Comparing the Perceived Intensity of Vibrotactile Cues Scaled Based on Inherent Dynamic Range

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***Abstract*— Wearable devices increasingly incorporate vibrotactile feedback notifications to users, which are limited by the frequency-dependent response characteristics of the low-cost actuators that they employ. To increase the range and type of information that can be conveyed to users via vibration feedback, it is crucial to understand user perception of vibration cue intensity across the narrow range of frequencies that these actuators operate. In this paper, we quantify user perception of vibration cues conveyed via a linear resonant actuator embedded in a bracelet interface using two psychophysical experiments. We also experimentally determine the frequency response characteristics of the wearable device. We then compare user perceived intensity of vibration cues delivered by the bracelet when the cues undergo frequency-specific amplitude modulation based on user perception compared to modulation based on the experimental or manufacturer-reported characterization of the actuator dynamic response. For applications in which designers rely on user perception of cue amplitudes across frequencies to be equivalent, it is recommended that a perceptual calibration experiment be conducted to determine appropriate modulation factors. For applications in which only relative perceived amplitudes are important, basing amplitude modulation factors on manufacturer data or experimentally determined dynamic response characteristics of the wearable device should be sufficient.**

I. INTRODUCTION

Vibrotactile feedback is widely used in wearable devices to convey relevant and timely information to users [1], [2], [3], [4]. Vibration cues are often provided via commercially available vibration actuators such as linear resonant actuators (LRAs) and eccentric rotating mass (ERMs) motors embedded in wearable systems like bracelets or sleeves [5], [6], due to the low cost of components and ease of integration. These actuators rely on their inherent dynamics to generate salient haptic cues [7]. The frequency response characteristics of the actuator influence the generated cues, where the amplitude of the output scales with the input signal's driving frequency [8]. Because these devices tend to have a narrow band of frequencies over which they operate, most vibrotactile feedback devices are used primarily for binary feedback (on/off) to notify users of the existence of a stimulus [9], [10]. Understanding user perception of vibration cue amplitudes across driving frequencies is essential for applications needing a wide range of salient vibrotactile cues (beyond binary).

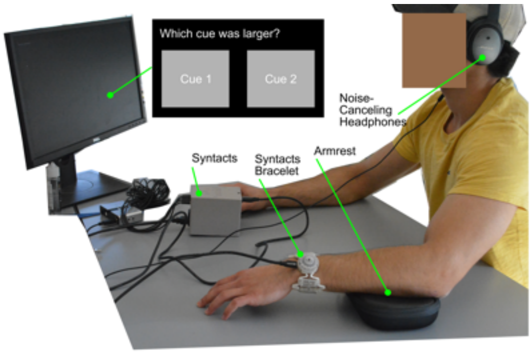

Fig. 1. We evaluated the perception of vibration cue intensity via psychophysical experiments. Subjects wore a Syntacts Bracelet on their non-dominant hand and received vibrotactile cues through the bracelet. They completed just noticeable difference and point of subjective equality intensity experiments, entering responses via a GUI.

Given the inherent frequency-dependence of vibration cue amplitudes generated by resonance-based actuators, cue designers must scale the amplitude of the driving signals of two cues with different frequencies to generate cues that are perceived to be of equal intensity. For example, an actuator driven at its resonant frequency will generate a vibration cue that is larger in amplitude than if driven above or below the resonant frequency with the same amplitude input. Cue designers can modulate the amplitude of the driving signal to generate cues that are, in theory, equivalent in output amplitude. This is similar to a phenomenon in the auditory domain, where loudness is associated with the magnitude of the auditory sensation. The perception of loudness has a primary dependence on the amplitude of the sound wave with an additional dependence on the frequency of the signal [11], [12]. Manufacturer-provided data about the frequency response of these vibration actuators can be used to modulate the amplitude of the driving signals to generate vibration cues of equal amplitudes regardless of input signal frequency; however, user perception of vibration cues transmitted by actuators embedded in wearables may be influenced by other factors such as the dynamic response of the mechanical housing of the actuator.

Most prior work has focused on the perception of vibration applied at the fingertips. For example, Pongrac evaluated the primary coding for vibrations and determined that frequency and amplitude had the greatest effect on perception [13]. In

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that work, the Just Noticeable Difference (JND) for vibration frequencies was reported for the fingertips, but JNDs of vibration cue amplitude were not reported. In another study, researchers determined the effect of vibration direction and device weight on the perceived intensity of vibrations in mobile devices held in the hand [14]. As wearable haptic feedback devices become more prominent, researchers are starting to provide results that quantify the perception of vibration cues applied at the wrist. Recent work by Consigny et al., for example, reported the amplitude thresholds for vibrations at standard frequencies and observed a maximum sensitivity at around 160 Hz, confirming prior findings for vibration perception at the wrist [15].

In this paper, we evaluate user perception of vibration cues conveyed via a bracelet interface using two psychophysical experiments (Fig. 1). First, we determine the minimum difference that is required to discriminate between vibration cue intensities (the just noticeable difference, or JND). Then, we determine the point at which two stimuli of different frequencies are perceived to have the same intensity, called the Point of Subjective Equality of Intensity (PSEI) [13], [16], [17], with a focus on how much users modulated the amplitude so that the signals felt equally intense. This modulation factor is compared to two other modulation factors: one based on the manufacturer-provided specifications and the other based on the experimentally determined frequency response of the actuator embedded in the bracelet interface. We test our hypothesis that modulation factors measured from our frequency response experiment will be a main predictor of those determined by our psychophysical experiments, in addition to those determined by the manufacturer-provided specifications. Our results provide insight into ways that designers can modulate the amplitude of driving signals for vibration cues to ensure that the intensity of the cue is consistent across frequencies.

II. METHODS

We conducted two psychophysical experiments to characterize human perception of vibrotactile cues displayed at the wrist via a bracelet interface, a just noticeable difference (JND) experiment to quantify the difference threshold for perceived vibration intensities for vibration cues at different frequencies, and a Point of Subjective Equality of Intensity (PSEI) experiment to determine the user-selected amplitude modulation factors that resulted in two vibration cues of different frequencies being perceived to have the same intensity. Additionally, we experimentally determined the frequency response of our vibration actuator inside the bracelet housing. These experiments are illustrated in Fig. 2, with representative (not experimental) data to explain the methods used in our protocol.

A. Participants

Eleven participants took part in this study (3 female, 8 male; ages 18 to 27, average 23.4; 9 right-handed). All participants provided their informed consent, and the protocol was approved by the Rice University Institutional Review Board (IRB-FY2022-7).

B. Equipment

We used a Syntacts bracelet, an external soundcard, and a Syntacts Amplifier [5] to generate the vibration cues at the wrist. The Syntacts bracelet contains four LRAs (Vybronics Model Number VG1040003D) distributed around the entire band. Only one of the four LRAs (located on the volar side of the wrist) was actuated during the experiments to lessen the cognitive influence of cue localization and reduce the ability for the vibrations to propagate through the bones of the wrist [18]. We designed vibration cues using the open-source platform Syntacts libraries [5]. To drive the LRAs, Syntacts outputs a signal via an external sound card (Startech.com ICUSBAUDIO7D) to generate the vibration cues felt by the user, which had a maximum output voltage of 5V. The amplitude defined by the Syntacts software defines the portion of the total output possible from the sound card that is driven by the signal. These signals are then amplified using the Syntacts amplifier (version 3.1).

To determine the mechanical output of the Syntacts bracelet, an experimental test rig that mimics a human wrist (wrist rig) was used (see Fig. 3). The 3D-printed wrist rig acted as the rigid skeletal structure of the wrist, and Ecoflex silicone molding (Ecoflex 00-30 Smooth-on) served as the tissue and skin [19]. Forces generated by the vibrotactor were measured with an ATI Nano25 load cell integrated in the wrist rig.

C. Psychophysical Experiment Design and Protocol

Two psychophysical experiments were conducted, JND and PSEI. For both, we used a two-alternative forced-choice (2AFC) test with two haptic stimuli. Thus, the participant always received two haptic cues (a reference and a comparison cue) and had to select which one was the largest. For both experiments, the order of cues was randomized.

At the beginning of the experiment, the subject placed the Syntacts Bracelet on the wrist of their non-dominant hand. The device was placed similarly to a watch and participants were told to tighten the device so that it would not shift on the wrist and so that the bottom tactor was in the center of the inner wrist (Fig. 1). Subjects wore Bose QuietComfort 25 Acoustic Noise Cancelling Headphones and listened to pink-noise during the experiment to mask any auditory cues generated by the actuators. Participants interacted with a GUI during the experiment, with instructions displayed on the screen and audibly explained by the experimenter.

The JND experiment used the method of constant stimuli and was conducted within a single block of trials [20]. The subject received the reference cue and a comparison cue with a pseudo-randomized amplitude with a one-second pause in between. Each cue was 500 milliseconds in duration, based on similar studies [21], [22], [23], [13], with the carrier frequency equivalent to the manufacturer-specified resonant frequency (170 Hz). We used the resonant frequency to ensure the tactor produced the greatest output possible –

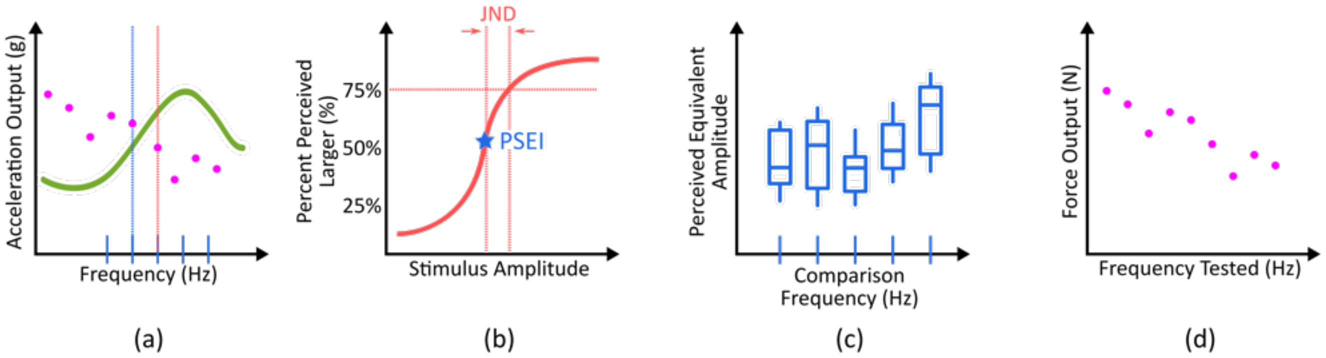

Fig. 2. Three experiments were conducted to characterize human perception of vibration cues and to measure the frequency response of the vibration actuator in the bracelet housing. This figure illustrates the approach taken, and the data presented in this figure are representative, not indicative of actual results.

(a) All aspects of the experimental investigation are illustrated. The manufacturer-reported frequency response of the commercial vibration actuator is represented in green. The dotted lines represent the reference frequencies of the vibration cues used in the JND (red) and PSEI (blue) experiments. The blue ticks on the x-axis represent the vibration cue frequencies tested in the PSEI experiment. The pink dots represent the measured values of output from the frequency response characterization experiment. (b) Each subject's psychometric curve is determined from the method of constant stimuli, and the JND for vibration intensity is defined. (c) The PSEI for each comparison cue is determined by the staircase method. (d) The experimental frequency response measuring force output is reported for the wearable device.

maximizing saliency for participants to distinguish between amplitudes. Subjects completed fifteen comparisons with nine amplitude levels distributed from 1.0 to 5.0 V in equal increments. The reference cue remained constant at 2.5 V.

After completing the JND experiment, subjects immediately began the PSEI experiment. The PSEI experiment used a reference frequency of 160 Hz with five comparison frequencies: one at 170 Hz (the reported resonant frequency of the actuator), two above 170 Hz, and two below 170 Hz. The frequencies below and above the resonant frequency were chosen to have the same predicted output magnitude based on manufacturer-provided data (160 and 185 Hz at 1.5 gravitational acceleration (g) and 150 and 210 Hz at 1.0 g). The maximum (5V) and minimum values (0V) of the amplitude were defined as boundaries to prevent saturation of the output signal commanded to the vibrotactors. The PSEI experiment consisted of fifteen individual blocks (three repetitions of five comparison frequencies). In each trial within a block, the participant received the reference cue and a comparison cue. The reference cue remained the same for every block (160 Hz, 2.5 V). Within a block, the comparison frequency remained constant and had one of five frequencies (150, 160, 170, 185, or 210 Hz). The amplitude of the comparison cue began at 0.50 V and was incremented by 0.25 V according to the staircase method [24]. Participants experienced each comparison frequency block three times in a randomized order. The number of trials within a block varied depending on the length of time it took for the subject to reach four reversals during the staircase method.

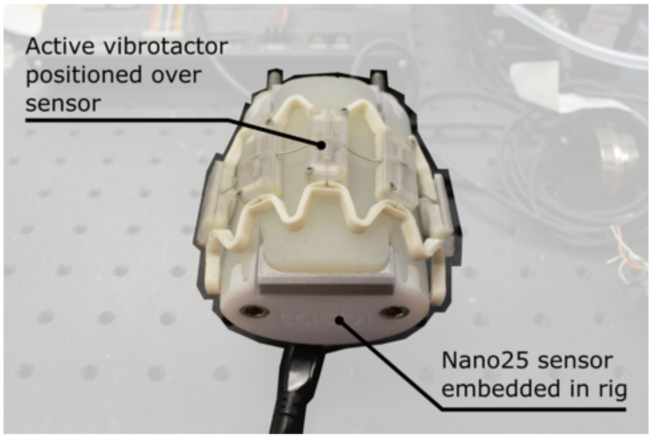

Fig. 3. Experimental testing rig for evaluating the response of vibrotactors to a ±5V amplitude sine wave.

Participants were asked to take a longer rest, of at least 30 seconds, every third or fourth block to reduce fatigue and to ensure no loss of sensitivity to the vibrotactile cues. If the subject was not able to discriminate amplitude between two signals and subsequently tried to drive the comparison signal to a higher amplitude than the maximum defined, the code automatically switched the direction of the staircase without adding to the recorded number of switches. For example, if the comparison frequency had an amplitude of 1.00 and the subject said the reference frequency was higher, the comparison frequency would be decreased to 0.95 instead of increased to 1.05.

D. *Experimental Characterization of Frequency Response*

Because the dynamic response of an actuator may vary from the manufacturer's published specifications due to manufacturing variability or how the actuator is mounted in a housing, we experimentally characterized our actuator. We mounted the Syntacts Bracelet on the experimental wrist rig with a 2N preload to allow the band to exhibit the tension experienced when tightened on a user's wrist. We provided a sinusoidally varying input signal to drive the LRAs and measured the resultant forces generated by the vibrotactors with the integrated force sensor. Like the psychophysical experiments, the frequency response characterization was performed using only the bottom tactor of the Syntacts Bracelet, which was oriented at the top of the wrist rig as shown in Fig. 3. The input signals were 5V peak-to-peak sinusoids ranging from 130 to 230 Hz at 5 Hz increments. The output force amplitude of the LRA was measured by a 6-axis force-torque sensor (ATI Nano25) for a duration of 10 seconds. The force outputs were taken as the peak-to-peak amplitude for the signals and are referred to as measured values for the remainder of the paper. The load cell was zeroed between the recordings at each tested frequency.

E. Data Collection and Analysis

A psychometric curve was fit to each subject's JND experiment data to determine their individual JND. The psychometric curve was determined using the generalized linear model within MATLAB with a binomial distribution and was measured as the absolute value of the difference between the PSEI and the comparison amplitude, in which PSEI is defined as the amplitude that corresponds to a response proportion of 50%. Our rejection criteria for the psychometric curve was data that did not extend beyond 90% [25]. For comparison purposes, the average of the JNDs from the accepted trials was used to determine error ranges for those rejected JNDs.

The PSEI was determined from the average of the last three reversals in the staircase data from Blocks 2 through 16, which were used as the final staircase value. The data for a block were rejected if the subject reached a boundary frequency four times. Across the same subject, the staircase values were averaged for all accepted blocks.

Data analysis for the validation of mechanical characterization used the last 5s of data from each 10s trial to ensure the data reflected the steady-state behavior of the system. The theoretical perceived equivalent amplitude was determined for each frequency by multiplying the mechanical output, force output for the measured values, and acceleration output for the manufacturer values, of 160 Hz by 0.5 and dividing that number by the mechanical output of the tested frequency. Multiplying the value of the output at 160 Hz by 0.5 is reflective of the reference cue for the PSEI experiments, which is half of the maximum output voltage of 5 V. The average staircase values were compared to the manufacturer and measured values using the theoretical perceived equivalent amplitude. This assumes a linear, one-to-one relation between the mechanical output and the subjective intensity.

III. RESULTS

A. Just Noticeable Difference

The psychometric curves used to determine JNDs for each subject are presented in Fig. 4. The JNDs for four of the eleven subjects were rejected because their psychometric curves did not extend beyond 90% [25]. The remaining subjects had JNDs between 0.05 and 0.35V, with an average JND of 0.20 V. The average JND was used to allow comparison across subjects in the comparison of amplitude modulation factors selected based on experimental characterization of the actuator versus those derived from the PSEI experiment.

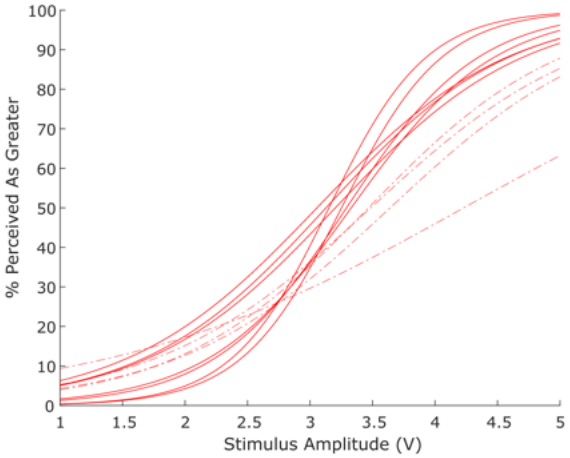

Fig. 4. Psychometric curves for each subject at each stimulus level for the JND study. Four participants had results that were excluded from analysis based on specified criteria, and are shown as dotted lines.

B. Point of Subjective Equality of Intensity

The average values of the amplitude modulation factors selected by participants in the PSEI experiments are reported as box-and-whisker plots in blue (Fig. 5). The average amplitude of the driving signal frequencies of 150, 160, 170, 185, and 210 Hz that were found to be equivalent to the reference signal were 2.66, 2.17, 1.98, 2.22, and 3.01 V, respectively, with standard deviations of 0.35, 0.21, 0.24, 0.52, and 0.61 V. Three of the eleven staircase trials were rejected based on the criteria outlined in Sec. II-E. Each rejection occurred for the comparison of 210 Hz with a maximum of 1 rejection per subject.

C. Experimental Characterization of Actuator Frequency Response

The frequency response of the actuator embedded in the Syntacts bracelet was determined by measuring the force output for a range of driving frequencies. These results are presented in Fig. 6, along with the extrapolated manufacturer data for the frequency response of the actuator. The driving signal frequencies for the psychophysical studies (150, 160, 170, 185, and 210 Hz) had measured force values of 1.16, 1.06, 1.10, 1.18, and 0.90 N, respectively.

D. Amplitude Modulation Factors Based on Manufacturer and Measured Data

Because the vibration actuator has a frequency-dependent response amplitude, for signals at different frequencies to generate equivalent output amplitudes, the driving signal should be amplitude-modulated. The amplitude modulation factor can be computed from the manufacturer specifications for the frequency response of the actuator. Alternatively,

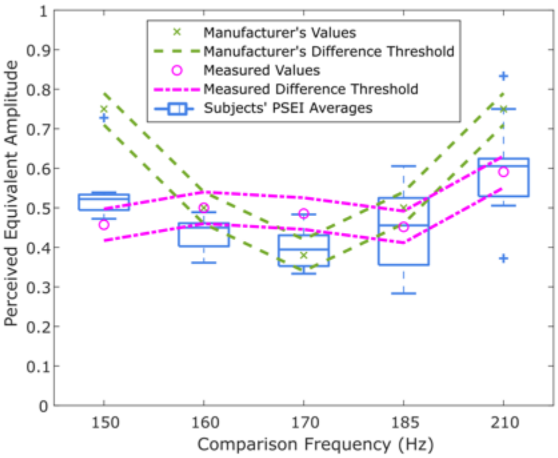

Fig. 5. Results from the PSEI experiment. Box and whisker plots show the average amplitude modulation factors across subjects for each frequency that were perceived to be equivalent to the 160 Hz reference cue with an amplitude scaling factor of 0.5 (resulting in a 2.5V driving signal). One subject's response for the 170 Hz test cue was an outlier (+). These values are compared to the amplitude modulation factors that result from inspection of the manufacturer data sheet (green x) or from experimental characterization of the vibration actuators (pink o). The green and pink dashed lines are based on the JND experimental results and define the boundary within which subjects, on average, cannot discriminate a difference in vibration intensity.

the amplitude modulation factor can be computed based on the experimentally determined frequency response of the actuator embedded in the Syntacts bracelet. In Table I, we report the amplitude scaling factors necessary to produce an output signal from the actuator that is equivalent in amplitude to the reference signal of amplitude 2.5V and 160 Hz using both the manufacturer-provided data and the experimentally determined frequency response.

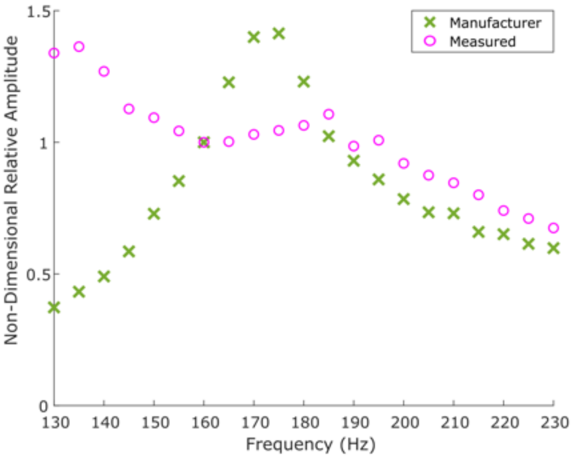

Fig. 6. Frequency response characteristics of the vibrotactile actuator. The manufacturer values were defined by manufacturer specifications and originally given in peak-to-peak acceleration (g). The measured values were defined by the experimentally determined force output (N). The mechanical output for the manufacturer and measured values are presented here, scaled by the output at 160 Hz (1.5 g and 1.06 N, respectively).

TABLE I

AMPLITUDE MODULATION FACTORS TO GENERATE EQUIVALENT OUTPUT AMPLITUDES FOR A 160 HZ 2.5V DRIVING SIGNAL BASED ON MANUFACTURER REPORTED VALUES AND EXPERIMENTALLY MEASURED VALUES. THE LISTED VALUES ARE THE SCALING FACTORS FOR A 5V DRIVING SIGNAL, SUCH THAT 0.5 WOULD INDICATE A 2.5V AMPLITUDE SIGNAL

Comparison Frequency (Hz)	Manufacturer Values	Measured Values
150	0.75	0.46
160	0.50	0.50
170	0.38	0.49
185	0.50	0.45
210	0.75	0.59

E. Comparison of Subject-Specified Amplitude Modulation Factors to Manufacturer and Measured Values

In the PSEI experiment, participants were asked to manually adjust the amplitude of driving signals of varying amplitudes to match the perceived intensity of a reference signal of 160 Hz and 2.5V felt via vibrotactors in the Syntacts bracelet. These modulation factors were applied to a 5V signal, such that a modulation factor of 0.5 results in a driving signal amplitude equivalent to the reference signal (2.5V). Figure 5 presents the amplitude modulation factors computed from manufacturer-reported data (green data points) and from experimentally determined frequency response characteristics (pink data points).

In our hypothesis, we stated that the measured modulation factors would be a main predictor of results from the psychophysical experiments in addition to being predicted by the manufacturer-provided specifications. To test this, we first compared two models – one simple and one complex. The simple model predicted human subject data with only manufacturer-provided values while the complex also included experimentally measured values as a factor. The comparison confirmed that including a term for measured values (the complex model) produced a significantly better prediction (F(1) = 5.99, p = 0.015).

Next, we ran an ANOVA on the complex regression model. Both factors were found to be significant: manufacturer values ($F(1) = 46.92, p < 0.001$) and measured values ($F(1) = 30.33, p < 0.001$). Thus, by including experimentally measured values we can better predict human response, compared to using manufacturer data alone – however, both are key predictors. This confirms our hypothesis, as both measured and manufacturer values are useful in understanding human response.

We also analyzed the correlation between the amplitude modulation factors determined from manufacturer-reported data and those derived from the experimentally determined actuator response. The overall root mean square error in modulation factor in relation to all subjects' PSEI across frequencies was 0.7376 for manufacturer values and 0.4981 for measured values. The root mean square error between the manufacturer values and the measured values was found to be 0.7890. The root mean square error for each frequency

TABLE II

RMS ERROR BETWEEN AMPLITUDE MODULATION FACTORS DETERMINED FROM MANUFACTURER AND MEASURED DATA VERSUS THOSE DETERMINED FROM PARTICIPANTS' PSEI

Comparison Frequency (Hz)	Manufacturer Values (V)	Measured Values (V)
150	1.1398	0.4983
160	0.3853	0.3853
170	0.2443	0.5061
185	0.5688	0.4990
210	0.9430	0.5821

TABLE III

AVERAGE DIFFERENCE BETWEEN SUBJECT PSEI AND MANUFACTURER AND MEASURED VALUES, SCALED BY INDIVIDUAL JND

Comparison Frequency (Hz)	Manufacturer Values	Measured Values
150	-6.85	2.17
160	-1.84	-1.84
170	0.12	-3.13
185	-2.46	-0.97
210	-4.93	0.04

and value comparison can be found in Table II.

Figure 7 displays the difference between the average amplitude modulation factor determined via PSEI for each participant and those determined by the manufacturer and measured values, scaled by their individual JND. The four participants with rejected JNDs were scaled by the average of the accepted JNDs. The average scaled error values are shown in Table III.

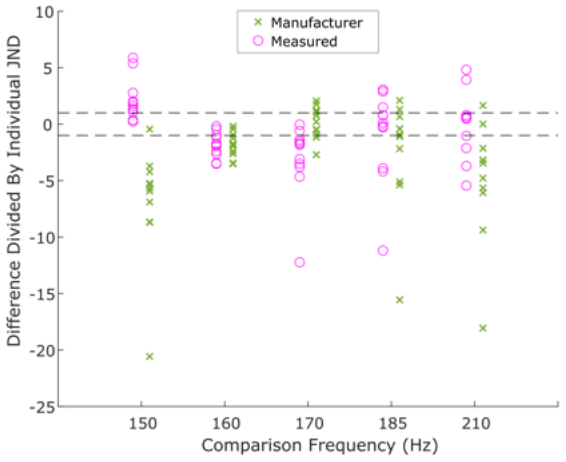

Fig. 7. The difference between the subject averages and the manufacturer and measured data is shown here, scaled by the individual JNDs of each subject. Data within the black dotted lines indicate differences that were within a JND for the subject, meaning there is no perceivable difference between the subject's psychometric-derived subjective equality and mechanical output-derived subjective equality. Positive errors indicate the subject perceived a higher amplitude as being equivalent to the reference than the theoretical value indicated, with the negative errors having the inverse relationship.

IV. DISCUSSION

Wearable devices increasingly integrate vibration actuators that convey haptic cues to a user. Often, these actuators have frequency-dependent amplitude responses, and cue designers must consider the dynamic response of the actuator when designing their vibration cues. In this paper, we evaluated human perception of vibration cues conveyed via a Syntacts bracelet with an embedded linear resonant actuator (LRA), quantifying the JND of intensity discrimination, and evaluating the Point of Subjective Equality of Intensity (PSEI). We asked participants to compare the perceived intensity of two vibration cues. We then compared amplitude modulation factors selected by participants to those predicted by the manufacturer-reported characteristics of the actuators and to those predicted by the experimental characterization of the actuator embedded in the Syntacts bracelet.

A. Just Noticeable Difference

The JND experiment was used to establish users' perceptual performance when discriminating vibration intensity at the wrist. We computed an average JND of vibration intensity for cues delivered at the reported resonant frequency of the actuator of 0.2 V, measured as the amplitude of the input driving signal. Four of the subjects' JNDs were rejected based on specified criteria, so we used the average of the retained JNDs as a substitute for their values when analyzing the difference between the expected values and their PSEI. This is reflective of researchers who use accepted JND values from the literature to determine thresholds in experimental protocols without psychophysical trials. It may have been more indicative of these participants' true perceivable difference if the highest of the accepted JNDs was used for this comparison.

B. Point of Subjective Equality of Intensity

We determined each participant's PSEI measured as the amplitude modulation factor over a range of comparison frequencies in relation to a reference cue of 160 Hz at 2.5 V. Users had more consistent responses at certain frequencies (150, 160, and 170 Hz), whereas for other frequencies there was greater variability in responses across subjects (185 and 210 Hz). When some subjects were presented with a vibration cue at 210 Hz, they were not able to modulate the amplitude in a way that generated a perceived intensity less than that of the reference cue. This contradicted our expectations of user responses if modulation factors were determined based on manufacturer or measured actuator response data. This finding would suggest that frequency is another characteristic that influences the perceived intensity of vibration cues, and may also suggest that for lower frequency signals, the amplitude modulation factors based on measured actuator responses are more likely to be indicative of the perceived subjective intensities. There may be a frequency component to subjective intensity, similar to what is seen in music [11]. As there are other unexplored characteristics that could affect perceived intensity, it is recommended that for applications where it is critical that users perceive cues of different frequencies to have equivalent intensity, researchers should conduct PSEI experiments before implementing vibration-based haptic cues to determine a user-specific equivalent amplitude.

C. Experimental Determination of Actuator Frequency Response

We compared the perceived intensities of vibrations modulated based on experimental data versus those modulated based on manufacturer specifications (see Fig. 5). For our experimental characterization of the actuator dynamic response, the maximum amplitude was observed at 130 Hz, while the peak amplitude reported by the manufacturer occurred at 170 Hz. A potential cause for this discrepancy is that the travel of vibration through the Syntacts actuator mounting case alters the resonant properties of the vibrotactors. We recommend that researchers perform a characterization of the vibrotactors within the device being used, especially for wearable devices that require housing the vibrotactor before attachment to the body.

D. Comparison of Modulation Factors

The amplitude modulation factors determined from measuring the dynamic response of the actuator in the Syntacts bracelet were significant in predicting the PSEI of participants. This finding indicates that the relative intensities can be determined directly by measuring the device output in addition to using the manufactured values (also a significant predictor). To better quantify the difference in terms of perception, the subjects' average JND was used to define a boundary for the PSEI. Most errors for individuals landed outside of the range of a single JND (the dotted and dashed lines in Fig. 7, indicating that defining the relationship between amplitudes of cues from difference frequencies based on the mechanical output may lead to noticeably different perceived subjective intensities. If the exact PSEI is critical to the task, it would be best to conduct a calibration study to ensure the given cues are within the JND for each user. As this study was performed using one vibrotactor, future research may want to address the possibility that the location of the vibration cue affects the subjective intensity of participants (since many wearable devices employ an array of vibrotactors). As both manufacturers and measured data are predictive of values determined by psychophysical results, utilizing this could save the designer time as they can modulate cues without extensive user testing.

V. CONCLUSION

Vibrotactile feedback is an increasingly common feature of wearables, and vibration cues are often provided via commercially available vibration actuators that have a frequency-dependent amplitude response (e.g., LRAs). Because vibrotactile feedback devices tend to have a narrow band of frequencies over which they operate, such devices are used primarily for notifications. They could have wider-ranging applications if user perception of vibration cues of varying amplitudes across a range of driving frequencies could be accurately characterized, which would make it easier for designers to estimate human response. In this paper, we quantified user perception of vibration cues conveyed via a bracelet interface using two psychophysical experiments (JND and PSEI). We also experimentally determined the frequency response characteristics of a vibration actuator embedded in a bracelet interface. From these results, we considered how amplitude modulation factors based on user perception were significantly predicted by a combination of both experimentally and manufacturer-provided specifications. This paper is the first contribution towards this type of characterization, specifically using LRAs. In future work, the methodology within this paper could be applied to other vibrotactile actuators.

Our results demonstrate the importance of characterizing the dynamic range of actuators embedded in casings rather than relying solely on manufacturer-reported data. When comparing amplitude modulation factors determined from psychophysical experiments to those derived from manufacturer-reported data, there were discrepancies. Including modulation factors derived from experimentally determined frequency response characteristics increased the prediction of results from the PSEI experiments when added to a statistical model that already accounted for manufacturer data. For applications in which designers rely on user perception of cue amplitudes across frequencies to be equivalent, it is recommended that a calibration PSEI experiment be conducted to determine appropriate modulation factors that can then be used in conjunction with manufacturer-provided values. For applications in which only relative perceived amplitudes are important, it is sufficient to base amplitude modulation factors on manufacturer data or experimentally determined dynamic response characteristics of the wearable device.

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