapped onto the perceptual space. When used together, perceptual space and adjective rating serve as an effective methodology for investigating human perceptual responses.

Many studies estimated perceptual spaces to study the perception of various haptic stimuli, including vibration [30]–[33], texture [34], [35], material [36], and motion effects [37]. In particular, perceptual spaces for the cases where haptic feedback was presented on fingertips were studied for vibration-augmented buttons [26], active interaction with a touchscreen [38], and haptic icons [39]. This paper reports a perceptual space for vibrotactile-augmented pinch selection, along with their extrinsic perceptual properties.

Fig. 2. Ring-shaped haptic device used in our studies. (a) Side view. (b) Worn on the index finger (also demonstrating the pinch gesture).

III. General Methods

This section describes general methods commonly used in Experiment 1 and 2. All experiments reported in this paper were approved by the Institutional Review Board of the Pohang University of Science and Technology (POSTECH; No. PIRB-2024-E005).

A. Device

We implemented a ring-shaped haptic device to generate and deliver vibrotactile stimuli to the palmar side of the proximal phalanx of the index finger, as shown in Figure 2. A linear resonant actuator (LRA; Jahwa Electronics, 122792; f_0 = 125 Hz) produced vibrotactile stimuli. The actuator had a size of 12×27×9.2 mm, which is relatively large but acceptable; commercial smart rings range in width from 7 mm to 9 mm [19], [20], [23], [40]–[43]. This LRA was selected for its wider frequency bandwidth, covering low frequencies, than other smaller LRAs. The device did not interfere with pinch interactions or convey unintended vibrations to other hand parts through direct contact with the actuator.

B. Vibration Profiles

We designed 36 vibration waveforms to augment pinch selection sensations by modulating four parameters, frequency, envelope shape, duration, and amplitude, of the following equation:

$$x(t) = AE(t)\sin(2\pi Ft), \tag{1}$$

where $x(t)$ is a vibration signal at time t, A is the amplitude, $E(t)$ is the envelope function, and F is the frequency. All vibration stimuli used in our work are depicted in Figure 3.

The envelope $E(t)$ was designed by combining two shapes and three durations. An envelope shape mimicked a typical tapping profile with a finger. In slow tapping, the contact force gradually increases, maintains a constant level, and then decreases. In comparison, during rapid tapping, the force initially spikes and then rapidly decreases. These distinct sensory experiences were simplified into two rectangular and linearly decaying envelopes for pinch selection. Then, we selected three durations, 70, 120, and 250 ms, for each envelope shape. These durations were based on the average tapping time of 133 ms (SD 83 ms), which was measured during touchscreen interactions using the index finger [44]. Combining the two shapes and three durations resulted in six envelopes.

As for frequency, we selected three values, 50, 150, and 250 Hz, to evoke different sensations. Low-frequency vibrations are mediated by the RA (rapidly adapting) 1 channel and produce fluttering sensations [45]. In contrast, high-frequency vibrations are processed by the PC (Pacinian) channel, resulting in smooth vibrational sensations [45].

We also used two levels of amplitude (weak and strong). Since the perceived intensity of vibration is influenced by its frequency, the amplitude was adjusted to be consistent across the three frequencies through a perceptual experiment. Using a reference vibration at 150 Hz, five participants adjusted the vibration amplitudes at other frequencies until they matched the perceived intensity of the reference. This procedure using the method of adjustment [46] was repeated for both amplitude levels. As a result, the peak-to-peak amplitudes used were 0.69 and 0.86 G for the 50 Hz stimuli, 0.23 and 0.40 G for 150 Hz, and 0.72 and 1.28 G for 250 Hz.

C. Pinch and Selection

Pinch is a gesture that quickly moves the thumb and index finger (or other middle or ring finger) to touch each other; see Figure 2b. Pinch detection is a widely used technique for selecting or activating interactive elements in XR environments, such as buttons, windows, hyperlinks, and 3D objects. The pinch gesture can be executed using eye-gaze or motion recognition. In the eye-gaze method, the user fixates their gaze on the target object and performs the pinch gesture for selection. Alternatively, the motion recognition method asks the user to move a virtual cursor through hand motion. The system tracks the user's hand movement and makes the cursor follow it. Once the cursor reaches the desired object, the user performs the pinch gesture to finalize the selection. In our experiment, we used the motion recognition method.

As shown in Figure 4, participants of both experiments sat in a chair and wore a head-mounted display (HMD; Meta Quest 2). They put the ring-shaped haptic device on their dominant hand's index finger while holding a controller on their non-dominant hand. Prior to the experiment, they were instructed on how to interact with the experiment program using pinch selection. They controlled a virtual cursor, represented by a round marker at the endpoint of a ray, by moving their dominant hand. To perform pinch selection, participants were required to make physical contact between the thumb and index finger, and they evaluated the sensations only when this actual contact occurred. Participants were instructed to perform the pinch gesture naturally, as they would when selecting a button in a typical interaction, without strict control over the speed of the pinch action. The hand motion and pinch gesture were tracked and detected using the HMD cameras. Participants also wore noise-canceling headphones that played white noise to eliminate auditory cues. The experiment environment was programmed using Unity.

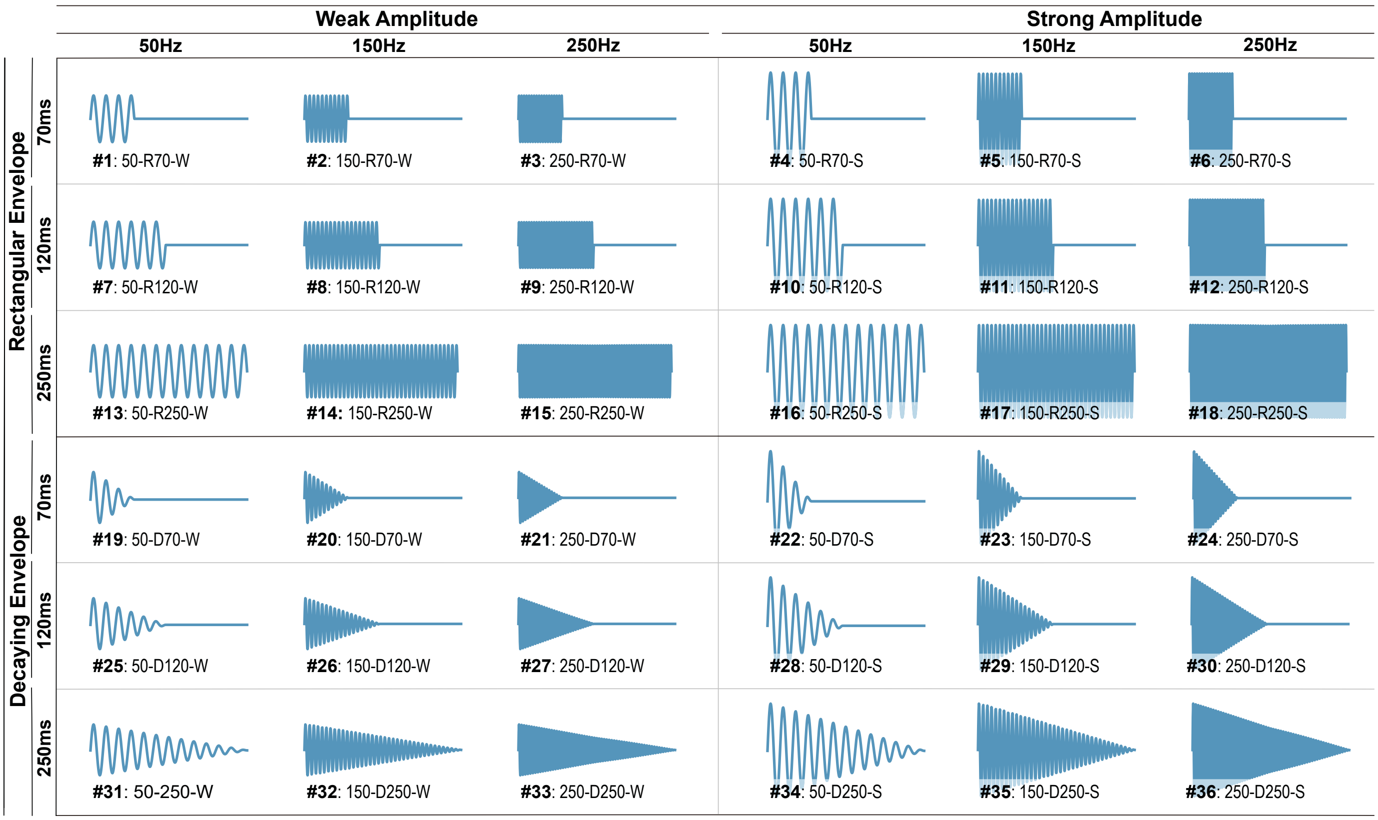

Fig. 3. Thirty-six vibration stimuli used to augment pinch feedback. They combine three frequencies, two envelopes, three durations, and two amplitudes. Notation: (Frequency)-(Envelope Shape)(Duration)-(Amplitude). Examples: 50-R70-W and 250-D250-S.

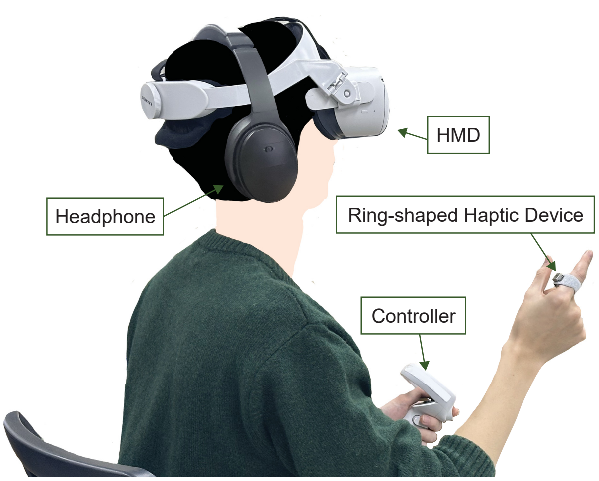

Fig. 4. Experiment setup.

IV. Experiment 1: Perceptual Space

This study aimed to estimate a perceptual space that visualizes the dissimilarity relationships among the 36 pinch feedback sensations defined in Section III-B and the original pinch sensation (no feedback). Participants evaluated the perceived similarity between the pinching sensations using a cluster sorting method [47]. This similarity data was converted to perceptual distances and then analyzed using multidimensional scaling (MDS) to construct perceptual spaces.

A. Methods

1) Participants: Twenty participants (10 males and 10 females; mean age 26.4 years) participated in this experiment. No participants reported known sensorimotor abnormalities. Only one participant was left-handed, while the others were right-handed, all by self-report. They received approximately 21 USD as compensation.

2) Experimental Conditions: An experimental condition was defined by the vibration profile used to augment the pinching feedback. All 36 profiles in Figure 3 were used, and another condition without haptic feedback was included as a baseline, composing 37 experimental conditions.

3) Procedure: A method that allows a participant to judge the dissimilarity between all pairs of stimuli directly is preferred to obtain the perceptual distance data required for MDS. The results of such methods can be regarded as ratio-scale data. However, this method is adequate only when the number of stimuli is relatively small, e.g., around ten [32], [33]. In our experiment, its large number of stimuli (37) makes direct pairwise dissimilarity assessment impractical. Thus, we chose to use an indirect alternative, the cluster sorting technique [47], which enables collecting similarity data in a reasonable amount of time.

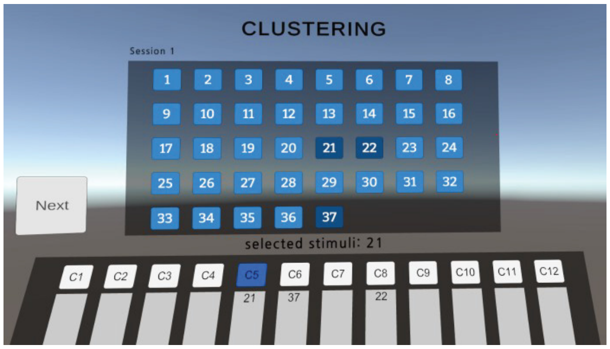

Fig. 5. Graphical user interface of the program used for Experiment 1.

Figure 5 shows the program interface used for the experiment. The program shows 37 buttons, and selecting each using the pinch gesture described in Sec. III-C presents the vibration feedback assigned to it. Participants' task was to perceive the 37 augmented pinch sensations by selecting the buttons and then group similar stimuli into the same cluster. They could experience all button feedback as many times as they wanted and were required to include at least one button in each cluster.

The experiment consisted of four sessions with different numbers of clusters (3, 6, 9, and 12, respectively). The order of the four sessions was balanced across participants using Latin squares. For practice, participants experienced all the buttons by pinching them in a random order before starting the main session. The vibration profiles were randomly assigned to the buttons in each session to prevent participants from relying on memory. The experiment took 50 minutes on average. At the end of the experiment, participants were interviewed about the criteria they used for clustering.

4) Data Analysis: The data obtained from the cluster sorting task were converted to dissimilarity scores between each pair of the augmented stimuli following the procedure in [47] and [26]. For each participant, the initial similarity score $s_{i,j}$ between the augmented stimuli i and j was set to zero. In the case where the stimuli i and j were assigned to the same group in a session with N clusters, the similarity score $s_{i,j}$ was increased by N. This procedure was repeated for every pair of the 37 stimuli.

Then, a normalized dissimilarity matrix $\{d_{i,j} \mid 1 \leq i, j \leq 37\}$ was generated through a linear transformation applied to the calculated similarity scores, such that

$$d_{i,j} = 1000 \left(1 - \frac{s_{i,j}}{3+6+9+12} \right), \quad (2)$$

where each pairwise dissimilarity score $d_{i,j}$ is normalized between 0 and 1000. Then, average scores were calculated from the individual scores.

Finally, non-metric classical MDS was applied to the average dissimilarity matrix to find perceptual spaces with appropriate dimensions. The goodness of fit was evaluated using Kruskal's Stress [48]. The stress S varies between 0 and 1, where a S value closer to 0 indicates a better fit.

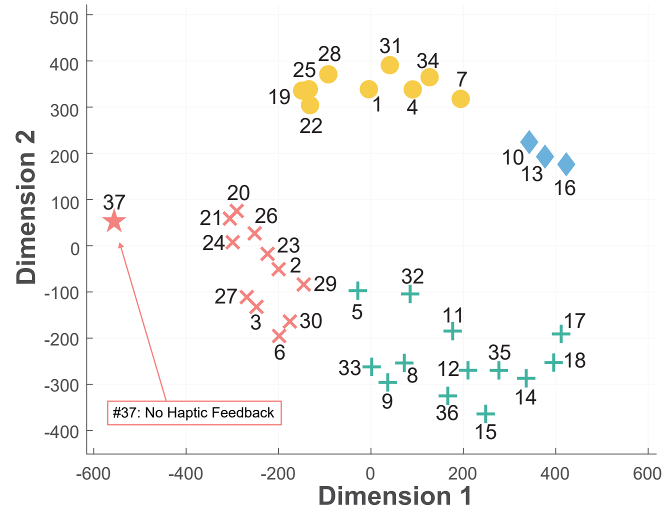

Fig. 6. 2D perceptual space for the 36 augmented pinches and one original sensation (#37, represented by a star symbol). Consistent colors and symbols denote groups identified through hierarchical clustering (#37 belongs to the red cross group).

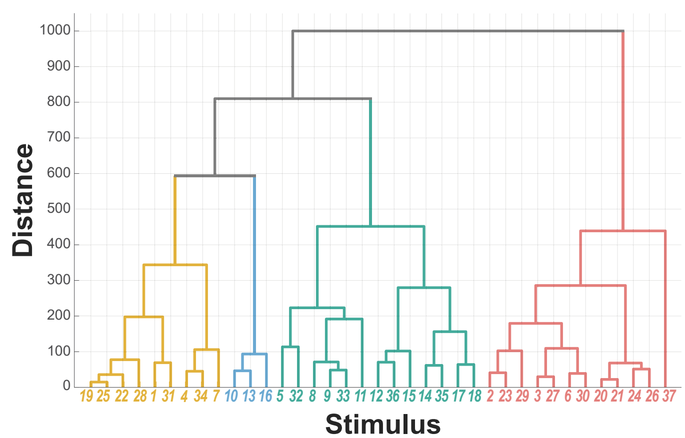

Fig. 7. Dendrogram of hierarchical clustering. Line colors are consistent with the four clusters in Figure 6.

B. Results

To determine the optimal dimension that preserves the perceptual distance data, we examined the stress S values of MDS while increasing the space dimension. The S values were 0.381, 0.111, and 0.088 as the dimensionality increased from 1 to 3. S values greater than 0.2 indicate poor fitting [48], and the dimension of two had sufficiently small S value. Moreover, the elbow point, where the improvement in S sharply drops, was observed at two dimensions. Thus, we decided to use a 2D perceptual space.

Figure 6 shows a 2D perceptual space that visualizes the pairwise perceptual dissimilarity relationships between the 37 pinch sensations. In the perceptual space, each point represents the position of a pinch sensation. It can be seen that the distribution of points forms an oval shape. Point #37, corresponding to the original pinch sensation without augmented

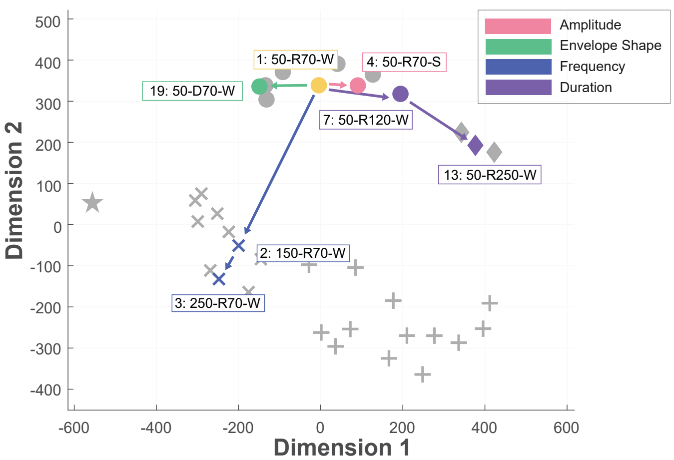

Fig. 8. Illustration of how augmented pinch sensation #1 (50-R70-W) changes in the perceptual space when its frequency, envelope shape, duration, and amplitude vary. Pinch sensation #1 was chosen as it presents a clear and intuitive case, and its trends of change applied across all points without exceptions. The factor effects are color-coded.

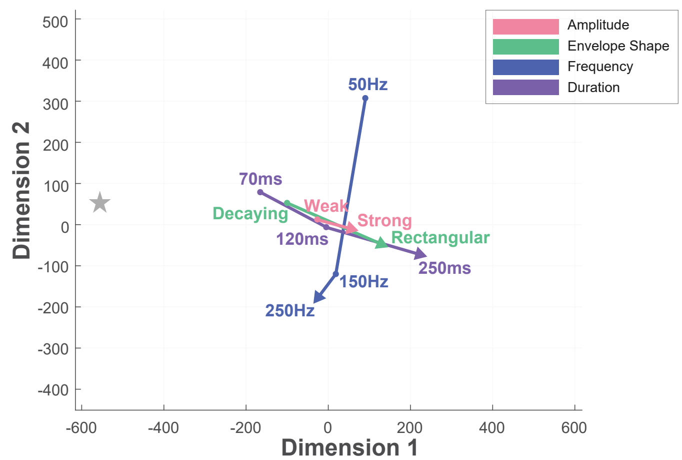

Fig. 9. Centroids of the augmented pinch sensation points that have the same levels for each design variable.

feedback, is largely separated from the oval point distribution. The spatially dispersed point distribution indicates that the sensations experienced during pinch interactions can be effectively diversified through vibrotactile feedback with different frequencies, envelope shapes, duration, and amplitude. We also applied hierarchical clustering with the farthest neighbor metric to the data. It resulted in four groups of points, as the dendrogram shows in Figure 7 and is represented using different colors and symbols in Figure 6.

C. Discussion

1) Grouping Results: The *blue* group in Figure 6 comprises three augmented sensations (#10, #13, and #16), all of which have the low frequency (50 Hz) and the rectangular envelope. As specified in Figure 3, #10 and #16 exhibit strong amplitudes with the medium (120 ms) and long (250 ms) durations, while the other #13 has the weak amplitude and the long duration. Thus, the three low-frequency stimuli are strong and/or long, and either effect increases the perceived intensity of a vibrotactile stimulus (the latter by the temporal summation of tactile perception [49]). Furthermore, this group is positioned farthest from the baseline condition (#37), suggesting that low-frequency feedback with strong perceived intensity generates a distinctly different sensation from the original pinch sensation.

The *yellow* group includes nine augmented stimuli (#1, #4, #7, #19, #22, #25, #28, #31, and #34). They all have the low frequency (50 Hz) but seem to be less intense in perceived intensity than those of the *blue* group when their amplitude, envelope shape, and duration are considered for energy integration. Hence, the low-frequency stimuli (50 Hz) (the blue and yellow groups) seemed to elicit distinctive sensations from the higher frequency stimuli (150 and 250 Hz), regardless of their amplitude, envelope shape, and duration.

The *red* group contains 11 augmented stimuli (#2, #3, #6, #20, #21, #23, #24, #26, #27, #29, and #30) and the original pinching stimulus (#37). All of them are of middle or high frequency (150 or 250 Hz). Most of them use the decaying envelope of the short (70 ms) or medium (120 ms) duration or the rectangular envelope of the short duration, except for stimulus #5 (70–150R-S). #5 is grouped into the *green* cluster but also close to the *red* group. Hence, the weak and short stimuli with the mid- or high-frequency tend to induce a small perceptual difference from the original pinch sensation.

Finally, the *green* group comprises the other 13 stimuli (#5, #8, #9, #11, #12, #14, #15, #17, #18, #32, #33, #35, and #36). This group shares the characteristics of the mid- and high-frequency vibrations with the *red* group, but it differs in having the medium (120 ms) and long (250 ms) durations. It indicates that longer vibrations significantly alter the sensation of pinch feedback, making them perceptually distinguishing.

2) Factor Effects: Figure 8 shows an example that demonstrates how an augmented pitch sensation moves in the perceptual space when its design variables (frequency, envelope shape, duration, and amplitude) change. Figure 9 summarizes the effects of the four design variables on the augmented pinch sensation by visualizing the centroids that have the same levels for each variable. Using these two plots, we discuss the four design variables' effects on the dissimilarity of augmented pinch sensations in what follows.

First, vibration frequency was dominant in changing the augmented pinch sensation. The augmented sensations were divided into two groups in Figure 6: *blue* and *yellow* (low-frequency vibrations) and *red* and *green* (mid- and high-frequency vibrations). Moreover, changing the frequency from 50 Hz to 250 Hz moved the centroid by the greatest distance (515.7) in Figure 9. This prominent effect of frequency arises owing to the inclusion of 50-Hz vibrations, which were described as noticeable patterns of fluctuations ("bumpy") by some participants in the post-experiment interviews. Some participants perceived the other 150- and 250-Hz conditions as "consistent." Note that the frequency effect was salient even though the vibration durations were designed as short

(70–250 ms) for confirmation feedback. Recall that we used a relatively large LRA to include 50-Hz vibrations in our experiments (Figure 2a). Most other smaller actuators cannot generate such low-frequency vibrations. Our results about the strong effects of frequency necessitate very small but wide-band actuators for wearable devices.

Second, vibration duration also had crucial effects on the augmented pinch sensation. The centroids moved by a large distance (436.1) in Figure 9 as the duration increased from 70 ms to 250 ms. Increasing vibration duration moved the sensation away from the original pinch sensation in the perceptual space (Figure 8 and 9). These results reconfirm that humans excel in distinguishing vibration duration [31], [50].

Third, vibration signals with the rectangular envelope elicited larger sensation changes from the original pinch sensation than those with the decaying envelope. This result is reasonable considering that the rectangular envelope transmits greater energy than the decaying envelope if their durations are identical, which increases the perceived intensity [51], [52]. Envelope shape had less prominent effects than frequency and duration, but they were sufficiently discernible; the distance between the two centroids was 267.0 in Figure 9. During the interview, several participants mentioned two distinct types of feedback termination sensation: clear ending and lingering ending. We surmise that the rectangular envelope provided a clear sense of termination, while the decaying envelope presented a lingering sensation due to its gradual fade.

Last, increasing the vibration amplitude from weak to strong moved the centroid by the smallest distance (102.7) in the perceptual space (Figure 9), farther from the original pinch sensation. It is acknowledged that we used relatively low vibration amplitudes in this work to make them appropriate for the use scenario of selection tasks in XR.

In summary, varying the level of a design variable induced the largest amount of change in the augmented pinch sensation in the order of frequency, duration, envelope shape, and amplitude. Regarding the direction of sensation change, duration, envelope shape, and amplitude showed a similar tendency for a higher energy stimulus by shifting the sensation farther from the original pinch sensation. However, the effect of frequency was unique in that the perceptual distances of the three frequency centroids from the original sensation were relatively similar, forming an almost orthogonal direction of sensation changes to the change directions of the other variables (Figure 9).

V. Experiment 2: Adjective Rating

The perceptual space obtained in Experiment 1 elucidates the perceptual relationships among the augmented pinch sensations in terms of their perceptual dissimilarities. For effective designs, we need more information about the perceptual properties that each vibration feedback elicits and how they change within the perceptual space. To this end, we performed another experiment in which participants evaluated each augmented pitch sensation by rating it for seven adjective pairs, each consisting of two extremes. The results were then mapped onto the perceptual space constructed in Experiment 1 to identify useful perceptual dimensions[1].

TABLE I
Adjective pairs.

#	Adjective 1	Adjective 2
1	Shallow	Deep
2	Crisp	Dull
3	Soft	Hard
4	Smooth	Rough
5	Negative	Positive
6	Trivial	Consequential
7	Cheap	Luxurious

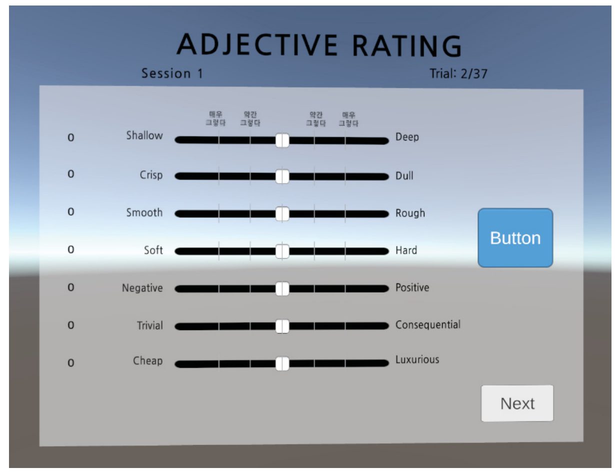

Fig. 10. Graphical user interface of the program used for Experiment 2.

A. Methods

1) Participants: Twenty participants (10 females and 10 males; mean age 26.2 years) took part in this experiment. No participants reported known sensorimotor abnormalities. All participants were right-handed by self-report. They received approximately 21 USD as compensation.

2) Experimental Conditions: The experimental conditions were identical to those used in Experiment 1.

3) Procedure: Table I shows seven bipolar adjective pairs used in this experiment. The first four pairs, *shallow-deep*, *crisp-dull*, *soft-hard*, and *smooth-rough*, were selected from the literature on button click rendering and haptic texture perception [26], [53]–[56]. Two other adjective pairs, *negative-positive* and *trivial-consequential*, were included as they capture important characteristics of confirmation feedback. *negative-positive* reflects whether a task has been successfully completed or has failed, while *trivial-consequential* conveys the perceived significance of the feedback. The last adjective pair, *cheap-luxurious*, was for more of a commercial value.

Participants' task was to rate how each augmented pinch sensation felt in terms of the adjective pairs. In each trial, participants could perceive an augmented sensation by activating a "Button" button on a GUI (Figure 10) using the pinch gesture

[1] A perceptual dimension is a fundamental attribute or axis along which humans can perceive, differentiate, or categorize sensory stimuli.

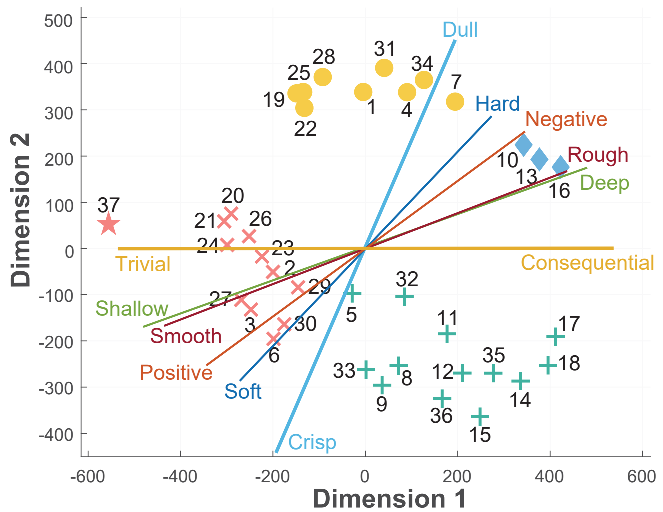

Fig. 11. Adjective pairs regressed into the 2D perceptual space. The length of each axis is proportional to the R^2 value of the regression, representing the degree of fit.

as many times as they wanted. To rate the sensation against each adjective pair, they moved the corresponding slider to the left or right using the VR controller held in their non-dominant hands. Moving a slider toward a particular adjective indicated that the feedback was perceived as closer to the sensation described by that adjective. All sliders were centered (i.e., zero) at the beginning of each trial. If the slider was at the far left, the score was -50; at the far right, the score was 50. The score was displayed on the left of the slider for the convenience and accuracy of the rating. Additionally, the sliders were designed to be sufficiently large to ensure precise adjustments, even with the non-dominant hands.

The experiment began with one practice session with four trials and was followed by two main sessions, each consisting of 37 trials. During the practice session, participants rated the seven bipolar adjective pairs for four randomly selected feedback stimuli for familiarization. In each main session, participants performed the adjective rating task for the 37 pinch feedback stimuli. The order of the stimuli was randomized per participant. The experiment lasted 70 minutes on average. Participants rested between the sessions and whenever they requested. At the end of the experiment, participants were interviewed about the rating criteria they used.

4) Data Analysis: The bipolar scores for each adjective pair, ranging from -50 to 50, were averaged across participants for each feedback condition. The relationship between the adjective pairs and the augmented pinch sensations was investigated using multiple linear regression analysis. The independent variables were the sensation coordinates derived from the perceptual space, and the dependent variables were the average scores for each adjective pair. The analysis represents each adjective pair by a line in the perceptual space, passing through the origin and oriented according to the standardized regression coefficients [29]. These lines define perceptual axes,

TABLE II
INTERSECTING ANGLES IN DEGREES BETWEEN ADJECTIVAL AXES.

	1	2	3	4	5	6	7
1 (Shallow-Deep)	—	46.8	1.0	26.4	16.3	20.0	35.3
2 (Crisp-Dull)	—	—	45.8	20.4	30.5	**66.8**	82.1
3 (Smooth-Rough)	—	—	—	25.4	15.4	21.0	36.3
4 (Soft-Hard)	—	—	—	—	10.2	46.4	61.7
5 (Negative-Positive)	—	—	—	—	—	36.2	51.5
6 (Trivial-Consequential)	—	—	—	—	—	—	15.3
7 (Cheap-Luxurious)	—	—	—	—	—	—	—

* Bold indicates the largest valid angle.

which capture variations in the sensations associated with the respective adjective pairs. The position of each augmented sensation in the perceptual space can be projected onto these axes to quantify the extent to which the sensation aligns with the attributes described by the adjective pairs.

B. Results

The results of adjective ratings are shown in Figure 11. Given the 2D nature of the perceptual space, identifying two principal perceptual dimensions is sufficient to represent all pinch selection sensations using coordinates.

The suitability of an adjective pair as a principal axis was judged using the R^2 score computed from multiple linear regression. The R^2 values were 0.837, 0.802, 0.766, 0.648, 0.701, 0.88, and 0.013 for *shallow-deep*, *crisp-dull*, *smooth-rough*, *soft-hard*, *negative-positive*, *trivial-consequential*, and *cheap-luxurious*, respectively. While most R^2 scores were adequate, R^2 for *cheap-luxurious* was exceptionally low, indicating a lack of correlation. Hence, *cheap-luxurious* is not appropriate for a principal axis.

Next, we examined whether the adjective dimensions were orthogonal to each other. The intersecting angles between all adjective pairs are presented in Table II. The pair closest to orthogonality was *crisp-dull* and *cheap-luxurious*, with an intersecting angle of 82.1°. However, this pair was excluded due to the lowest R^2 score of *cheap-luxurious*. Other than that, the most orthogonal pair was *crisp-dull* and *trivial-consequential*, with an intersecting angle of 66.8°.

Consequently, *crisp-dull* and *trivial-consequential* were selected as the two dimensions best representing all of the augmented and original pinch sensations. These dimensions demonstrated high R^2 values, with 0.837 for *crisp-dull* and 0.88 for *trivial-consequential*. The stimuli were effectively clustered into the four regions formed by crossing the *crisp-dull* and *trivial-consequential* axes. Additionally, they are important and intuitive factors for designing interactive elements.

C. Discussion

1) Principal Perceptual Dimensions: In the experimental results, the adjective pair *trivial-consequential* ($R^2 = 0.88$) was identified as the most adequate axis for designing vibration stimuli to augment the pinch gesture. In Figure 11, the stimuli groups with strong perceived intensity, *blue* and *green*, were close to *consequential*, while those with weak perceived intensity, *red* and *yellow*, were located in the region of *trivial*. It suggests that the dimension *trivial-consequential* is significantly correlated with the three variables of envelope shape, duration, and amplitude. These are the variables affecting perceived intensity; the combination of envelope shape, duration, and amplitude determines the total energy of the stimulus, thereby changing its perceived intensity.

The other primary perceptual dimension, *crisp-dull*, had an R^2 value of 0.802 and distinguished the stimuli by frequency. Figure 11 indicates that low-frequency stimuli, represented by the *blue* and *yellow* groups, elicited *dull* sensations, while high-frequency stimuli, represented by the *red* and *green* groups, induced *crisp* sensations.

These two perceptual dimensions allow us to summarize the perceptual properties of the four stimulus groups as: the *green* group—(*consequential, crisp*), the *red* group—(*trivial, crisp*), the *blue* group—(*consequential, dull*), and the *yellow* group—(*trivial, dull*). These classifications are consistent with the distribution of the centroids by all conditions: frequency, amplitude, envelope shape, and duration, as in Figure 9.

2) Alternative Single Perceptual Dimension: As shown in Table II, *negative-positive* has the intersecting angle ranging from 10.2° to 36.2° with all other adjective axes. Thus, this dimension can be the most adequate axis when one dimension is chosen to explain all other properties of the stimuli. In Figure 11, the properties *shallow*, *crisp*, *smooth*, *soft*, and *trivial* shared the same region with *positive* in the perceptual space, indicating their association. The stimuli evoking *deep*, *dull*, *rough*, *hard*, and *consequential* properties were located closely together with *negative*, which represents their correlations.

3) Eliciting Target Properties: We discuss how to design augmented pinch sensations that have the target characteristics of each adjective pair. For easier explanation, Figure 12 shows the six adjective axes (excluding *cheap-luxurious*) and the coordinates of eight stimuli projected to the six axes, taken from the perceptual space in Figure 11. The eight stimuli were chosen from two subgroups of each of the four groups: #10 and #16 (*blue*), #28 and #34 (*yellow*), #3 and #21 (*red*), and #8 and #35 (*green*). These points were the closest to the centroids of the eight subgroups. The original sensation #37 was also included in Figure 12 as the baseline.

For the *crisp-dull* dimension, the original pinch stimulus #37 is gathered with the *green* and *red* groups, which are slightly shifted toward *crisp* in Figure 12. It indicates that stimuli with mid- (150 Hz) and high-frequency (250 Hz) vibrations produce mildly crisp sensations. In contrast, stimuli with a low frequency (50 Hz) convey significantly dull feelings. This trend aligns with the frequency variations shown in Figure 9, reinforcing the critical role of frequency in shaping the *crisp-dull* property. However, variations in amplitude, envelope shape, and duration had no noticeable effects.

For the *trivial-consequential* property, baseline #37 was perceived as very *trivial*. This property closely corresponds to variations in envelope shape, duration, and amplitude, as shown in Figure 9. Increasing the stimulus total intensity shifts the perception of a pinch toward *consequential*. However, vibration frequency had a weak influence on this property.

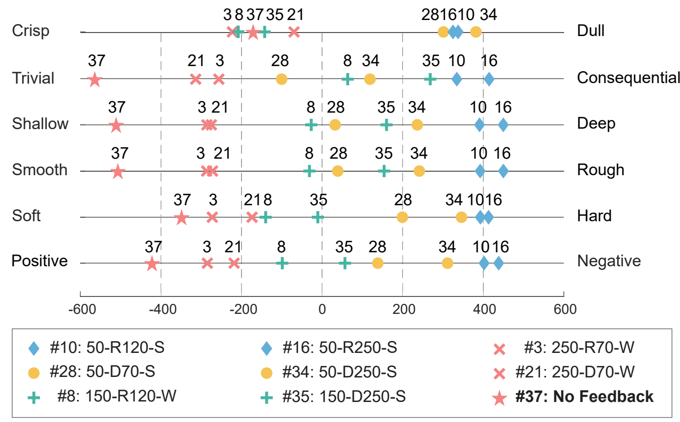

Fig. 12. Positions of the original pinch and eight augmented sensations projected onto perceptual dimensions.

The *shallow-deep* and *smooth-rough* properties share nearly the same axes in Figure 11. Thus, the coordinate mapping results in Figure 12 are also very similar. The original pinch sensation is very *shallow* and *smooth*. As with the *trivial-consequential* property, the baseline feedback #37 maintains a distinct distance from the other stimuli, indicating that the perception of a pinch is significantly altered when a vibration is applied. While frequency and envelope shape had minimal impact, duration and amplitude were the dominant factors in modulating these sensations.

For the other properties, *soft-hard* and *negative-positive*, the original sensation #37 feels the softest and the most positive, respectively. Introducing lower-frequency stimuli shifted the perception toward *hard* and *negative*. These properties were influenced more by frequency than by the other parameters.

4) Difficulties Evoking Cheap-Luxurious Sensation: The *cheap-luxurious* axis is commonly used in feedback design. However, we found additional vibrations to pinch interaction could not reliably affect the perception of *cheap-luxurious*. Post-experiment interviews revealed that the *cheap-luxurious* perception was highly subjective. A general tendency was that the sensation was rated as *luxurious* if participants found it appealing or non-annoying, whereas the less preferred feedback was perceived as *cheap*.

VI. General Discussion

A. Design Guidelines

This study addressed augmenting the perception of a pinch gesture, which is widely used for selection during interaction in an XR environment, using simple vibration feedback generated from a smart ring. In this use scenario, a soft touch sensation, naturally produced by the physical contact between two fingers, is added with a programmable vibration stimulus, and the user receives the combined stimuli, which may elicit a considerably altered percept. Two experiments, one to construct a perceptual space and the other to determine the primary perceptual dimensions, were conducted, and their methods and results were presented in the previous sections.

Based on these results, we can summarize design guidelines for the augmented pinch feedback, as follows:

1) The original pinch sensation can be effectively expanded by varying the frequency, envelope shape, duration, and amplitude of a sinusoidal vibration added to it.
2) The distribution of augmented pinch sensations is represented well by a 2D perceptual space.
3) The sensation augmentation effectiveness of the four design variables is ordered as frequency $>$ duration $>$ envelope shape $>$ amplitude.
4) Varying vibration frequency in a large range (50–250 Hz) is highly effective for diversifying the augmented pinch sensation even for short vibrations.
5) Vibration duration is an important factor for the augmented sensation's identity even when it is short from 70 ms to 250 ms.
6) Envelope shape, duration, and amplitude jointly function as an intensity factor and influence the perceptual characteristics of augmented pinch sensations.
7) Two perceptual dimensions, *crisp-dull* and *trivial-consequential*, comprehensively represent vibration-augmented sensations in the 2D perceptual space.
8) To evoke a dull sensation of pinching, decrease the frequency; conversely, increase the frequency to elicit the crispness of selection sensation.
9) To evoke the sense of consequence during the user's selection, increase the intensity of the vibration. As the intensity weakens, the sensation becomes trivial.
10) To evoke hard, negative, rough, and deep sensations, decrease the frequency or increase the intensity.
11) Conversely, increase the frequency or decrease the intensity for soft, positive, smooth, and shallow sensations.

B. Applications

The findings presented in this paper substantiate the feasibility of vibration-augmented pinch feedback to provide assorted sensations to users. This advantage can be leveraged for many purposes. For example, different XR applications may benefit from tailored selection feedback sensations. If the application is for productivity, as Apple Vision Pro aims, pinch feedback that feels *consequential* and *dull* can be appropriate for selection. When users play an XR game, they may prefer *positive* and *crisp* augmented pinch sensations.

We can also diversify pinch feedback sensations to make them more informative by associating different meanings to the sensations. For example, suppose a virtual button selected by a pinch gesture represents a valid action command given the application's state. In this case, a *positive* augmented sensation can be provided as feedback to notify the user that the command is valid and the application will execute the designated action. Contrarily, if the command is invalid, a *negative* augmented sensation should be more appropriate, which can deliver a natural error message to the user.

The design guidelines presented in Section VI-A are likely to facilitate application developers to design the actual vibration stimuli suitable for the use scenarios above.

VII. Conclusions

This study was concerned with diversifying the touch sensation of a user's pinch gesture used for interaction in XR by adding a vibration stimulus generated from a smart ring. We evaluated the pairwise similarity between the original pinch and 36 augmented sensations with different vibration frequencies, amplitudes, envelope shapes, and durations in Experiment 1. This data was processed by MDS to estimate a perceptual space that accounts for the sensations of augmented pinch stimuli in an Euclidean metric space. In Experiment 2, we analyzed the subjective perceptions of augmented sensations to obtain explicit verbal descriptions of the space. The data was best explained in a 2D space using the *trivial-consequential* and *dull-crisp* axes. Based on these results, we provide useful guidelines for designers aiming to evoke specific tactile sensations when implementing vibrotactile feedback in smart rings, which are among the first to our knowledge.

Our study also has a few limitations. We primarily explored basic variations of vibrotactile feedback. More complex stimulus patterns can convey richer semantic meanings and elicit a broader range of perceptual effects. Additionally, the perceived sensation of a pinch can be influenced by other factors, such as pinch force, velocity, and the duration for which the index finger and thumb remain in contact. However, this study applied the same vibration feedback regardless of how participants executed the pinch gesture. For future work, we plan to incorporate sensors that dynamically adapt the feedback to the user's pinch movement, enabling a more responsive and personalized experience. We anticipate that this approach will enhance the consistency of perceived feedback properties, further refining the perceptual space of vibrotactile interactions in smart rings.

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