7-2024

Effects of Wall and Freespace Damping Levels on Virtual Wall Stiffness Classification

Emma Treadway
Trinity University

Kristian Journet

Andrew Deering

Cora Lewis

Noelle Poqiz

Effects of Wall and Freespace Damping Levels on Virtual Wall Stiffness Classification

Emma Treadway, *Member, IEEE*, Kristian Journet, Andrew Deering, *Member, IEEE*, Cora Lewis, *Student Member, IEEE*, and Noelle Poquiz

***Abstract*—Virtual damping is often employed to improve stability in virtual environments, but it has previously been found to bias perception of stiffness, with its effects differing when it is introduced locally within a wall/object or globally in both the wall and in freespace. Since many potential applications of haptic rendering involve not only comparisons between two environments, but also the ability to recognize rendered environments as belonging to different categories, it is important to understand the perceptual impacts of freespace and wall damping on stiffness classification ability. This study explores the effects of varying levels of freespace and wall damping on users' ability to classify virtual walls by their stiffness. Results indicate that freespace damping improves wall classification if the walls are damped, but will impair classification of undamped walls. These findings suggest that, in situations where users are expected to recognize and classify various stiffnesses, freespace damping can be a factor in narrowing or widening gaps in extended rate-hardness between softer and stiffer walls.**

***Index Terms*—Perception and psychophysics, haptic rendering, stiffness perception, human haptics.**

I. Introduction

CONTACT transitions are a common feature of human interaction with the world, occurring when we come into contact with objects. In haptic rendering where a virtual environment is employed to represent the physical world, contact transitions are characterized by a discontinuity where the user passes from a freespace environment to a wall or object environment. While freespace ideally allows unrestricted movement, virtual walls and objects are designed to prevent ingress [1]. A common method of rendering walls or objects is therefore to model them as unilateral virtual springs, designed to push the user back outside the wall harder the farther into the wall they have penetrated. In many applications, objects or barriers of varying stiffness may be required; for example it is desirable for users of medical or dental simulations to be able to distinguish between the different tissues, organs, bones, or teeth with which a tool might come into contact.

Much attention has understandably been given to the stability of virtual environments, with prior work exploring a variety of controllers, hardware architectures, and limiting factors such as the maximum possible stiffness that can be rendered while maintaining coupled stability—for example, see [1]–[5]. However, if the aim of haptic rendering is to represent realistic differences in material properties, then stability alone is not sufficient. More realistically, the virtual environment being rendered needs to be sufficiently transparent to represent the desired properties to the user [6], and the differences between the various environments one wishes the user to distinguish need to be perceptually relevant.

Previously, stiffness perception has been related to a number of different cues, including terminal force and position [7], [8], mechanical work [7], [9], rate-hardness [6], [10], extended rate-hardness [11], and rate of change of force [12]. The effects of the controller used to render a virtual stiffness have also been studied [6], [10], [11]. Much of the prior work on stiffness perception has quantified (either as a just-noticeable-difference or with the bias induced) participants' ability to distinguish two surfaces as determined by certain conditions [13], [14]. This work has revealed influences on perception of stiffness that can be caused by the presence of damping and vice-versa, in both situations with and without contact transitions [14]–[16]. Of particular relevance to the perception of virtual walls with contact transitions is the work of van Beek et al. [15], which determined that adding damping to a virtual environment (VE) globally (both inside and outside of a virtual object) had different effects on stiffness perception as compared to adding it only inside the object, and linked these changes to several parameters that are potentially relevant to stiffness perception: maximum indentation, adjusted rate-hardness the ratio of maximum force to maximum indentation, and work.

While perceptual thresholds necessarily play some role, they do not completely predict a user's ability to recognize surfaces with different properties; rather, the ability to recognize a rendered virtual surface as corresponding to, for example, healthy vs. diseased tissue, relies on the ability to *classify* environments [17]. Classification involves not only the limits of peripheral sensing thresholds, but also memory and the "noisy communication channel" through which sensory information is processed [17] (p. 276). If users are intended to be able to learn from or use simulations relying on the ability to recognize different object or wall properties, then an understanding of how classification performance is impacted by hardware and modeling decisions is required.

The known influence of local and global damping on stiffness bias [15] implies that damping in freespace could also influence stiffness classification; we explored this at a preliminary level in [18], though results were inconclusive based on the conditions used. In this study, we test two hypotheses related to a VE which features a contact transition between freespace and a virtual wall (modeled as a damped spring). We hypothesize that (1) *altering the damping in*

The authors were with the Department of Engineering Science, Trinity University, San Antonio, TX 78212. Email: etreadwa@trinity.edu

Manuscript received August 2, 2023; revised February XX, 2024.

freespace affects the ability to classify virtual walls by their stiffness, and (2) *these effects will differ based upon the damping level present inside the virtual wall.* In Section II, we review background on the effective levels of stiffness, mass, and damping present in a virtual environment. Section III describes the two new experiments in this study: first, we present a stiffness classification experiment in which four levels of damping are rendered in freespace, spanning the range between local damping (high damping rendered inside the wall only) and global damping (high damping both inside and outside the wall). Second, to determine whether wall damping alters the effects that freespace damping has on the ability to classify walls by stiffness, we performed a second stiffness classification experiment: the same four freespace VEs were paired with virtual walls featuring the same stiffnesses but *low* damping. Classification results are presented in Section IV, along with an examination of participants' exploration strategies, followed by discussion of the findings and conclusions in Sections V–VI.

II. Background

For a relatively stiff single-degree-of-freedom haptic device with lumped mass parameter M_h and damping B_h, the device can be modeled as the impedance

$$Z_h = M_h s + B_h. \tag{1}$$

A common method for rendering VEs is to employ a relatively light device under impedance control to produce force F_u felt by the user. In this scheme, the VE is represented as an impedance $Z_{VE}(s)$, which converts device motion $\dot{x}$ into the desired force required to render the desired environment [19], [20]. While impedance control is commonly used open-loop, better performance can be achieved by closing a loop on the desired force experienced by the user, particularly for rendering freespace (by compensating for the hardware on which the VE is rendered). The closed-loop driving point impedance $\mathcal{Z}(s)$ with controller C(s) is given by

$$\mathcal{Z}(s) = \frac{F_u}{\dot{x}} = Z_{VE}(s) + \frac{Z_h}{1 + C(s)}. \tag{2}$$

See [21] for details, including a block diagram schematic.

The dynamic response $\mathcal{Z}(s)$ of a VE can also be expressed as a combination of effective impedance primitives; for any passive driving point impedance response (phase between -90 and 90 degrees), the primitives will be limited to effective stiffness (ES), damping (ED), and mass (EM) [22]. These primitives have previously been used to describe perceptual changes in damping due to delay and filtering [22] and proposed for use in designing conditions in haptic environments with contact transitions [21].

In these experiments, we employ VEs with stiffness K_{VE} and/or damping B_{VE} of the form

$$Z_{VE}(s) = K_{VE}/s + B_{VE} \tag{3}$$

along with a proportional controller, $C(s) = C_p$, acting on force error. Freespace environments feature $K_{VE} = 0$, resulting in effective impedances across all frequencies within the device bandwidth of

$$\begin{aligned} ES_{free} &= 0, \\ ED_{free} &= B_{VE} + B_h/(1 + C_p), \\ EM_{free} &= M_h/(1 + C_p). \end{aligned} \tag{4}$$

The wall environments have nonzero stiffness, resulting in VEs that transition from low-frequency impedances of

$$\begin{aligned} \lim_{\omega \to 0} ES_{wall} &= K_{VE}, \\ \lim_{\omega \to 0} ED_{wall} &= B_{VE} + B_h/(1 + C_p), \\ \lim_{\omega \to 0} EM_{wall} &= 0 \end{aligned} \tag{5}$$

to the high-frequency impedances

$$\begin{aligned} \lim_{\omega \to \infty} ES_{wall} &= 0, \\ \lim_{\omega \to \infty} ED_{wall} &= B_{VE} + B_h/(1 + C_p), \\ \lim_{\omega \to \infty} EM_{wall} &= M_h/(1 + C_p) \end{aligned} \tag{6}$$

as the device properties begin to dominate the closed-loop response [18]. Naturally, these continuous approximations more realistically break down beyond the Nyquist frequency, and the behavior reverts to the uncompensated physical properties (Z_h); similarly, these behaviors only hold in the linear domain of motor performance, and do not account for saturation. It is notable that, while ES and EM are different between freespace and the virtual wall, the ED expressions in (4–6) are the same; we capitalize on this behavior to study the effects of varied levels of damping inside and outside of a virtual wall.

III. Methods

Two experiments were designed to investigate the effects of freespace damping on participants' ability to classify the stiffness of virtual walls rendered with and without damping. Experiment 1 featured high damping inside the virtual walls, while Experiment 2 featured low wall damping; participants in both experiments classified walls paired with a variety of freespace damping levels. For both experiments, the experimental protocol was the same, and only the conditions differed as described in Section III-A below.

A. Experimental Conditions

Both experiments featured VEs in the form of (3), in each case employing a stiff environment paired with freespace to create a virtual wall. The freespace always consisted of $K_{VE} = 0$ with virtual damping B_{VE} that varied by condition. A high damping value of $B_{VE} = 50$ Ns/m was selected based on pilot testing to be as large as practical without causing excess participant fatigue. Two intermediate values were then evenly spaced between zero and 50 Ns/m to create four freespace damping levels: $B_{VE} = 0$, 16.67, 33.33, or 50 Ns/m. In each experiment, participants were asked to classify virtual walls by stiffness in four conditions featuring these freespace damping levels, with multiple trials in each condition.

The virtual walls presented in both experiments for participants to classify were always one of three different stiffnesses

TABLE I
SUMMARY OF EXPERIMENTAL CONDITIONS

Property	Experiment 1 Value(s)	Experiment 2 Value(s)
Wall K_{VE}	Randomized: {3000, 5000, 8333} N/m	Randomized: {3000, 5000, 8333} N/m
Wall B_{VE}	50 Ns/m	0
Freespace K_{VE}	0	0
Freespace B_{VE}	Per Condition: {0, 16.67, 33.33, 50} Ns/m	Per Condition: {0, 16.67, 33.33, 50} Ns/m

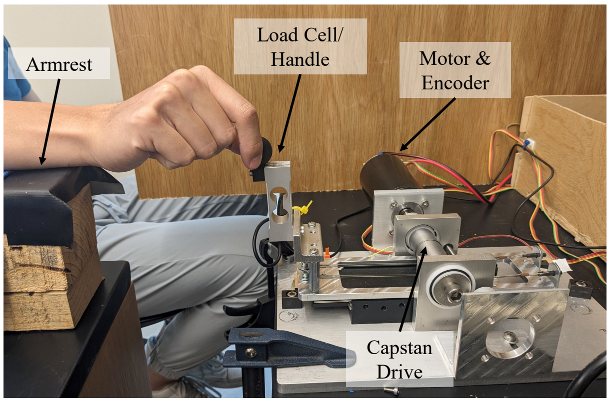


Fig. 1. Single degree-of-freedom haptic device. Participants encountered the virtual wall pulling the handle towards their body. A wooden divider blocked participants' view of the device.

(soft, 3000 N/m; medium, 5000 N/m; or stiff, 8333 N/m), presented randomly in each trial. The two experiments are distinguished only by the damping level paired with this virtual wall stiffness: Experiment 1 (Damped Wall) includes virtual damping $B_{VE} = 50$ along with each K_{VE}, whereas Experiment 2 (Undamped Wall) features $B_{VE} = 0$ inside the virtual wall. Since we had hypothesized that the effects on stiffness classification of freespace damping may vary with wall damping, these values were selected to give the largest possible contrast between wall damping levels in the two experiments. A summary of values used in the VEs (3) for each experiment can be found in Table I.

B. Apparatus and Control

The VEs employed in this study were rendered on the custom single-degree-of-freedom haptic device shown in Fig. 1. The device features a Maxon RE65 motor that drives a Del-Tron HPS3-4 linear slide via a 1-inch capstan drive. Position is measured via a US Digital encoder (E2-1024-315-IE-H-D-B) on the motor's back shaft, and forces applied to the handle are measured with a Transducer Techniques LSP-10 load cell. For this device, $M_h = 1.60$ kg and $B_h = 17.3$ Ns/m [18]. To prevent exceeding hardware limitations, current to the motor is software-limited to 8 A, which corresponds to a saturation force of 34.1 N.

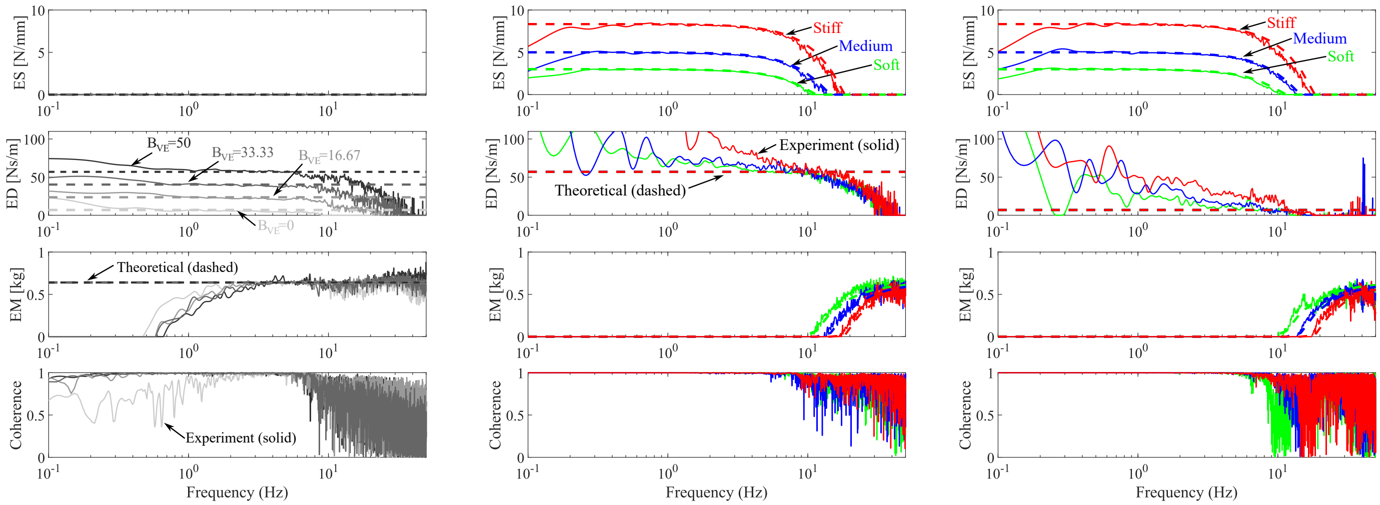
Rendering and data acquisition were performed using MATLAB/Simulink Desktop Real-Time, with a Sensoray S626 data acquisition card and a sampling rate of 1 kHz. As described in the previous section, closed-loop impedance control (2) was used to render both the freespace and stiffness VEs that compose the unilateral virtual wall environment. The velocity estimate for damping was computed using a first-difference method. All conditions were rendered using closed-loop impedance control (2) with proportional control gain $C_p = 1.5$ to compensate for the unpowered device dynamics. The device was oriented such that participants moved the handle towards themselves to encounter the virtual wall, and the wall was located at approximately the halfway point between the hard stops.

The predicted closed-loop responses for the VEs can be seen in the dashed lines of Fig. 2 in terms of the effective impedances. For simplicity, we refer to these conditions throughout the paper by the value of B_{VE} present in the freespace VE, but as predicted by (4), the effective damping experienced by participants is actually slightly higher in each condition: 6.9, 23.6, 40.3, and 56.9 Ns/m. Performance as rendered on the physical device is shown with solid lines in the same figure: each of the four freespace environments and six stiffness environments was excited manually for three minutes, with as wide a range of frequencies as possible produced by moving and tapping on the device handle. Force and position data were used to generate a Transfer Function Estimate of the driving point impedance in Matlab with a 10000-point Hann window, using a velocity estimate based on a first difference of position lowpass-filtered with a cutoff frequency of 100 Hz. The most notable departures from the predicted behavior are in effective damping for the stiffness VEs; however, the damping levels in Experiments 1 and 2 are clearly offset as intended. The bottom row of plots shows magnitude-squeezed coherence, which is a measure of correlation between the force and position signals; differences in predicted and rendered the effective impedances at frequencies with low coherence most likely reflect a lack of excitation rather than a departure from expected behavior. For example, spikes in ED around 40 Hz as coherence rolls off are more likely due to poor estimation of the transfer function than to an actual ED being rendered.

C. Classification Protocol

Participants performed a forced-response classification task following a protocol approved by the Trinity University Institutional Review Board. In each experiment, the four conditions with differing freespace damping parameters were conducted in a randomized order for each participant. In each condition, participants were tasked with classifying a series of virtual walls as soft, medium, or stiff. If they were curious, participants were told that we were studying the effects of changing freespace properties on their ability to distinguish the different wall stiffnesses; however, participants were not given details like which of the four conditions was which or what we expected to find until after completing the whole experiment.

Participants were instructed to hold the grip attached to the load cell with their thumb and forefinger. They were instructed to tap on the virtual wall by pulling the grip back and forth, always feeling the wall as they enter and leave it rather than dwelling in or pressing on the wall; this instruction was important since tapping and pressing excite different frequencies during the contact transition, which alter stiffness



(a) Freespace Conditions (b) Damped Wall (Exp 1) (c) Undamped Wall (Exp 2)

Fig. 2. Effective impedances for the experimental conditions, based on theory (dashed) and experimental system identification (solid). Experimental curves are based on 3 minutes of manual excitation of each environment at a range of frequencies. For (a) the four freespace VEs (employed in both experiments), (b) the stiffness VEs employed in Experiment 1 featuring high damping and (c) the stiffness VEs employed in Experiment 2 featuring low damping, the figures present, from top to bottom, the effective stiffness (ES), mass (EM), and damping (ED), followed by coherence. High coherence indicates frequencies at which there is strong correspondence between the input and output variables (force and position) used to compute the effective impedances.

perception [10], and participants exploring stiffness with a hand-held tool have better discrimination when tapping [12]. If needed, the experimenter would demonstrate a tapping motion to the participant on the device or by tapping on the edge of the table with a pen or pencil.

At the start of each condition, the soft, medium, and stiff walls were presented in order to the participant at least twice to acclimate them to the condition; participants were allowed to feel the three walls as many times as they desired before beginning the condition, until they felt comfortable with distinguishing them. During each condition, participants performed 46 trials in which they were instructed to tap on a randomized (soft, medium, or stiff) wall and identify it as soft, medium or stiff; responses were recorded by the experimenter. Participants wore noise-cancelling headphones, which played pink noise to mask the sound of the device. Their fields of view were also obstructed by a wooden partition to prevent visual feedback. The experiment took between about 45 minutes and 1 hour 30 minutes for each participant (since participants could take as much time on desired on each trial).

D. Participants

The data presented in this paper includes 12 right-handed participants between the ages of 19 and 24 years, 5 female, for Experiment 1; for Experiment 2 it includes 9 right-handed and 3 left-handed individuals between 19 and 21 years of age, 9 female. However, as detailed below, several complications arose in data collection which caused us to exclude data gathered from additional participants beyond these 24.

After 12 participants had completed Experiment 1, it was discovered that the load cell had been damaged between the fifth and sixth sessions (forces were two to three times noisier for participant six and the subsequent participants, and experimenters verified that this notably impacted how the VEs felt). After replacing the load cell, we reached out to the affected individuals to invite them to return and repeat the experiment. Since not all seven participants elected to return, the reported data for participants 6-12 presented in this paper represents a mix of individuals who opted to return and repeat the experiment and new participants who were recruited to replace those who were not interested in returning.

In Experiment 2, due to an error in experimental setup and instructions, it was discovered after-the-fact that two participants were able to see their hands and the device during data collection, which is a confounding factor since both visual and haptic feedback are known to influence perception [9]; their data was excluded and two additional individuals were recruited since neither was interested in repeating the study.

E. Analysis

Our primary goal in this study is to analyze participants' ability to classify the three different wall stiffnesses under different freespace damping conditions. However, since any effects may occur through modification of participants' exploration strategies, we also describe a number of exploration parameters that will be investigated across conditions. Performance and exploration parameters are calculated for each participant in each condition.

1) Classification Performance: The information transfer (IT) in an absolute identification experiment measures the number of distinct levels that can be transmitted/perceived reliably [17]. IT is typically measured in bits, where one bit corresponds to two distinguishable levels, two bits corresponds to four distinguishable levels, and so on. Experimentally, IT estimated based on the number of times n_{ij} that response j is given when stimulus i is presented:

$$IT = \sum_{j=1}^{K}\sum_{i=1}^{K} \frac{n_{ij}}{n} \log_2 \left(\frac{n_{ij} n}{n_i n_j} \right), \quad (7)$$

where $n_i = \sum_{j=1}^{K} n_{ij}$ and $n_j = \sum_{i=1}^{K} n_{ij}$, n is the total number of trials, and K is the number of stimuli [17]. In this case, $n = 46$ and $K = 3$, with other values for each condition dependent upon the VE randomization and participant responses[1].

Another complimentary metric used to quantify classification performance is the percent or fraction of correct responses, which indicates the ratio of correctly identified conditions to the total number of trials. Examining these two metrics together is more meaningful than individually due to the complimentary information that they provide. For example, a participant who always guessed soft in a trial where the randomization simply displayed a large number of soft springs could exhibit a high percent correct, but a low IT. On the other hand, a participant who could perceive distinct differences between conditions but mixed up which was soft, medium, or stiff would exhibit a high IT, but a low percent correct. Both demonstrate different types of poor classification performance that could not be identified based on one metric alone.

For each individual participant, a linear regression on performance (in terms of both IT and percent correct responses) vs. B_{VE} was performed to determine whether each individual experienced a positive or negative correlation between freespace damping and performance. To establish what effects had statistically significant influence on performance (IT and percent correct), we applied two-way Analysis of Variance (ANOVA) in SPSS, with factors of wall damping (low/high) and freespace damping (0, 16.67, 33.33, and 50 Ns/m). If interaction effects were significant, we subsequently performed a simple main effects analysis; if a simple main effect was found to be significant, pairwise comparisons of estimated marginal means were used to determine which conditions differed. Effect sizes are reported in terms of partial η^2, and interpreted per [23]: a medium effect size corresponds to partial $\eta^2 > 0.06$ and large to partial $\eta^2 > 0.14$.

2) Exploration: In addition to performance, participants' exploration strategies were analyzed from the recorded force and position during their trials. We selected a subset of metrics which have been previously connected to stiffness perception in VEs, and therefore could be expected to differ across the soft, medium, and stiff walls; by calculating these metrics across all trials or wall contacts for each condition, we seek to identify differences in exploration strategy induced by freespace damping conditions that could explain changes in stiffness perception. To calculate performance metrics, velocity was estimated from the encoder reading by the first difference method, and filtered with a first-order lowpass filter (cutoff frequency 100 Hz). The force was also lowpass-filtered with the same cutoff frequency. Because participants were allowed to feel each presented VE as many times as they wanted, exploration can be characterized either based on characteristics of the whole trial until they gave their response to classify the wall as soft/medium/stiff or based on each wall contact.

The following characteristics were calculated for each separate contact with the virtual wall across all trials (typically including multiple contacts per trial), and then averaged across the entire condition:

- **Contact velocity** [15] (while the velocity itself does not likely determine the perceived stiffness, this variable is expected to be influenced by damping condition and may partially account for differences in other exploration parameters).
- **Terminal force**, calculated as the maximum force exerted during each tap [9], [15].
- **Indentation**, or the maximum position reached during each tap [15].
- **Absolute work**, calculated as the sum of the absolute values of the integrals of force vs. displacement moving towards and away from the maximum indentation [9].
- **Rate-hardness**, calculated as the initial force rate of change divided by the initial penetration velocity over the first two samples of surface penetration [10].
- **Extended rate-hardness**, calculated as the peak force rate of change during the first 100 ms (100 samples) after contact divided by the initial penetration velocity, per [11].

Per trial, we examined the following characteristics, which were then averaged across the 46 trials.

- **Peak force** exerted during the duration of each trial.
- **Maximum indentation** into the virtual wall during the duration of each trial.
- **Number of contacts** with the wall during a trial, based on how many times the recorded position passed from freespace into the virtual wall. Because participants are allowed to feel each wall as many times as desired before answering, conditions with more contacts may suggest that participants had a harder time deciding which response to give. For this calculation and the per-tap metrics listed above, any taps with 5 ms or less of wall contact or 15 ms or less of time outside the wall preceding the contact are discounted from these calculations; these thresholds were determined from observation of the data to eliminate ricochet-type subsequent contacts with very low contact velocities.
- **Time** to classify each wall is also calculated; however, we note that since responses were recorded by the experimenter and not the participant, this measurement may also differ based on who was recording data for each trial.

Since our primary goal of analyzing exploration is to understand the effects of freespace damping within a single wall damping condition, repeated measures (within-subjects) ANOVA (RMANOVA) was used to determine whether each exploration parameter was significantly affected by freespace damping condition in each of the two experiments separately, as this allows us to account for large differences between indi-

[1]Over $5(3^2) = 45$ trials are required with three stiffness levels to minimize bias in IT estimation [17]. The upper limit of IT expected for this experiment would be 1.58 bits, if the three walls were displayed 15, 15 and 16 times in a trial.

vidual participants. Greenhouse-Geiser corrections for sphericity were taken where needed. For conditions with $p < 0.05$, posthoc multiple comparison testing was used to determine which conditions differed.

IV. Results

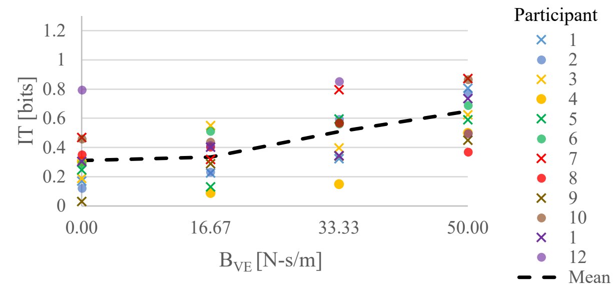
A. Classification Performance

Results from Experiment 1 (Damped Wall) for each participant are shown in terms of IT in Fig. 3a and percent correct in Fig. 3c. For Experiment 1 (Fig. 3a) all but one participant (12, shown in purple, with very high IT in the lowest damping condition) had a positive correlation between freespace damping and IT despite large individual differences in performance, with an average slope of +0.007 bits in IT for each Ns/m of damping. For percent correct vs. the freespace damping (Fig. 3c), again all but one individual (participant 11) had a positive correlation; the average slope is +0.4% per Ns/m of damping. Since R^2 values for these fits are quite low (on average, 0.51 for percent correct and 0.62 for IT), we do not mean to imply linearly increasing performance, but the consistency of the trend suggests a positive correlation between freespace damping and classification performance.

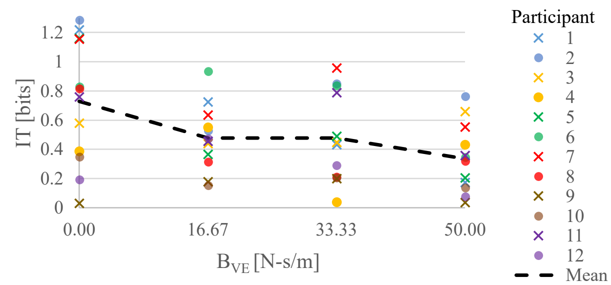
Results from Experiment 2 (Undamped Wall) are shown for each participant in Figs. 3b and 3d. We note that the data log file for participant 6 in the 50 Ns/m damping condition for this experiment cut off the final two trials, so only 44 randomized trials were recorded—because this data is nearly complete, we have included it in our analysis, but we acknowledge that there are potential impacts on the reliability of the IT estimation in this trial. Conversely to results from the first experiment, 9 of the 12 participants in Experiment 2 had a negative correlation between freespace damping level and percent correct (all but participants 3, 9, and 10), and 10 participants had a negative correlation between damping level and IT (all but participants 3 and 9); the slopes average -0.2% and -0.007 bits per Ns/m of damping. The R^2 values are lower than for Experiment 1 (0.40 for percent correct and 0.39 for IT).

Pooled responses for each stiffness are shown in Fig. 4 for each condition in the two experiments, represented as confusion matrices; perfect performance would appear as 3 black squares from top left to bottom right. Regardless of condition, the majority of participants performed better than chance across all three walls in both experiments, indicating some basic ability to distinguish between the wall stiffnesses in all cases; this is also demonstrated by the low occurrence of confusion between the soft and stiff springs in the confusion matrices. With a damped wall (Experiment 1), there is a particularly notable increase in participants' ability to correctly identify the softest wall as freespace damping increased. For the undamped walls, both the softest and stiffest wall were identified correctly more frequently in lower freespace damping conditions.

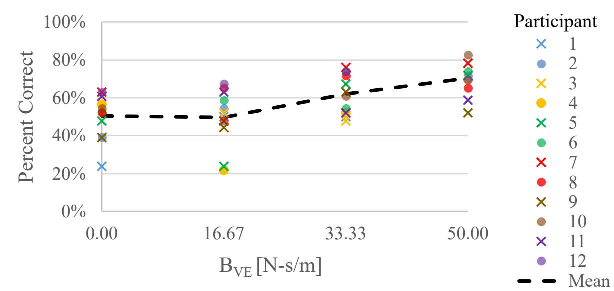
Combined stiffness classification performance from the two experiments is shown by wall damping condition in Fig. 5a and by freespace damping condition in Fig. 5b. From the 2-way ANOVA for IT, a significant interaction effect ($F(3, 88) = 8.82, p < 0.001$, with partial $\eta^2 = 0.23$) was found, indicating



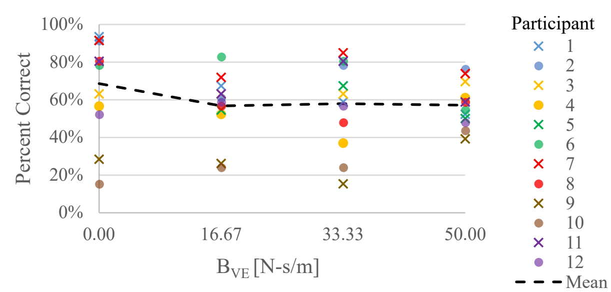
(a) IT, Damped Wall (Exp 1)



(b) IT, Undamped Wall (Exp 2)



(c) % Correct, Damped Wall (Exp 1)



(d) % Correct, Undamped Wall (Exp 2)

Fig. 3. Stiffness classification performance in terms of (a-b) information transfer and (c-d) percent correct responses for both Experiment 1 (high damping inside the wall) and Experiment 2 (low damping inside the wall). Each participant's performance is shown in a different color for each damping condition; the dotted line connects group means. Note that the two groups of participants are different between Experiments 1 and 2.

that the main factors of wall damping ($F(1, 88) = 1.13, p = 0.291$) and freespace damping ($F(3, 88) = 0.93, p = 0.429$) do not sufficiently describe the interaction, and thus simple main effects of each factor within the other must be examined. For percent correct, there was also a significant interaction effect ($F(3, 88) = 0.41, p = 0.009$, partial $\eta^2 = 0.12$), while

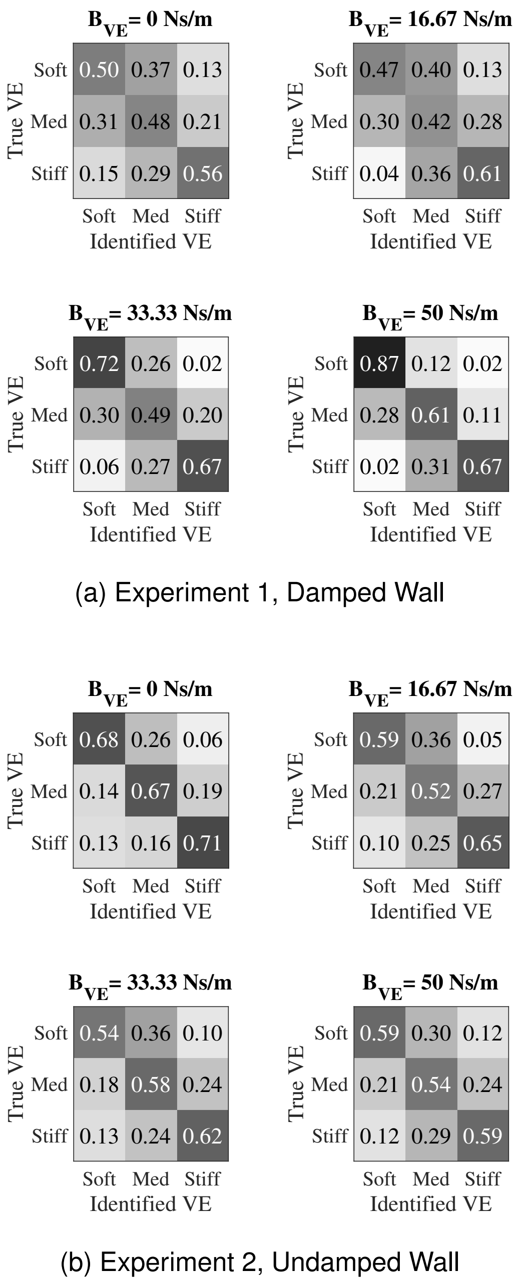


Fig. 4. Results from (a) Experiment 1 and (b) Experiment 2, averaged across participants. Each confusion matrix indicates how frequently (as a number and a color, with white corresponding to 0 and black corresponding to 1) participants gave the response soft/medium/stiff (columns) each time soft/medium stiff was actually displayed (rows). Each row sums to 1, since all VEs of a certain "true" value were identified as either soft, medium, or stiff.

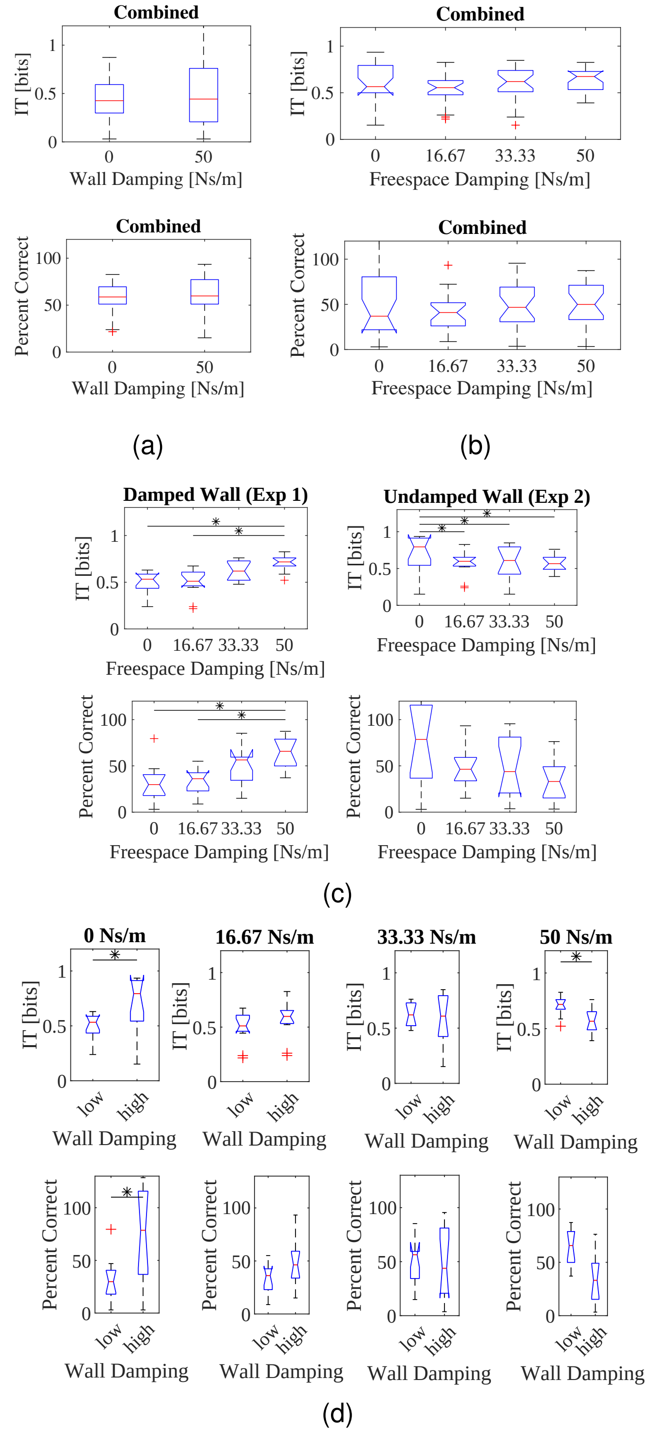


Fig. 5. Information transfer and percent correct from the combined experiments presented as boxplots (a) by wall damping and (b) by freespace damping illustrate how no significant main effects exist due to the significant interaction effect. However, significant simple main effects do exist (c) when separated by wall damping condition (i.e., separated by experiment) or (d) separated by freespace damping condition. Stars indicate $p < 0.05$ for simple main effects.

freespace damping had $F(3,88) = 1.68, p = 0.177$ and wall damping had $F(1,88) = 0.32, p = 0.575$. These interaction effects can be seen when the data is separated by wall or freespace damping (Fig. 5c and 5d).

Simple main effects analysis reveals that freespace damping has a significant influence on IT in both wall damping cases: $F(3,88) = 4.72, p = 0.004$ with a damped wall (Experiment 1) and $F(3,88) = 5.03, p = 0.003$ with an undamped wall (Experiment 2), with partial η^2 of 0.14 and 0.15, respectively (i.e., freespace damping has a large simple main effect on IT). Pairwise comparisons between estimated marginal means indicate significant differences in IT between the following pairs of freespace damping conditions with damped walls (indicated with stars in Fig. 5c): $B_{VE} = 0$ and 50 ($p = 0.002$) and 16.67 and 50 Ns/m ($p = 0.003$); for undamped walls, there were significant differences between $B_{VE} = 0$ and all other freespace conditions (with $p = 0.017$ for $B_{VE} = 16.67$, $p = 0.017$ for $B_{VE} = 33.33$, and $p < 0.001$ for $B_{VE} = 50$). For percent correct, simple main effects analysis indicates that freespace damping has a significant effect with a large effect size when the wall is damped (Experiment 1: $F(3, 88) = 4.32, p = 0.007$ with partial $\eta^2 = 0.13$); for undamped walls, however, the effect of freespace damping was not significant, with $F(3, 88) = 1.43, p = 0.240$ for Experiment 2. Pairwise comparisons of the estimated marginal means suggest that the significant differences in Experiment 1 were between the 0 and 50 Ns/m freespace damping conditions ($p = 0.004$) as well as between 16.67 and 50 Ns/m ($p = 0.003$).

For wall damping (Fig. 5d), simple main effects analysis indicates a significant effect on IT only in the highest and lowest freepsace damping conditions: $F(1, 88) = 16.43, p < 0.001$ for $B_{VE} = 0$ with partial $\eta^2 = 0.157$ and $F(1, 88) = 9.14, p = 0.003$ with partial $\eta^2 = 0.094$ for $B_{VE} = 50$ Ns/m, while ($F(1, 88) = 1.943, p = 0.167$ for 16.67 Ns/m and $F(1, 88) = 0.09, p = 0.765$ for 33.33 Ns/m). Wall damping had significant main effects on percent correct in the $B_{VE} = 0$ condition ($F(1, 88) = 7.17, p = 0.009$, partial $\eta^2 = 0.08$) and approached significance for $B_{VE} = 50$ Ns/m ($F(1, 88) = 3.89, p = 0.052$), but was not significant at the intermediate freespace levels: $F(1, 88) = 1.09, p = 0.300$ for 16.67 Ns/m and $F(1, 88) = 0.39, p = 0.535$ for 33.33 Ns/m.

B. Exploration

Altering the freespace properties has the potential to change participants' exploration strategies, which could account for some of the perceptual differences.

1) Per-tap characteristics: Exploration parameters calculated per tap and then averaged across the entire condition for each participant are shown in Fig. 6. For Experiment 2 (undamped wall), the results exclude S3—the position traces reveal that this participant failed to follow instructions to tap, and did not exit and re-enter the wall on most trials. This may explain this participant's relatively consistent performance across conditions in terms of both IT and percent correct, as well as the lack of negative correlation between performance and freespace damping[2].

With a damped wall (Experiment 1), participants' mean contact velocity (Fig. 6a) was significantly affected by freespace damping condition ($p = 0.01$, $F(3, 33) = 4.40$), with significant differences between the 0 and 50 Ns/m conditions as well as between 16.67 and 50 Ns/m conditions, in each case with lower contact velocity in the higher damping condition. While the same trend can be seen in Experiment 2, it was not significant ($p = 0.06$, $F(1.45, 14.47) = 3.65$). There was not a large difference between the contact velocities achieved by participants in the two different experiments.

[2]Excluding S3 from the analysis of IT and percent correct does not alter the conditions between which differences were reported in Section IV-A.

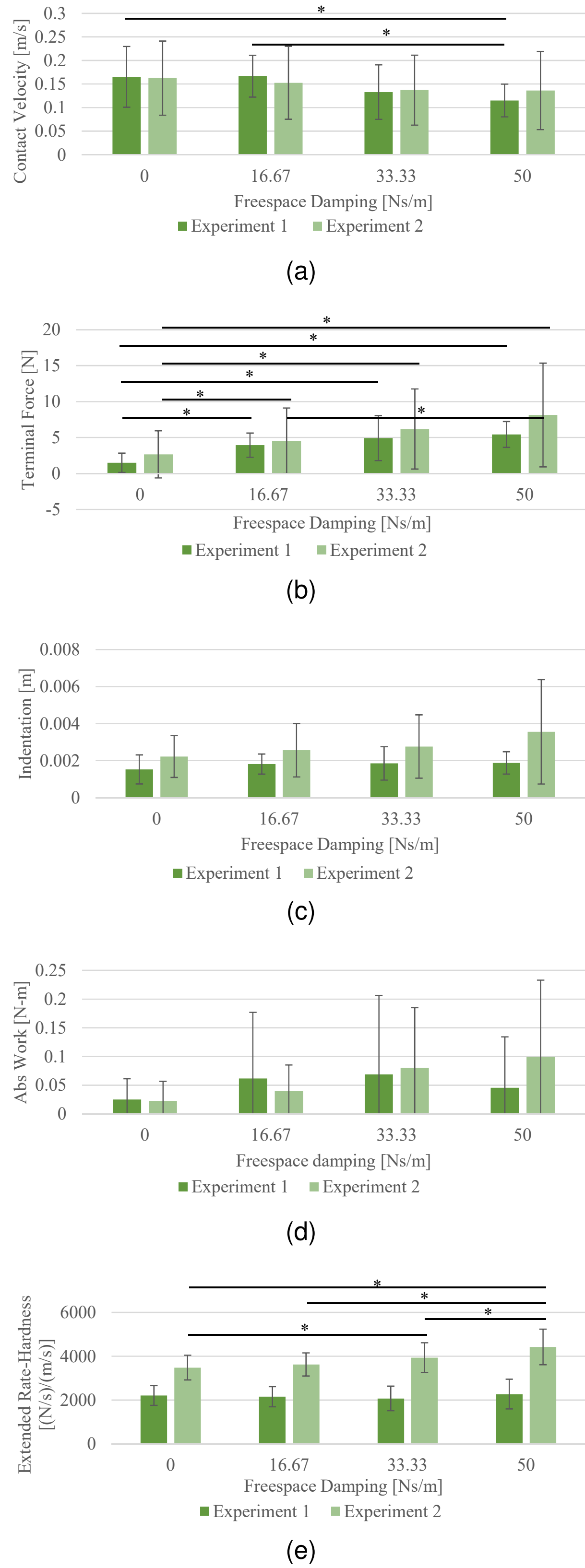


Fig. 6. Exploration parameters measured per tap and averaged across the condition for each participant. In all cases, error bars represent one standard deviation of the mean values across participants, and significant differences between conditions ($p < 0.05$) are indicated by stars.

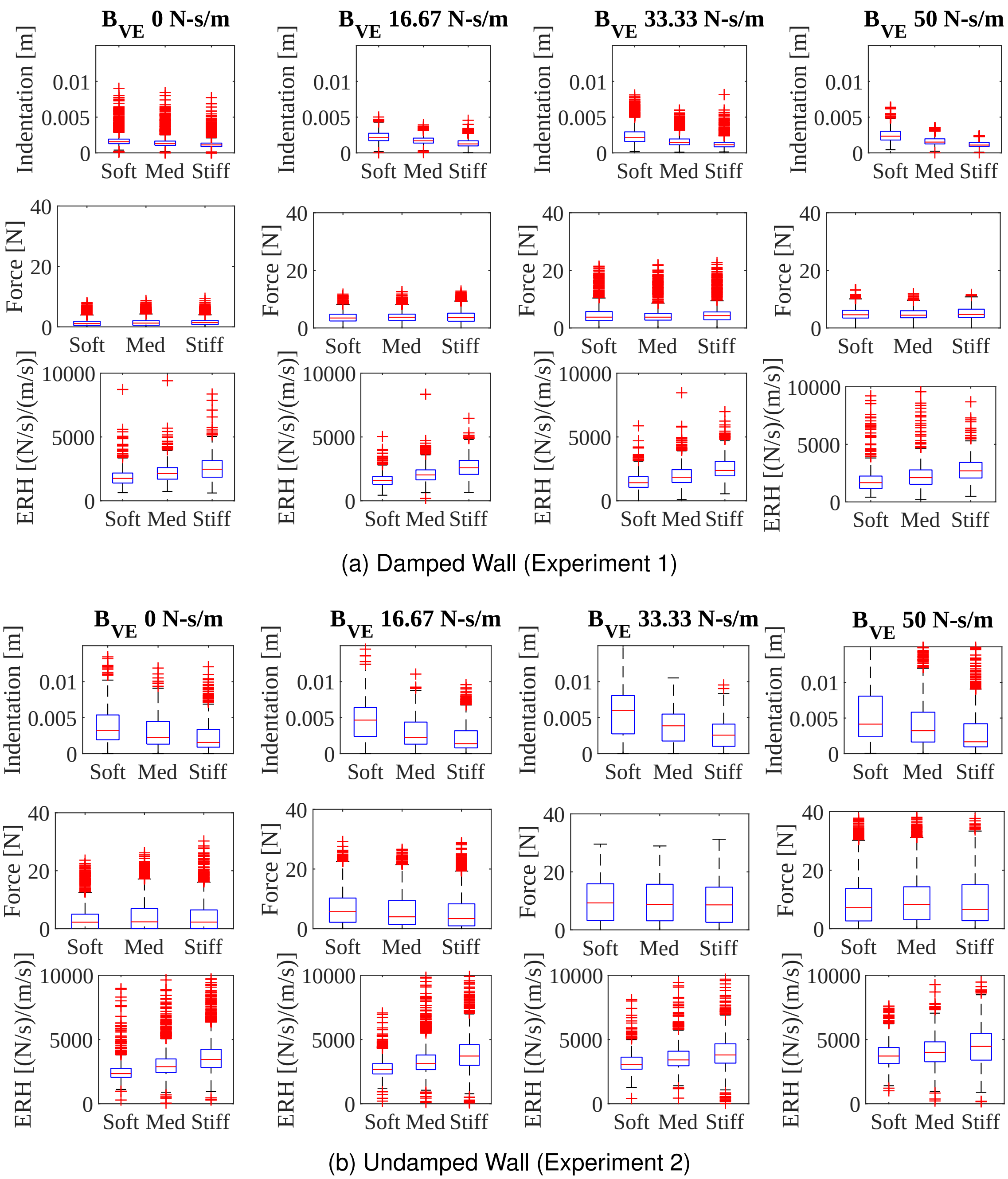


Fig. 7. Exploration parameters (indentation, terminal force, and ERH) for all taps while the soft, medium, and stiff walls were displayed (a) with high wall damping in Experiment 1 and (b) with low wall damping in Experiment 2. For each experiment, the four conditions for freespace damping are shown from lowest (left) to highest (right).The boxplots represent all taps across all participants (excluding S3 in Experiment 2).

Terminal force (Fig. 6b) increased with freespace damping, with many significant differences between conditions, as indicated by the stars in the figure: for the damped wall (Experiment 1) $F(1.80, 19.8) = 9.39, p < 0.01$ with significant differences between the 0 freespace damping condition and all other conditions, and for the undamped wall (Experiment 2), $F(1.49, 14.9) = 15.3, p < 0.01$ with significant differences between all but two pairs of conditions (the 16.67/33.33 Ns/m and 33.33/50 Ns/m conditions). Examination of the forces from all taps indicates that only a single participant (S12 in Experiment 2) ever exceeded the saturation torque for the device, and only during the 50 Ns/m condition.

Mean indentation (Fig. 6c) remained relatively constant across freespace damping conditions in Experiment 1 ($F(3, 33) = 0.85, p = 0.48$); in Experiment 2, RMANOVA suggested significant differences between some conditions ($F(1.68, 16.8) = 3.97, p = 0.04$), but posthoc multiple comparison testing did not reveal any condition pairs with $p < 0.05$. As can be seen in Fig. 7, indentation appears to have been more closely tied to which stiffness was presented than to the condition, whereas force remained quite consistent across wall stiffnesses. Comparing across the two experiments, participants interacting with undamped walls (Experiment 2) tended to achieve higher indentations than participants tapping damped walls.

For absolute work (Fig. 6d), there was no significant effect of freespace damping condition in either experiment: $F(1.54, 17.0) = 2.04, p = 0.17$ for Experiment 1 and $F(1.75, 17.5) = 3.21, p = 0.07$ for Experiment 2. Comparison of the two experiments also shows no consistent trends in absolute work with a damped vs. undamped wall.

Rate-hardness (not shown in a figure) did not vary significantly by damping condition, nor did it correlate well with the displayed stiffness. Extended rate-hardness (ERH) (Fig. 6e) was unaffected by freespace damping for damped walls ($F(3, 33) = 1.62, p = 0.20$ for Experiment 1) but significantly affected for undamped walls ($F(3, 30) = 12.6, p < 0.01$ for Experiment 2), with differences between the 50 Ns/m condition and all other damping conditions as well as between the 0 and 33.33 Ns/m conditions. Different wall damping levels resulted in large differences in ERH between experiments. Additionally, in both experiments ERH varied with the presented stiffness, as seen in the bottom rows in Fig. 7.

2) Per-trial characteristics: Trends in peak force per trial and in maximum indentation per trial mimic those presented in the per-contact results of Fig. 6b and 6c, but with higher mean values since only the most forceful tap per trial is represented (since the trends are so similar, we omit the graphs). Statistical analysis indicates that freespace damping significantly affects peak force per trial in both experiments, with higher freespace damping leading to higher mean maximum forces for each trial: for damped walls (Experiment 1), $F(1.73, 19.1) = 7.50, p < 0.01$, with posthoc testing finding significant differences between the 0 freespace damping condition and all other conditions. For Experiment 2, $F(1.42, 16.7) = 5.75, p = 0.02$ with significant differences between the 33.33 and 50 Ns/m freespace damping conditions (although several other condition pairs had p-values approaching significance—e.g., the 0 and 50 Ns/m pair have $p = 0.052$). Peak indentation per trial, on the other hand, was not affected by freespace damping condition ($p > 0.2$ for both experiments). Undamped walls (Experiment 2) also tended to lead to higher maximum indentations than damped walls (Experiment 1).

Mean time per trial (Fig. 8a) had no significant trends for either experiment by condition ($F(1.49, 16.38) = 3.09, p = 0.08$ for Experiment 1 and $F(3, 33) = 2.10, p = 0.12$ for Experiment 2). Comparing across the two experiments, there is also no consistent trend of whether the damped or undamped walls were faster for participants to distinguish. However, freespace damping did significantly alter the number of contacts participants made with the wall in each trial (Fig. 8b) when the walls were damped (Experiment 1): $F(3, 33) = 12.14, p < 0.01$, with higher damping leading to fewer contacts with the virtual walls, which may imply that participants found them easier to distinguish. With undamped walls, however, no inverted trend was present to suggest matched wall and freespace damping leads to fewer contacts; in fact, mean contacts per trial also decreased with increasing freespace damping for Experiment 2, although differences were not significant ($F(1.70, 17.02) = 2.12, p = 0.15$).

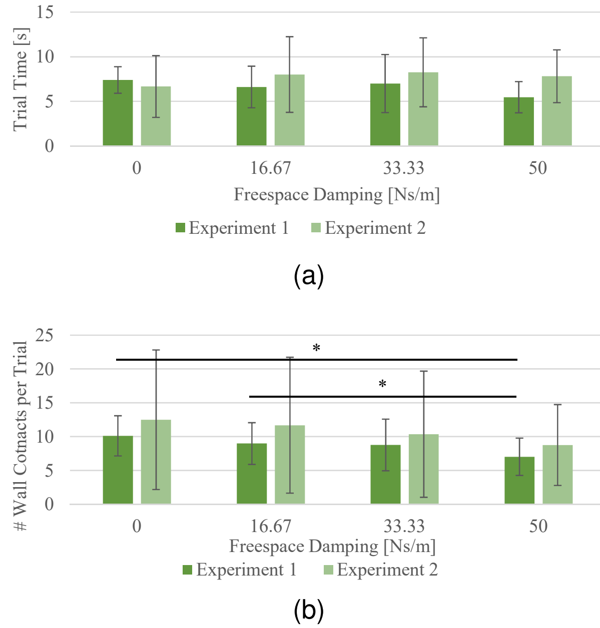


Fig. 8. Exploration parameters measured per trial. In all cases, error bars represent one standard deviation of the mean values per participant and significant ($p < 0.05$) differences between conditions are indicated by stars.

V. Discussion

The results of these experiments support both main hypotheses: (1) that altering freespace damping significantly affects participants' ability to classify virtual walls by their stiffness (as measured by IT and percent correct), and (2) that these effects differ based upon the damping level inside the virtual wall. Specifically, we found that when the wall was damped (Experiment 1), the highest freespace damping resulted in significantly better IT and percent correct responses than the lowest two freespace damping levels, with an overall trend supporting improving performance from 0 to 50 Ns/m freespace damping (though indications are that the trend is not linear). Conversely, when the wall was undamped (Experiment 2), the trend was reversed, with the zero freespace damping condition significantly outperforming all others in terms of IT; a similar trend existed for percent correct responses, but was not statistically significant.

There were large variations in IT and percent correct between participants in both experiments, which are comparable to ranges in similar studies [18], [21]. The randomization of freespace damping condition order may partially account for some of the variation, as participants may have either shown improvement through learning or developed fatigue throughout the four conditions. It is worth noting, however, that the participants in Experiment 1 who repeated the experiment did not perform notably better than other participants—the highest-performing individual on average for Experiment 1 was participant 12, who only completed the experiment once. Despite large differences in individual ability (e.g., compare participants 1 and 9 in the second experiment), the effect sizes for the significant differences in IT that resulted from different wall damping conditions in each experiment were large.

These results contribute to an extended understanding of the effects of local and global damping: van Beek et al. [15] previously found that globally-damped objects were perceived as softer than locally-damped ones; the lowest and highest freespace damping conditions from Experiment 1 (damped wall) in our study correspond, respectively, to local and global damping as described by van Beek. Our results suggest that locally-damped virtual walls are significantly more difficult to classify by stiffness than globally-damped walls. Beyond local and global damping, we also explored the effects of injecting damping only in freespace (Experiment 2); while the differences were not as pronounced as in Experiment 1, the opposite trend was present at least in the extremes, as the 50 Ns/m condition for Experiment 2 had lower IT than the lower freespace damping conditions.

While we have established that freespace damping can in fact affect stiffness classification and that the damping inside the wall changes the nature of this effect, future work is still needed to understand the mechanism behind this interaction. Matching properties inside and outside of virtual walls had previously been hypothesized to be important [21], but had not been systematically explored until now. Since perceptual thresholds for stiffness are influenced by all portions of the device frequency response (also including mass and damping) [14] such that ED and ES may not be completely separable to the user, it is logical that mismatched ED between freespace and the virtual wall in a classification task would make classification more difficult, as perceptual thresholds contribute to classification performance. While our results are consistent with a hypothesis that improved classification performance is facilitated by matching freespace and wall damping, they are not sufficient to establish it as fact.

Of the exploration characteristics that we examined, only a few varied significantly with damping. While terminal force was greatly affected by freespace damping condition (Fig. 6b), participants appear to have maintained relatively consistent force within a given condition as shown in Fig. 7, relying on other cues to distinguish between the soft, medium, and stiff virtual walls. In contrast to the results from [15], we did not see significant effects on indentation from local vs. global damping; this discrepancy may be due to differences for tapping- vs. pressing-type explorations [12].

In examining our exploration results, it appears that the perceptual connection between ERH and perceived hardness [11] likely played a role in creating the differing effects of freespace damping in the two experiments. Since perceptual thresholds are often characterized by Weber fractions [17], or changes relative to a reference level, it is notable that the percentage differences in ERH between the soft and stiff walls differ across conditions and experiments. In Experiment 1 with high wall damping, the low freespace damping condition resulted in a median ERH of 2473.0 (N/s)/(m/s) for the stiff wall and 1754.2 (N/s)/(m/s) for the soft wall, which means that the stiffest spring's ERH was 1.41 times higher than the softest (bottom left panel of Fig. 7a); in the highest (50 Ns/m) freespace damping condition on the other hand, the median ERH was 1.62 times higher in the stiff vs. soft wall contacts (bottom right panel of Fig. 7a)—this potentially suggests larger perceivable differences in stiffness in the highest damping condition, which could explain the improved classification performance. In Experiment 2, on the other hand, the opposite was true: the low freespace damping condition resulted in median stiff ERH that was 1.47 times the soft wall's ERH (bottom left panel of Fig. 7b), while the high freespace damping condition's stiff spring median ERH was only 1.20 times the ERH of the softest wall (bottom right panel of Fig. 7b). And while ERH depends on contact velocity, the differences in relative ERH between conditions and experiments are not completely explained by changes in the contact velocity due to freespace damping, which actually remained relatively consistent across most conditions in the two experiments (Fig. 6a).

VI. Conclusions

This work explored the effects of damping in freespace and inside of virtual walls on the perceptual ability to classify walls by their stiffness. Results from a pair of perceptual experiments demonstrated that freespace damping can in fact have opposite effects on the ability to classify virtual walls by stiffness, depending on the corresponding damping employed inside of the wall: when wall damping is high, increasing the freespace damping improves the ability to classify walls by stiffness, but for undamped walls, higher freespace damping impairs classification. While the highest damping level in these experiments (an ED of 56.9 Ns/m) is unlikely to be practically employed in most haptic rendering applications, the other damping levels employed could potentially come about as a result of hardware design in a non-backdrivable device. We caution designers of virtual environments and haptic devices to be aware of the perceptual influences that altering damping may have on stiffness perception, particularly since it would be easy to assume that one could modify freespace without changing wall perception.

These results lead us to believe that it is not the absolute level of damping in either freespace or the virtual wall that is most important, due to a strong interaction effect between the influences of wall damping and freespace damping on classification. While one explanation could be that a match between freespace and wall damping leads to the best performance, future work experiments which employ wall damping in the middle of the range of freespace damping and/or which do not precisely match the rendered levels of freespace damping are needed to explore that hypothesis more fully. Similarly, future study on the impacts of varying mass between freespace and virtual walls is warranted to see whether similar effects exist for other effective impedances, as well as to help extend understanding of these interactions to environments with higher physical or virtual mass.

Acknowledgments

The authors would like to thank the participants who completed these experiments for their time and energy. This work was supported in part by *ADVANCED* Motion Controls' University Outreach Program and by a McNair Scholars Program grant from the U.S. Department of Education.

References

[1] J. Colgate and J. Brown, "Factors affecting the Z-Width of a haptic display," in *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*. San Diego: IEEE, 1994, pp. 3205–3210.

[2] J. E. Colgate, "On the intrinsic limitations of force feedback compliance controllers," in *Robotics Research*, K. Youcef-Toumi and H. Kazerooni, Eds. New York: ASME, 1989, pp. 23–30.

[3] R. J. Adams, M. R. Moreyra, and B. Hannaford, "Stability and Performance of Haptic Displays: Theory and Experiments," in *Proceedings ASME International Mechanical Engineering Congress and Exhibition*, Anaheim, 1998, pp. 227–234.

[4] N. Colonnese and S. Chan, "Z-Qualities and Renderable Mass-Damping-Stiffness Spaces: Describing the Set of Renderable Dynamics of Kinesthetic Haptic Displays," in *2019 IEEE World Haptics Conference, WHC 2019*. Tokyo: IEEE, 2019, pp. 325–330.

[5] N. Diolaiti, G. Niemeyer, F. Barbagli, and J. K. Salisbury, "Stability of haptic rendering: Discretization, quantization, time delay, and Coulomb effects," *IEEE Transactions on Robotics*, vol. 22, no. 2, pp. 256–268, 2006.

[6] D. A. Lawrence, L. Y. Pao, M. A. Salada, and A. M. Dougherty, "Quantitative experimental analysis of transparency and stability in haptic interfaces," in *Proc. Fifth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME Dynamic Systems and Control Division*. Atlanta: ASME, 1996, pp. 441–449.

[7] H. Z. Tan, N. I. Durlach, G. L. Beauregard, and M. A. Srinivasan, "Manual discrimination of compliance using active pinch grasp: The roles of force and work cues," *Perception & Psychophysics*, vol. 57, no. 4, pp. 495–510, 1995.

[8] A. Pressman, L. J. Welty, A. Karniel, and F. A. Mussa-Ivaldi, "Perception of delayed stiffness," *International Journal of Robotics Research*, vol. 26, no. 11-12, pp. 1191–1203, 2007.

[9] M. Di Luca, B. Knörlein, M. O. Ernst, and M. Harders, "Effects of visual-haptic asynchronies and loading-unloading movements on compliance perception," *Brain Research Bulletin*, vol. 85, no. 5, pp. 245–259, 2011.

[10] D. A. Lawrence, L. Y. Pao, A. M. Dougherty, M. A. Salada, and Y. Pavlou, "Rate-hardness: a new performance metric for haptic interfaces," *IEEE Transactions on Robotics and Automation*, vol. 16, no. 4, pp. 357–371, 2000.

[11] G. Han and S. Choi, "Extended rate-hardness: A measure for perceived hardness," in *EuroHaptics*, A. K. et Al., Ed., vol. 6191 LNCS, no. PART 1, Amsterdam, 2010, pp. 117–124.

[12] R. H. LaMotte, "Softness discrimination with a tool," *Journal of Neurophysiology*, vol. 83, no. 4, pp. 1777–1786, 2000.

[13] L. Jones and I. Hunter, "A Perceptual Analysis of Stiffness," *Experimental Brain Research*, vol. 79, pp. 150–156, 1990.

[14] W. Fu, M. M. Van Paassen, and M. Mulder, "Human Threshold Model for Perceiving Changes in System Dynamics," *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 5, pp. 444–453, 2020.

[15] F. E. van Beek, D. J. F. Heck, H. Nijmeijer, W. M. B. Tiest, and A. M. Kappers, "The effect of global and local damping on the perception of hardness," *IEEE Transactions on Haptics*, vol. 9, no. 3, pp. 409–420, 2016.

[16] M. Rank, T. Schauß, A. Peer, S. Hirche, and R. L. Klatzky, "Masking effects for damping JND," in *Haptics: Perception, Devices, Mobility, and Communication. EuroHaptics 2012. Lecture Notes in Computer Science, vol 7283*, P. Isokoski and J. Springare, Eds. Berlin, Heidelberg: Springer, 2012, pp. 145–150.

[17] L. A. Jones and H. Z. Tan, "Application of psychophysical techniques to haptic research," *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 268–284, 2013.

[18] E. Treadway and K. Journet, "The Effect of Freespace Properties on Unilateral Stiffness Classification," in *IEEE World Haptics Conference*. Montreal: IEEE, 2021, pp. 715–720.

[19] M. Mihelj and J. Podobnik, *Haptics for Virtual Reality and Teleoperation (Vol. 64, Intelligent Systems, Control and Automation: Science and Engineering)*. Springer, 2012.

[20] C. R. Carignan and K. R. Cleary, "Closed-loop force control for haptic simulation of virtual environments," *Haptics-e*, vol. 1, no. 2, pp. 1–14, 2000.

[21] E. Treadway and R. B. Gillespie, "Unilateral and Bilateral Virtual Springs: Contact Transitions Unmask Device Dynamics," *IEEE Transactions on Haptics*, vol. 12, no. 2, pp. 205–216, 2019.

[22] N. Colonnese, A. F. Siu, C. M. Abbott, and A. M. Okamura, "Rendered and characterized closed-loop accuracy of impedance-type haptic displays," *IEEE Transactions on Haptics*, vol. 8, no. 4, pp. 434–446, 2015.

[23] J. Cohen, *Statistical power analysis for the behavioral sciences*, rev. ed. New York: Academic Press, 1977.

Emma Treadway received the B.S. degree in Engineering Science from Trinity University in 2011, and her M.S.E. and Ph.D. degrees in Mechanical Engineering from the University of Michigan, Ann Arbor in 2017 and 2019, respectively. She is an Assistant Professor in the Department of Engineering Science at Trinity University, San Antonio TX, USA. Her current research interests include haptics, rehabilitation robotics, and the role of affect in engineering education.

Kristian Journet received the B.S. degree in Engineering Science from Trinity University in 2022, and is working in electrical engineering.

Andrew Deering received the B.S. degree in Engineering Science from Trinity University in 2023 and is currently working as a Robotics Software Engineer at Wilder Systems in Austin, TX, USA. His current professional interests include robotics, aeronautics, autonomous navigation, and computer vision.

Cora Lewis is a student at Trinity University working towards her B.S. degree in Engineering Science with an interest in electromechanics.

Noelle Poquiz is an undergraduate student at Trinity University intending to major in Engineering Science. She enjoys being in choir, video games, and painting.