Passive and Active Kinesthetic Perception Just-noticeable-difference for Natural Frequency of Virtual Dynamic Systems

Yanfang Li* Rice University
Ali Israr† Rice University
Volkan Patoglu‡ Sabancı University
Marcia O'Malley§ Rice University

Abstract

This paper investigates the just-noticeable-difference (JND) for natural frequency of virtual second order dynamic systems. Using a one degree-of-freedom haptic device, visual and/or haptic sensory feedback were presented during interactions with the system. Participants were instructed to either perceive passively or actively excite the system in order to discriminate natural frequencies. The JND for this virtual resonance task ranged from 3.99% to 6.96% for reference frequencies of 1 Hz and 2 Hz. Results show that sensory feedback has a significant effect on JND in passive perception, with combined visual and haptic feedback enabling the best discrimination performance. In active perception, there is no significant difference on JND with haptic and combined visual and haptic feedback. There is also no significant difference between active perception and passive perception for this JND experiment. The presentation of systems with equivalent natural frequencies but different spring stiffness resulted in no large bias toward larger stiffness and no significant difference in JND for equivalent systems. This finding indicates that human participants do not discriminate natural frequency based on the maximum force magnitude perceived, as indicated by prior studies.

Keywords: Haptic perception, dynamics, discrimination

Index Terms: H.1.2 [Model and Principles]: User/Machine Systems—Human factors

1 Introduction

There has been significant interest in utilizing virtual environments with haptic feedback for purposes of training motor skills. Record and replay strategies for training display desired environment interactions (motions and/or forces) to a passive human user, who then tries to mimic these interactions [3, 4, 5, 8, 22]. Others have utilized the flexibility of a haptic virtual environment to display augmented errors to participants during tasks or reaching movements, in order to elicit better performance in terms of reduced errors over time [2, 13, 14, 15, 21]. The authors' prior work has studied the effects of various forms of haptic assistance on both performance enhancement and training for manual control tasks [13]. Shared control is a means of augmenting the virtual system dynamics in a way that provides assistance to the human user when completing the task. For the authors' target hitting task, an error-reducing shared controller was utilized, and was shown to improve task performance and also increase skill retention between training sessions. However, the error-reducing shared controller did not have a significant effect on task performance after a month-long training protocol [13]. Human performance of the manual control task used in the authors' prior studies is influenced by the participant's ability to perform system identification in order to excite the virtual dynamic system near its resonant frequency. A long term goal is to understand the participants' ability to identify dynamics of external systems in order to improve the performance of the shared controller for training in haptic virtual environments. Haptic assistance for training is approached from the perspective of optimization, where the rate of adaptation of the human's actions to a solution is enhanced in order to improve task performance. A better understanding of human sensitivity to varying system dynamics will enable improved design of a shared control algorithm for the authors' manual control task.

To this end, it is necessary to further understand a human's ability to perceive and identify the natural frequency of systems that they manipulate. The natural frequency of a dynamic system can be thought of as a signature of the system's inherent behavior. If a human can identify this signature, or discriminate between signatures of one or more dynamic systems, they may be able to refine their control of the system to elicit desired behavior. A shared controller may be useful for speeding the process of control refinement. Previous studies have examined vibrotactile frequency discrimination thresholds on passive fingerpads, forearm, thenar eminence and sternum using pulse-like or sinusoidal displacement waveforms for a wide range of frequencies and amplitudes (see a review in [7]). The frequency thresholds, expressed as Weber fractions, varied from 0.02 to 0.72 (equivalent JND are 2% to 72%). Variability in the size of JND was largely due to different experimental conditions, stimulus artifacts (frequency and amplitude) and due to presence of another stimulus (the masker) along with the target stimulus [7]. In these studies, discrimination thresholds were estimated mostly by exciting the mechanoreceptors embedded in the skin (cutaneous sensation) and not by receptors located in joints, tendons and muscles (kinesthesis) [10]. Israr *et al.* [7] estimated the frequency Weber fractions in the entire kinesthetic-cutaneous continuum by passively simulating the index fingerpad of the left hand with sinusoidal displacement waveforms thus supplemented, in some cases, limb motion with cutaneous excitation. Although many studies determined passive frequency JNDs, the authors are not aware of any data on active frequency JNDs that are required for the design of an improved shared controller. Rinker *et al.* [17] investigated frequency JND in pseudo-active movements of the finger and the JNDs were similar to those obtained passively in [7]. In the present study, a human's ability to discriminate natural frequency of virtual dynamic systems is investigated by asking participants to actively excite the system while coupled with a handle of a single degree-of-freedom haptic device[1]. The device displays dynamical forces on the handlebar grasped by the participants. In order to compare the discrimination performance with the case when interaction forces of the system are presented on the passive hand, natural frequency JNDs are also

*e-mail: yvonneli@rice.edu
†e-mail: ai1@rice.edu
‡e-mail: vpatoglu@sabanciuniv.edu
§e-mail: omalleym@rice.edu

[1]The active mode and the passive mode refer to active kinesthetic perception and passive kinesthetic perception as defined in [10]. Active kinesthetic perception refers to availability of combined information through afferent kinesthetic units and their efference copy to an observer while passive kinesthetic perception refers to the information available to an observer through afferent kinesthetic units only.

measured by exciting the dynamic system with an external source and asking participants to hold the handle.

Another objective of the present study is to investigate the influence of different sensory feedback (vision, haptics or combined) on the discrimination ability. In the manual control task, it is important to understand the potential assistance that can be provided by haptic-only or visual-only feedback, or if supplementing haptic with visual feedback is better than incorporating them individually. Previous studies have reported effectiveness of multisensory feedback in different experimental tasks. For example, Poling *et al.* [16] determined discrimination thresholds for surface roughness with a stylus-based force-feedback device (PHANToM) and concluded that the effectiveness of sensory feedback depended on the grating amplitude. In a dynamical task, Sternad *et al.* [18] investigated rhythmic bouncing of a ball with a racket and concluded that inclusion of haptic feedback enhanced stability performance than when visual information was presented alone. Morris *et al.* [12] performed a force skill learning task by presenting temporal force patterns on a passively moving human hand along spatial trajectories. The task of the experiment was to recall a force pattern in a test trial that was presented in a training trial with haptic-, visual-, or combined feedback. Their results showed that accurate recall was marginally higher with visual-training than with haptic-training, but combined visual and haptic training resulted in significantly higher accuracy than visual- and haptic-training alone. In a manual excitation task similar to the authors' task, Huang *et al.* [6] reported that haptic feedback augmented with vision significantly improved the control of their dynamic system. In order to investigate if haptic feedback assists in the discrimination task of the present study, different combinations of haptic and visual sensory feedback are presented. Visual-only (V), haptic-only (H) and combined visual and haptic (V+H) feedback are presented in the passive mode, while haptic-only (H) and combined visual and haptic (V+H) feedback are presented in the active mode. Visual-only feedback in the active mode is not tested because it is not possible to eliminate efference kinesthetic cues in the experiment.

The remainder of the paper is organized as follows: Section 2 describes the experimental methods and Section 3 presents results of the experiment. We discuss the results in Section 4 followed by conclusions in Section 5.

2 Methods

2.1 Apparatus

The experimental apparatus consists of a one degree-of-freedom custom built haptic device that displays forces on a palm grip handle as shown in Figure 1. The forces generated at the handle are proportional to the voltage applied to the DC motor with a built-in tachometer that serves as an actuator of the device. A position encoder (Renishaw RGH24), and an accelerometer (Crossbow CXL02LF1Z) are mounted on the handle assembly to measure instantaneous states of the handle used to render interaction forces charaterizing the virtual dynamical system.

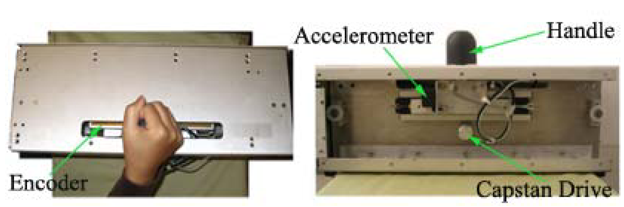

Figure 1: One degree-of-freedom haptic interface top view (left) and side view (right)

The haptic device synthesizes a virtual resonance task by rendering a linear mass-spring system as shown in Figure 2. The sensed motion of the handle is used to excite a virtual spring that is connected to a virtual cart of specified mass. The dynamics of the handle are cancelled in the virtual task by estimating effective mass of the handle in the direction of motion and incorporating inertial forces due to the effective mass, thus treating the handle massless in the virtual task. Whenever the handle is excited either by the computer system (passive) or by a human participant (active), the resulting motion of the virtual cart is determined solely by dynamics of the virtual system and is graphically displayed to the user along with an image of the handle position (see Figure 2). The natural frequency of the virtual system is proportional to the ratio of the virtual spring and mass of the rendered virtual system.

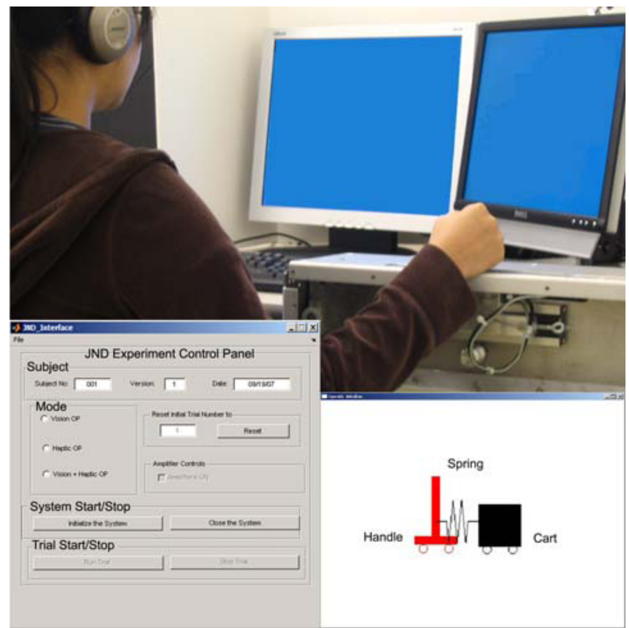

Figure 2: JND experiment set-up, showing 1-DOF haptic device held by participant and dual screen display. Inset shows screen shots of the experiment control GUI (right) and graphical display of virtual environment (left).

2.2 Participants

Five male and one female (21-31 years old with an average age of 27 years old) took part in the study. Four participants were tested in five experimental conditions and two reference natural frequencies (total 10 experimental series), and two participants completed five experimental conditions for one natural frequency each. All participants are right-handed by self-report and have no known hand/arm impairments that can influence the outcome of this study. All participants except one had prior exposure to haptic perception experiments.

2.3 Stimuli

This study employed a stimulus that was derived from the spring and mass parameters of the virtual system. Participants were presented either with the forces due to reference natural frequency (ω_0) or with the forces due to test natural frequency ($\omega_0 + \Delta\omega$), where $\Delta\omega$ was the increment of natural frequency, with equal a priori probabilities. In order to focus participant's attention on the natural frequency and eliminate effects of force magnitudes on the discrimination experiment, two equivalent systems with two different stiffnesses were associated with each natural frequency. Thus, the reference natural frequency is derived from either (m_{11}, k_1) or (m_{12}, k_2) and the test natural frequency is derived from either the parameter set (m_{21}, k_1) or (m_{22}, k_2), with equal probabilities of encounter. Pilot data of the system response showed that peak forces due to the four system parameters were similar and force magnitude cues were not a factor in the discrimination task. The duration of the stimulus was randomly selected from ten equally spaced levels between 4 and 6 seconds.

2.4 Procedure

Participants sat comfortably in front of two computer screens and the one degree-of-freedom device resided on a table to the right of their torso (see Figure 2). The screen on the left displayed the main experiment graphical user interface for participants to select their responses. The right-hand screen provided real-time animation of the virtual system. The one degree-of-freedom force feedback device conveyed interaction forces due to the dynamics of the virtual handle-cart system to participants.

A series of experiments were conducted to estimate just-noticeable-difference (JND) for natural frequencies of manually excited dynamic systems in two excitation cases (active or passive) and with three sensory feedback (visual-only, haptic-only and visual+haptic) for each reference frequency. One case is when no active excitation is applied by the participant and the computer system excites the virtual mass-spring system with an initial displacement between the virtual cart and the handle. This case is referred to as "passive perception". The other case is when the participant constantly excites the virtual system with approximate sinusoidal motion to match with the natural frequency of the system. This case is referred to as "active perception". The typical trajectories of the virtual cart and the handle for both cases are illustrated in Figure 3. Three types of sensory feedback were provided in the passive perception case, namely visual-only, haptic-only, and visual+haptic. For visual-only conditions (V), participants recieved motion cues by monitoring the movement of the virtual handle-cart system displayed on the computer screen on the right. For haptic-only conditions (H), the computer with graphical representation was turned off and participants were instructed to focus on the interaction forces by holding the physical handle of the one degree-of-freedom device. For visual and haptic conditions (V+H), both visual and haptic cues were presented to participants simultaneously. For the active perception cases, only haptic and visual+haptic sensory feedback conditions were tested since it is aberrant to excite the system with visual feedback alone. Thus for each reference natural frequency, JND is estimated in five experimental conditions. A summary of JND experiments is presented in Table 1.

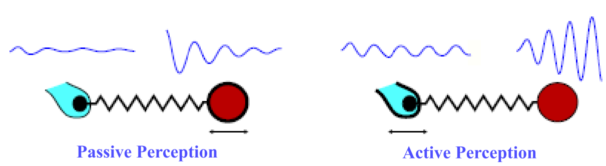

Figure 3: Typical trajectories of handle position/human input (left) and virtul cart trajectories (right) versus time for passive perception and active perception

JNDs were estimated for 1 Hz and 2 Hz reference natural frequencies using one-interval two-alternative forced-choice (1I-2AFC) procedure of signal detection theory [11]. In each trial, the participant was either presented with the reference stimulus (ω_0) or with the test stimulus ($\omega_0 + \Delta\omega$). The participant's task was to click on a button marked as "lower frequency" for the reference or "higher frequency" for the test natural frequency. Correct answer feedback was provided after the completion of each trial. The reference and test natural frequencies remained the same within one experimental run. One experimental run corresponded to one experimental condition. Each run had 80 trials and lasted about 15-20 minutes. Out of 80 trials, the first 16 were training and the next 64 were test trials. Each experimental condition was tested in three increment frequencies, namely 5%, 10% and 15%. The order of each increment frequency was randomized and tested in a single day with sufficient rest between each run. Thus for one reference natural frequency, each participant was tested for 1200 trials. The order of sensory feedback and excitation cases was the same as presented in Table 1. There were five participants for each reference stimulus. Four participants were tested for both reference natural frequencies and the two remaining participants were tested with only one reference frequency. The order of the reference frequency was randomized for participants tested with two natural frequencies. At the end of experiments, performance scores were plotted and some participants were asked to repeat runs that showed large variations in the performance.

Table 1: Summary of experimental conditions

Experimental Condition	Excitation Case	Sensory Feedback
1	Passive Perception	Visual-only
2	Passive Perception	Haptic-only
3	Passive Perception	Visual+Haptic
4	Active Perception	Haptic-only
5	Active Perception	Visual+Haptic

Participants were instructed before each day's testing and given a few training trials to get familiar with the experimental task. During the experiment, pink noise was presented through head phones to eliminate possible auditory cues from the environment and hardware. A cardboard and cloth screen was placed in front and around the participant to isolate the testing setting from the outside environment. Participants signed consent forms before the experiment and all experiments were completed with the pre-approved IRB policy of Rice University.

2.5 Data Analysis

The 2×2 stimulus-response matrices for 64 test trials in all experimental runs were analyzed to estimate the just-noticeable-difference for two natural frequencies and five experimental conditions (see Table 1). For each run, sensitivity index (d') and response bias (β) were determined as:

$$d' = Z(H) - Z(F) \tag{1}$$

and

$$\beta = -\frac{Z(F) + Z(H)}{2} \tag{2}$$

where $Z(.)$ is the inverse function of the normal distribution, H is the hit rate of the test stimulus and F is the false alarm rate. $\beta = 0$ indicates an unbiased response. $d' = 1$ is set as the performance threshold for JND. Generally, the value of d' is roughly proportional to the increment and each increment case resulted in an estimate of JND using $d'/(\Delta\omega/\omega_0)$. In each experimental condition, d' is plotted as the function of increments for all participants and a slope is determined by taking the average of all $d'/(\Delta\omega/\omega_0)$ values [20]. The mean JND for each condition is the inverse of this slope. Analysis of variance (ANOVA) is utilized to

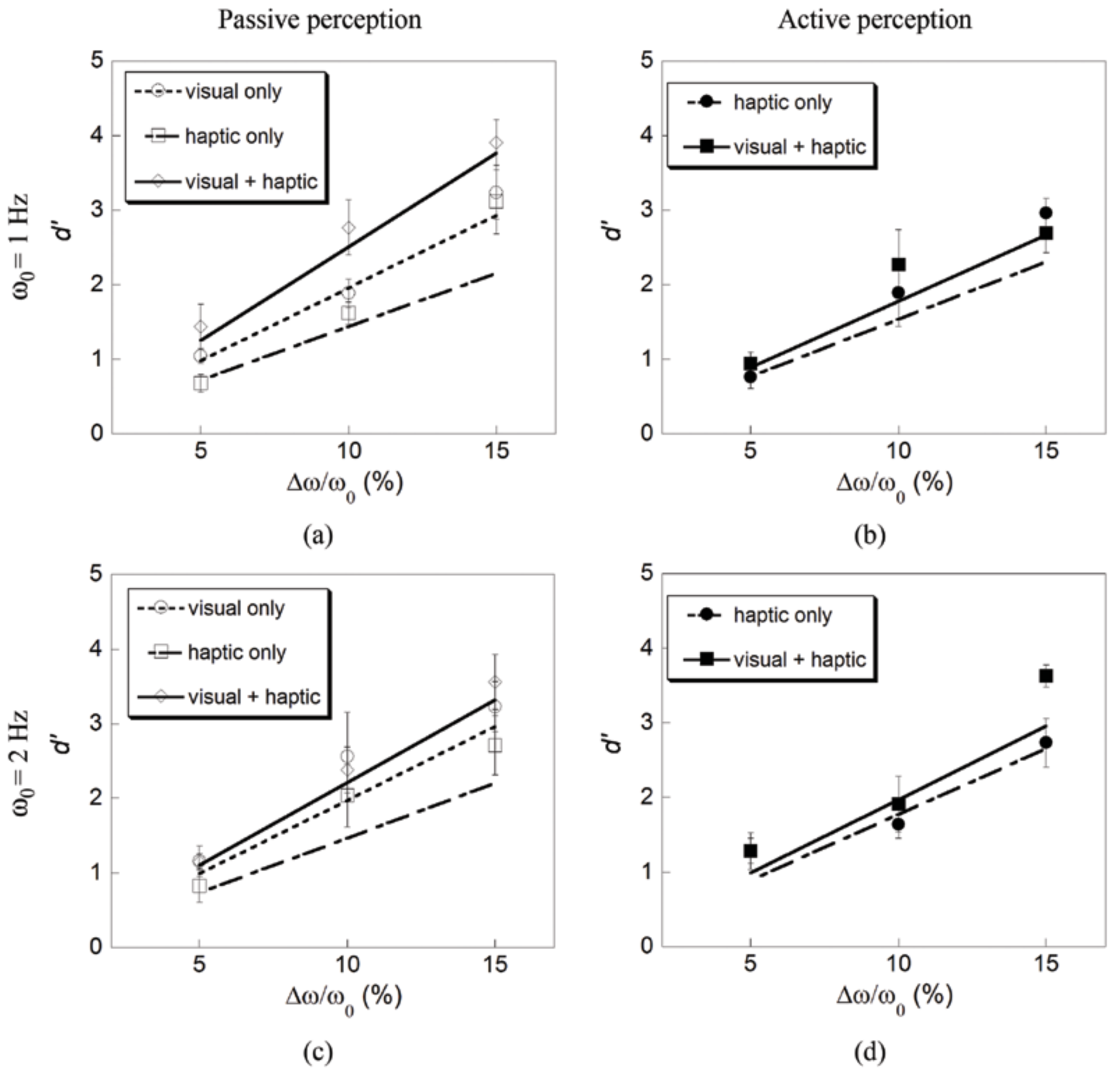

Figure 4: The average sensitivity index (d') for two reference frequencies and five experimental conditions as a function of increment frequencies. Average slope lines are plotted and error bars indicate variation of the mean across five participants. (a) 1 Hz in the passive perception case, (b) 1 Hz in the active perception case, (c) 2 Hz in the passive perception case, and (d) 2 Hz in the active perception case.

determine significant differences of JNDs between experimental conditions and reference frequencies. The d' obtained in one increment case resulted from 64 trials and each estimate of JND is considered as an independent observation in the ANOVA yielding 150 (2 frequencies, 5 experimental conditions, 3 increment cases, 5 particiapnts per frequency) JND estimates in the experiment. In order to further explore the influence of different sensory feedback on JNDs for natural frequency, another statistical analysis method, difference of least square mean, is used. This analysis method takes into account all the JNDs for different conditions by using an adjusted mean for each condition that isolates the effect of each individual condition, then gives out specific comparison between each two conditions. In this way we can compare all five experimental conditions at two natural frequencies, such as visual-only at 1 Hz vs. haptic-only at 1Hz, while post hoc tests can only give out comparison between visual-only and haptic-only conditions combined for both 1 Hz and 2 Hz. The mean of each experimental condition and natural frequency were compared using both the difference of least square mean method and the conventional post-hoc method. Due to similarity in significance results in the two methods the post-hoc results are not reported in the paper.

3 Results

For each experimental run, sensitivity index (d') and bias (β) were calculated. Bias ranged from -0.66 to 0.77 with the average bias of $\beta = 0.0027$ for all experimental conditions. Near zero response bias indicates that participants were generally not biased towards any particular response and were consistent in following experiment instructions.

Figure 4 shows the average sensitivity index (d') (pooled across all participants) as a function of increment frequencies for five experimental conditions. Error bars represent standard error of the mean at each increment frequency. The top two panels show sensitivity index for 1 Hz reference natural frequency, while the bottom two panels are for 2 Hz reference natural frequency. Panels on the left are for passive perception cases and panels on the right are for active perception cases. As expected, average of sensitivity index (d') increased proportionally to the increment frequency in all experimental conditions. A line with a slope equal to the average of each $d'/(\Delta\omega/\omega_0)$ for each experimental condition is also drawn in Fig. 4. The mean JND in the experimental condition was the inverse of the slope of the line. Steeper slopes corresponds to smaller JND and vise versa. In the passive perception case, gradual slopes were obtained with haptic-only feedback and steeper slopes were obtained when visual and haptic cues were combinely presented at both reference natural frequencies (left panels in Fig. 4). Similar results were obtained in the active perception case line slopes with visual+haptic feedback were steeper than the line slopes with haptic only feedback in both reference natural frequencies (right panels in Fig. 4).

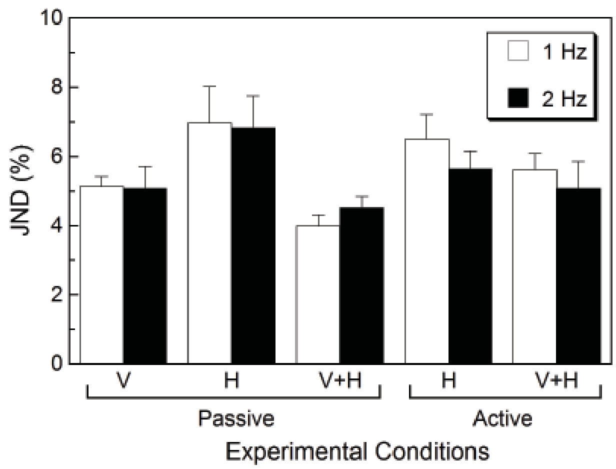

Figure 5: Average JNDs for natural frequency in five experimental conditions and two reference frequencies. Error bars represent standard error of the mean across participants.

Figure 5 shows the average JNDs for five experimental conditions at two reference natural frequencies. Error bars show standard error of the mean pooled across participants. The average JNDs for all experimental conditions varied from 3.99% to 6.96% at 1 Hz and from 4.52% to 6.82% at 2 Hz reference natural frequency. At both reference natural frequencies, smallest JNDs were obtained in visual+haptic feedback in passive perception case and largest were obtained for haptic-only feedback in passive perception case. A repeated measures ANOVA (reference natural frequency as between-subject factor, experimental condition as within-subject factor) showed that effects of reference natural frequency did not have a significant effect on the JND values $[F(1,28) = 0.21, p = 0.654]$ and experimental condition effects were significant $[F(4,25) = 12.38, p < 0.001]$. The interaction term was not significant $[F(4,25) = 0.91, p = 0.4734]$ indicating similar trends in experimental conditions with the two reference natural frequency. A summary of significance between different conditions measured by difference of least square mean method is listed in Table 2, an asterisk indicates statistical significance.

4 Discussion

This paper presents an experiment to determine JND for natural frequency of manually excited virtual dynamic systems. Using a single degree-of-freedom haptic device, JNDs were obtained for 1 Hz and 2 Hz reference natural frequencies for two excitation methods and three sensory feedback modalities. Passive perception of natural frequency was achieved by actively exciting the handle of the haptic device, grasped by the participant. Active perception of natural frequency required the participant to excite the system through their own movement of the haptic interface handle. Previous studies have determined frequency and period discrimination thresholds (or

Table 2: Summary of Significance Measured by Differences of Least Square Means

Frequency	Sensory Feedback	Excitation Case	p-value
1	V vs. H	passive	0.049*
1	V+H vs. H	passive	0.001*
1	V+H vs. V	passive	0.22
1	V+H vs. H	active	0.34
2	V vs. H	passive	0.06
2	V+H vs. H	passive	0.01*
2	V+H vs. V	passive	0.55
2	V+H vs. H	active	0.54
1 vs. 2	V	passive	0.96
1 vs. 2	H	passive	0.88
1 vs. 2	V+H	passive	0.57
1 vs. 2	H	active	0.36
1 vs. 2	V+H	active	0.58
1	H	passive vs. active	0.62
1	V+H	passive vs. active	0.08
2	H	passive vs. active	0.54
2	V+H	passive vs. active	0.55

Weber fractions) for low-frequency sinusoidal waveforms by moving participants' fingerpads loosely placed on a contactor [7, 17]. However, a human's ability to discriminate frequency of a manually excited dynamic system has not been reported in the literature. The present work serves to define these discrimination thresholds for active perception of natural frequency, while also comparing results to passive perception. Results of the present study show that there is no significant difference in JND between active and passive perception methods of determining natural frequency.

In related work, Dingwell *et al.* [1] investigated the strategy that human participants use while manually controlling an external spring-mass system through the use of "catch trials". Their results indicate that human participants employ a low impedance controller, suggesting the existence of internal models of the external system. For the manual control resonance discrimination task implemented in this paper, human participants might similarly be constructing internal models of the task. If such internal models are in use, then the natural frequency discrimination task can be addressed by identifying the spring-mass parameters characterizing the dynamics of the virtual system. For proper system identification, persistence of excitation is an important requirement. When active perception is employed, human participants can ensure rich excitations since they determine the input to the system being identified. For the passive perception case, the excitation signal is determined by the haptic environment and controller. In the case that the excitation signal is sufficiently rich in frequency content, the method of excitation, be it active or passive, may not impact the discrimination task. Results of the JND experiment presented here indicate that whether the excitation input is self-generated or rendered by the virtual environment/haptic interface, participants were able to identify the system with the sensory information made available to them. Therefore, no significant difference in JND exists between the two excitation protocols. A study conducted by Lederman *et al.* [9] regarding constrained manual exploration for haptic recognition of common objects suggests that the loss of somatosensory information results in poor identification performance. Along these lines, reducing the available sensory information by methods such as asking participants to wear a compliant glove while grasping the handle (thus depriving participants of cutaneous sensory information) or using an inappropriate excitation signal may impair the performance of passive perception and result in significant differences between the two cases.

Results also showed that there was no significant effect of reference natural frequency on the JND values in the 1-2 Hz range. This was not the case in many previous studies in which JNDs varied with increasing reference frequency and amplitude [7, 17]. One possible reason could be that the range of the reference frequency in the present study was relatively small to allow manual excitation within the achievable range for human manual control [19]. JNDs obtained in the previous studies may also be larger than those reported in the present study because the amplitude of stimulation in the present study was larger. It was shown in [7, 17] that the thresholds decreased comparatively when the amplitude of the stimulus increased, particularly in the low frequency range..

In both active and passive perception, JNDs were largest with haptic-only (H) feedback and smallest when haptic cues were supplemented with the visual feedback (V+H). For the passive perception case, V+H feedback resulted in JNDs that were significantly smaller than for H feedback alone. Conversely, for the active perception case, inclusion of visual feedback did not show significant effects in the participants' discrimination performance. Therefore, inclusion of haptic feedback enhances a human's discrimination performance when interacting with the virtual dynamic system, but when the human actively excites the system, haptic-only feedback is sufficient. This conclusion is consistent with the results reported by Huang *et al.* [6] for a similar resonance dynamic task.

In our pilot study participants performed poorly when the conditions were randomly presented to them. Participants were unaware of the tasks in each condition. Even with training trials and correct answer feedback supplemented to the testing, the performance was poor. In literature with similar experimental tasks, a human performance in combined visual and haptic sensory feedback is better (if not similar) than either visual sensory feedback or haptic sensory feedback [6, 12, 16, 18]. So we tested visual-only condition first and visual+haptic condition in the last, first passive tasks and then active tasks. In the reported data, statistical analysis failed to show significance in the JND in visual condition and the JND in visual+haptic condition. We assumed with evidence that the human performance did not improve in the later condition as a consequence of training. The order was used to make participants familiar with the task and not as a training tool. In the end of experiments, we tested some participants in randomly chosen conditions and performance did not change.

The JNDs obtained in the present study are tied to a human's ability to identify the key parameters of a virtual second order dynamic system. The physical parameters of the system (mass and stiffness) can be altered while maintaining the behavioral characteristics (natural frequency) of the system. Changing the physical parameters (while keeping natural frequency constant or allowing it to vary) results in different interaction forces exerted on the handle of the haptic device. In order to eliminate any dependency on force cues for the natural frequency discrimination task, two equivalent systems with different mass and stiffness but equal natural frequency were introduced in the experiments. Thus, the same reference natural frequency is rendered with two distinct physical parameter sets, resulting in distinct interaction force profiles. In [17], the authors suggest that participants might be using the so-called intensity perception as a basis of frequency discrimination. If intensity perception is the strategy used in the present study, a large bias value would result if the participants tended to vote for a "higher" frequency when the maximum force rendered through the task dynamics was larger. However, there exists no bias in the present study, indicating that subjects are equally as likely to select the lower intensity (lower force) set of parameters as they are for the higher intensity set. Since there is no significant difference in JND for equivalent systems, participants in this study are not using maximum force cues alone to discriminate natural frequency for the virtual second order dynamic system.

5 Conclusions

This paper has presented a study of just-noticeable-difference (JND) for natural frequency of virtual second order dynamic systems. A one degree-of-freedom haptic device was used to investigate of human discrimination abilities for both active perception (user excitation) and passive perception (device excitation). The JND values obtained ranged from 3.99% to 6.96% for reference frequencies of 1 Hz and 2 Hz. Sensory feedback was varied to test human performance with visual-only, haptic-only, and combined visual and haptic feedback during the discrimination task. While excitation method did not significantly affect JND, the feedback modality had a significant effect. Combined visual and haptic feedback enabled the best discrimination of virtual system natural frequency. Force magnitude was determined not to be the cue utilized by participants for frequency discrimination.

Acknowledgements

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