Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces
for Virtual Environment and Teleoperator Systems
Salt Lake City, UT, USA, March 18-20, 2009

Effects of Magnitude and Phase Cues on Human Motor Adaptation

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ABSTRACT

Recent findings have shown that humans can adapt their internal control model to account for the changing dynamics of systems they manipulate. In this paper, we explore the effects of magnitude and phase cues on human motor adaptation. In our experiments, participants excite virtual second-order systems at resonance via a two-degree of freedom haptic interface, with visual and visual plus haptic feedback conditions. Then, we change the virtual system parameters and observe the resulting motor adaptation in catch trials. Through four experimental conditions we demonstrate the effects of magnitude and phase cues on human motor adaptation. First, we show that humans adapt to a nominal virtual system resonant frequency. Second, humans shift to higher and lower natural frequencies during catch trials regardless of feedback modality and force cues. Third, participants can detect changes in natural frequency when gain, magnitude, and phase cues are manipulated independently. Fourth, participants are able to detect changes in natural frequency when the feedback (visual or visual plus haptic) is delayed such that the phase shift between the nominal system and catch trial system is zero. The persistent ability of participants to perform system identification of the dynamic systems which they control, regardless of the cue that is conveyed, demonstrates the human's versatility with regard to manual control situations. We intend to further investigate human motor adaptation and the time for adaptation in order to improve the efficacy of shared control methodologies for training and rehabilitation in haptic virtual environments.

KEYWORDS: Rhythmic motion, motor adaptation, internal models, catch trials.

INDEX TERMS: H.1.2 [Models and Principles]: User/Machine Systems—Human Factors; H.5.2 [Information Interfaces and Representation]: User Interfaces—Haptic I/O.

1 INTRODUCTION

Humans frequently perform motor tasks that require interactions with external dynamic systems, such as driving a car or wielding a tool. Such systems may be underactuated or may have higher order control mappings, thereby requiring training in order for the human to learn proper control of the system [1,2]. For rhythmic tasks such as pumping a swing or bouncing a ball, the perception of the dynamic behavior of the external system directly affects the control input planned and executed by the user [3]. However, psychophysical analysis of actively controlled dynamic systems, which may shed light on the mechanisms used by humans to execute motor tasks, has received little attention. A broader understanding of human motor control could directly benefit researchers who develop training protocols or simulations to teach new motor skills.

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Virtual environments have been explored as a means to teach new motor skills in domains such as surgery, assembly, and pilot training. Haptic guidance schemes have been incorporated in virtual environments to improve performance and to reduce training duration and user workload. Virtual fixtures, record-and-play, shared control, and error-based guidance schemes have shown potential to improve user performance during task completion and to accelerate learning rates, by guiding the user to perform the task in a preferred manner [4-10]. However, the design of effective training schemes is not a trivial task, and results of most training studies are either non-generalizeable or inconclusive.

Our own prior work has studied the effects of various forms of haptic assistance on both performance enhancement and training for manual control tasks [10,11]. In particular, shared control has been proposed as the most general active haptic guidance scheme for training where feedback is provided by a controller, which is dependent upon the system states [10]. A shared controller dynamically intervenes, through an automatic feedback controller acting upon the system, to modify the (coupled) system dynamics during training. By modifying the coupled system dynamics in a favorable manner, shared control algorithms have the potential to accelerate the learning (parameter tuning) process by focusing user attention and skill refinement on key dynamic properties of the controlled systems, thereby improving learning times and training efficacy. In [11] we incorporated an error-reducing shared controller for haptic guidance, and demonstrated improved task performance and increased 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. We concluded that assistance designed with knowledge of the task and an intuitive sense of the motions required to achieve good performance does not necessarily result in training efficacy, and shared controllers should be systematically designed to beneficially influence motor skill acquisition.

Performance of the manual control task used in our 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 [12]. Our 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 response and adaptation to varying system dynamics will enable the improved design of shared control algorithms for our manual control task and other target applications.

It has been shown that humans can adapt their feedforward control commands over time [13,14]. This adaptation can be viewed as successful training of a new skill. Control parameter adaptation during object manipulation was observed by Huang et al. [15] in a recent study of online control during object manipulation. They investigated a simple rhythmic object manipulation task in a virtual environment and determined that participants could identify and excite distinct virtual system natural frequencies with visual only, haptic only, or combined visual and haptic feedback. They observed that participants appeared to tune control parameters of a general feedback strategy.

We hypothesize that the ability to learn new motor skills depends on the ability to form a control model, and to tune control parameters. To tune control parameters, one must perceive the dynamic behavior of the excited system. To this end, we investigate manipulation of second-order dynamic systems, which can be characterized by their natural frequency. In our previous studies we determined the just-noticeable-difference (JND) for natural frequency of virtual second-order dynamic systems [16]. The objective of the current paper is to determine whether amplitude or phase cues are the primary cues for identification of a controlled system's dynamic behavior when exciting the system at its resonant frequency. To this end, we explore the ability of humans to resonate virtual mechanical systems with distinct natural frequencies, which was observed by Huang et al. [15]. We investigate the effects of magnitude and phase cues, and feedback modality, on the human's ability to adapt their control commands for a manually excited virtual second-order system. We employ a "catch trial" procedure, which first enables the participants to adapt to the dynamics of the nominal system. Then, in randomly selected trials, some features of the system are changed in order to monitor the participants' ability to identify the new systems that differ in magnitude cues or phase cues or both when compared to the nominal system.

The remainder of the paper is organized as follows: Experimental methods are explained in Sec. 2 and results are presented in Sec. 3. The paper concludes with concluding remarks in Sec. 4.

2 Methods

2.1 Experimental Setup and Virtual Environment

The experimental setup consisted of a desktop computer, a monitor screen and a two degree-of-freedom force feedback haptic device (IE2000, Immersion Corp.). Participants sat in front of the monitor screen and held the joystick of the haptic device with their dominant hand. The elbow of the participants was supported to obtain a natural and comfortable holding posture, and the entire setup was isolated using partition walls (Fig. 1). The visual cues were updated at a rate of 60 Hz on the computer screen while the haptic rate was set at a typical 1000 Hz. Participants wore noise cancellation headphones playing pink noise to mask possible auditory cues from the environment and the hardware.

During the experiment, two rectangular masses were displayed on the computer screen (see Fig. 1). The motion of one mass, m_1, was directly coupled with the joystick motion. The extreme positions of the joystick corresponded to the extreme positions of m_1 on the computer screen, thus creating a one-to-one mapping between the joystick and m_1. The second mass, m_2, was connected

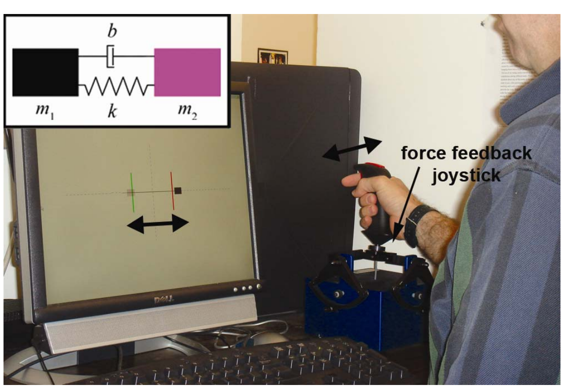

Figure 1. Experimental setup and virtual environment. (inset) A virtual two mass system connected by a spring-damper system.

to m_1 by a virtual spring and damper, thus indirectly controlling the motion of m_2 with the joystick motion. The instantaneous states (position, velocity and acceleration) of m_2 were calculated by the following second-order dynamic equation using Euler's method of numerical integration,

$$\ddot{x}_2 + 2\zeta\omega_n\dot{x}_2 + \omega_n^2 x_2 = 2\zeta\omega_n\dot{x}_1 + \omega_n^2 x_1 \qquad (1)$$

where, $\dot{x}_1$ and x_1 are respectively the velocity and displacement of m_1 and $\ddot{x}_2$, $\dot{x}_2$ and x_2 are acceleration, velocity and displacement of m_2. ω_n is the natural frequency of the second-order system and ζ is the damping ratio. The physical mass, damping and friction of the joystick were assumed to be negligible, since the joystick is a high-fidelity impedance-type haptic interface. Hence, throughout the discussion, the human is assumed to be a perfect position source for the haptic device. The forces (torque) applied at the motors of the haptic device, F, was calculated by

$$F = b(\dot{x}_2 - \dot{x}_1) + k(x_2 - x_1) \qquad (2)$$

where b and k are the damping coefficient and spring stiffness connected between m_1 and m_2. The natural frequency of the system was defined as $\omega_n = \sqrt{k/m_2}$ and the damping ratio was $\zeta = b/2\sqrt{km_2}$.

2.2 Procedure

Four healthy male students of Rice University (S1-S4, 18-32 years old, avg. 23 years) participated in the study. Three participants (S1-S3) were right handed and had prior experience with haptic devices. No participant reported any sensory or motor impairment. All participants signed consent forms approved by the IRB of Rice University. Each participant completed two sets of five-day testing with one type of sensory feedback presented in each set. Daily testing did not last more than 45 minutes with sufficient rest in the testing period.

Participants were asked to smoothly oscillate m_1 at the natural frequency of the virtual second-order dynamic system by moving the joystick along the x-axis in a sinusoidal manner throughout 10-second long trials. The participants were told that if the excitation was at the natural frequency of the virtual second-order system, the amplitude of oscillations of m_2 would grow largest for constant amplitude excitation of m_1. To facilitate constant amplitude excitation, two vertical green bars (±0.2 screen units apart from the center of the screen, corresponded to about ±10 degree of joystick displacement from the neutral center position) were displayed during every trial. If m_1 moved beyond a bar, the color of the corresponding bar was changed to red and remained red until the mass was brought back within the bars. In order to ensure that the excitation was constrained to move only along the x-axis, a resistive damped-cubic-stiffness force field was applied along the y-axis. At the end of the trial, the frequency spectrum of the last 8 seconds of hand oscillation was calculated by Fast Fourier Transform (FFT). As performance feedback, a message indicating if participant's hand oscillation was greater than, lower than or within 5 percent of the system natural frequency was displayed so that the participant could increase, decrease or keep same their input frequency.

Four experimental conditions (C1-C4) were tested. C1 was the training or learning phase, in which participants familiarized themselves with a nominal system. C2, C3, and C4 were conditions with catch trials. In C2, the virtual system's physical parameters were selected such that the target systems had either higher or lower natural frequency from the nominal system, while maintaining the same damping ratio and gain. In C3, three pairs of target systems were considered. The systems in the first two pairs had natural frequencies equal to the nominal natural frequency but

Table 1. Summary of exp. conditions and system parameters

Sys ID	Exp. Cond	# of trials	change in	mass (kg)	stiffness (N/m)	ω_n (Hz)	ζ	gain	delay (msec)	Fig.2 panel
0	C1	40/20	N/A	3	120	1	0.1	1	0	(a)
1a	C2	120	k	3	240	1.42	0.1	1	0	(b)
1b				3	60	0.71	0.1	1	0	
2a			m_2	1.5	120	1.42	0.1	1	0	
2b				6	120	0.71	0.1	1	0	
3a			k- m_2	2.15	173	1.43	0.1	1	0	
3b				4.25	85	0.71	0.1	1	0	
4a	C3	360	ζ	3	120	1	0.2	1	0	(c)
4b				3	120	1	0.05	1	0	
5a			gain	3	120	1	0.1	2	0	(d)
5b				3	120	1	0.1	0.5	0	
6a			m_2-gain	1.5	120	1.42	0.1	2.68	0	(e)
6b				6	120	0.71	0.1	4.93	0	
7	C4	120	delay	3	120	1	0.1	1	250	(f)
8				1.5	120	1.42	0.1	1	186	

shifted in magnitude by changing either the damping ratio or the gain (the gain corresponded to a constant multiplied by the two terms on the right hand side of Eq. 1). The third pair had target systems with higher and lower natural frequencies, whose magnitudes were shifted such that the two target systems and the nominal system shared a common magnitude at the resonant frequency of the nominal system. In C4, a delay was incorporated between the two masses that resulted in a shift in phase.

C1 was tested at the beginning of each test session. On the first day, 40 trials of C1 were completed, while on the later four days of testing, 20 trials were completed in order for the participants to reach the performance level achieved at the end of the first day. If the input frequency for 8 out of last 10 trials was not within the 5-percent performance range, then the participants were asked to complete 10 more trials until the performance goal was met. After C1, participants completed one run of C2, followed by three runs of C3 and finally one run of C4, with only one run completed on a given day. Each run had 120 trials, divided into twelve blocks of ten trials each. Nine out of ten trials were the same as in C1, while one randomly selected trial from the last five trials was a "catch trial". In the catch trial, one or more system parameters were changed to generate different magnitude and/or phase cues. The purpose of the catch trial was to observe human adaptation to target dynamic systems which were different than the adapted nominal system.

In C2, three pairs of target systems were tested. The spring stiffness, the mass of m_2, or both stiffness and mass were changed to obtain the target frequencies as detailed in Table 1. Bode plots of the three systems at two target natural frequencies are shown in Fig. 2b. The magnitude and phase plots of these systems overlapped, but resulted in different torques applied at the device motors. Each target system was randomly presented twice in C2. In C3, system parameters were selected to test three cases. The first case presented target systems with higher and lower damping ratios (Fig. 2c). The second case presented target systems with higher and lower gains (Fig. 2d). In the third case, physical system parameters were selected such that the target systems and the nominal system shared a common magnitude point at the resonance peak of the nominal system (Fig. 2e). Trial arrangement of C3 was similar to C2, i.e., twelve catch trials were presented in a run of 120 trials, with each target system randomly presented twice in a run. Three runs of C3 were tested in three consecutive days, resulting in six repetitions of the six target systems. In C4, the phase of the systems was changed by introducing a time delay in the simulation. In one case, a time delay of 250 msec was introduced to the nominal system, resulting in a phase lag of 90 degrees. In the other case, a delay of 186 msec was incorporated in the system with higher natural frequency such that the target system and the nominal system had the same phase. The frequency responses of the two target systems are shown in Fig. 2f. Each target system was randomly presented six times in a 120 trial run.

A summary of system parameters, number of trials used in the experimental conditions, and associated frequency response plots are detailed in Table 1. System 0 was the nominal system. Systems 1, 2 and 3 were three equivalent target systems used in C2, where (a) indicates the high resonance systems and (b) the low resonance systems. Systems 4, 5 and 6 were used in C3 and systems 7 and 8 were presented during C4. Systems 4, 5 and 7 had the same natural frequency as the nominal system while systems 6 and 8 had different natural frequency from the nominal system. Systems 4 and 5 had the same phase but were shifted in magnitude at the 1 Hz nominal resonance frequency. System 7 had the same magnitude but the phase was different than the nominal system at the resonance frequency. These target systems were used to determine if changing either the magnitude or phase cue affected participants' adaptation to the nominal system. Systems 6 had the same magnitude but different phase, whereas system 8 had different magnitude and same phase as the nominal system at the resonance frequency. These systems determined if changing either the magnitude or phase cue would yield the same behavior as when both cues were changed (target systems of C2). The parameters for the nominal system remained the same throughout the four conditions and are shown in Table 1. The Bode plot of the

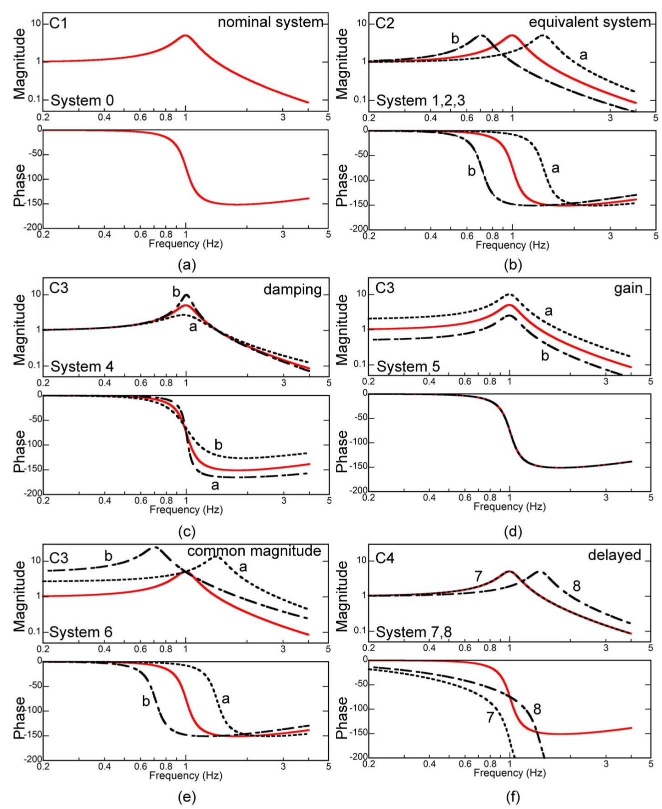

Figure 2. Bode (magnitude and phase) plots of second-order systems. (a) nominal system, (b) equivalent systems of C2, (c) systems differ in damping ratio, (d) systems differ in gain, (e) systems with common magnitude at resonance, and (f) delayed systems of C4. Bold solid curve in each panel represents frequency response of the nominal second-order system.

nominal system is shown in Fig. 2a. The system had a natural frequency of 1 Hz, where the magnitude ratio was about 5 and phase shift was about -73 degrees.

All experimental conditions were tested with visual-only (V) feedback and with visual and haptic combined (V+H) feedback. In the V feedback cases, the two masses were graphically displayed on the computer screen. In the V+H feedback cases, the visual feedback was accompanied by the dynamical forces presented through the force feedback haptic device. The order of the feedback conditions was randomized among participants, but for one sensory feedback modality all four conditions associated with the feedback were completed first and then the conditions with the other feedback were completed.

2.3 Data Analysis

Force, displacement, and velocity data were collected at a rate of 50 Hz during every trial. The hand displacement data was processed in MATLAB using time-frequency scripts. The spectrogram profiles were obtained and the frequency with the largest intensity at each sample instant was extracted. A plot of the largest frequency as a function of the duration of a trial showed varying hand motion frequency while controlling the nominal or the target system. Trajectory error is introduced as a measure of performance, defined as the absolute difference between the hand frequency profile and the ±5% bounds of natural frequency of the target system accumulated across a 10 second trial. Statistical tests such as analysis of variance and Student's t-test were used to determine differences among systems, conditions and sensory feedback at a 95% significance level (i.e., α=0.05).

3 Results

In this study, a human's ability to adapt to the natural frequency of a dynamic system is investigated. Performance varied among participants but similar trends were observed for the various conditions and feedback modalities. Thus the data was pooled across participants, and averages and standard errors (error bars) are presented. Figure 3 shows the principal hand frequency component across 40 trials tested on the first day with the nominal system (C1). Each data point represents the average of hand input frequency. The solid line shows the nominal natural frequency and dashed lines mark the ±5% bounds of the natural frequency. Open markers represent the mean with V feedback and solid markers show V+H feedback means. In any feedback condition, participants could successfully detect the resonance frequency and were able to excite the system at this frequency.

Figure 4 shows the participants' ability to identify and shift their excitation to the natural frequency of the target systems during catch trials with (a) V and (b) V+H feedback. Bold dashed lines present target natural frequencies of 0.71 Hz and 1.42 Hz. The three dashed time-frequency profiles show hand frequency profiles with the three target systems at each natural frequency. The solid profiles are the mean of the three profiles. On average,

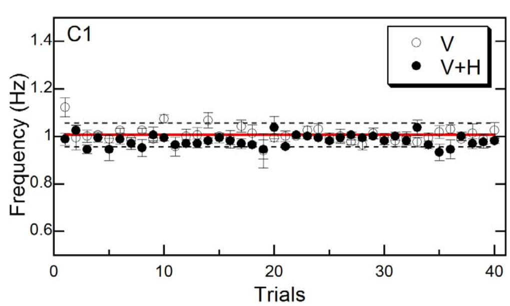

Figure 3. Average hand frequency on first day of testing in C1 with V (open circles) and V+H feedback (solid circles).

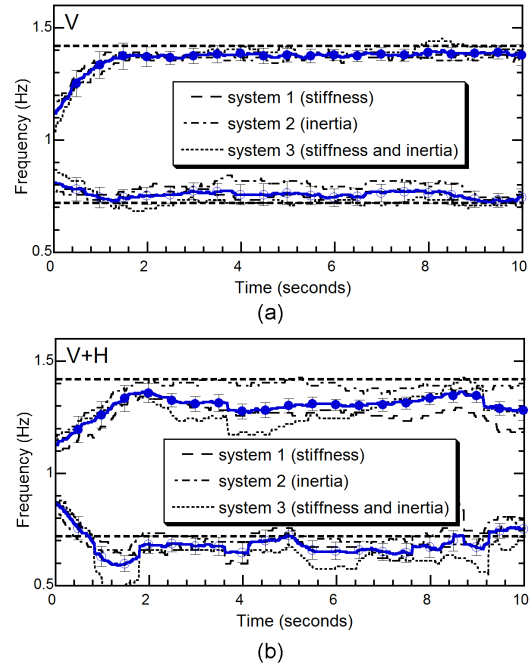

Figure 4. Time-frequency profiles of hand displacement in C2 with (a) V feedback and (b) V+H feedback.

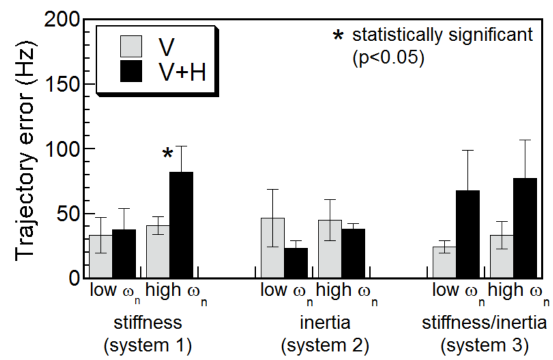

Figure 5. Average trajectory errors for three equivalent systems presented in C2. An asterisk indicates the mean error is significantly different for feedback modality.

the hand frequency converged towards the target natural frequencies with V and V+H feedback, although deviation of hand frequency with V feedback appears smaller than that with V+H feedback. Figure 5 shows trajectory errors of hand frequency with the two feedback modalities. The error bars represent the standard error of the mean. Large trajectory errors were mainly due to the inability of S4 to converge to the target frequencies. Other participants showed mixed trends. A repeated two-way ANOVA (feedback and equivalent systems as within subject factors, eight data points at each factor) failed to show significant effects of feedback and equivalent systems on the trajectory errors for the systems with low natural frequency ($p>0.05$), and for the systems with high natural frequency only the feedback modality has a significant effect [$F(1,7)=7.09$; $p=0.03$]. A pairwise two-tailed t-test (df=7) was used to test the significance between the trajectory error with the two feedback conditions and an asterisk on top of the bars indicates if the mean error was significantly different with V and V+H feedback.

Figure 6 shows hand time-frequency profiles in C3 and C4 with (a) V and (b) V+H feedback. Each profile is the average time-frequency profile of four participants. The profiles for systems 4, 5 and 7 (Fig. 6a and Fig.6b) show that participants were able to identify the resonant frequency of the target system and provided the corresponding input frequency, regardless of changes in magnitude and phase cues. Participants maintained their input excitation frequency very close to the nominal frequency with different magnitude cues (systems 4 and 5) almost from the beginning of a trial, except when the system was incorporated with a delay. When the phase was different due to time delay (system 7), participants had difficulty converging to the nominal frequency. Figure 7 shows the mean trajectory error as the height of vertical bars in catch trials of C3 and C4 with V and V+H feedback. A pairwise two-tailed t-test (df=23) was used to test the significance between the trajectory error with the two feedback conditions. An asterisk on top of the bars indicates if the mean error was significantly different with V and V+H feedback. Large errors with the delayed system (system 7) indicate participants' unfamiliarity with the delayed system.

When the natural frequencies of the target systems were different than the nominal system, the participants' excitation frequency converged towards the target natural frequency. However, the participants, on average, were not able to accurately identify the target natural frequency. This was indicated by large trajectory errors in Fig. 7. With respect to the feedback modality, pairwise t-tests on individual target systems failed to show significant differences in trajectory errors with the two feedback conditions, except for the target system with high gain (system 5a), where the trajectory error was significantly higher with V feedback, and with delay (system 7), where the trajectory error was higher with V+H feedback.

Visual inspection of the trajectory error data showed that the error is greater when only one factor, such as magnitude or phase, was changed compared to cases where both factors were changed (as in C2) and the t-test showed significance among such target systems with both feedback (comparison of low frequency systems of C2 against system 6b, df=46, and comparison of high frequency systems of C2 against systems 6a and 8 combined, df=70).

4 Concluding Remarks

In this study, we investigated the effects of magnitude and phase cues on human motor adaptation while exciting a virtual system with linear second-order dynamics. The motivation for this study is to determine the factors affecting the adaptation to and excitation of the second-order system dynamics, with the intention of taking advantage of this information to design more effective haptic training schemes. In particular, if the factors affecting human motor control and adaptation during manipulation are properly identified, assistance algorithms can be optimized by modifying the coupled system dynamics to emphasize the dominant factors and to help users to better focus on the important aspects of the task.

In the experiment, the participants were first over-trained with a rhythmic task, in which they were required to smoothly oscillate a linear second-order system at the resonance frequency determined according to the nominal set of physical parameters (C1). Participants acquired the skill fairly quickly and could successfully excite the system at the proper frequency with both types of sensory feedback. Hence, results confirm previous observations in [15] where participants were also able to excite a similar system at its resonance frequency for both feedback modalities. The oscillations about the target frequency are more pronounced in the V+H

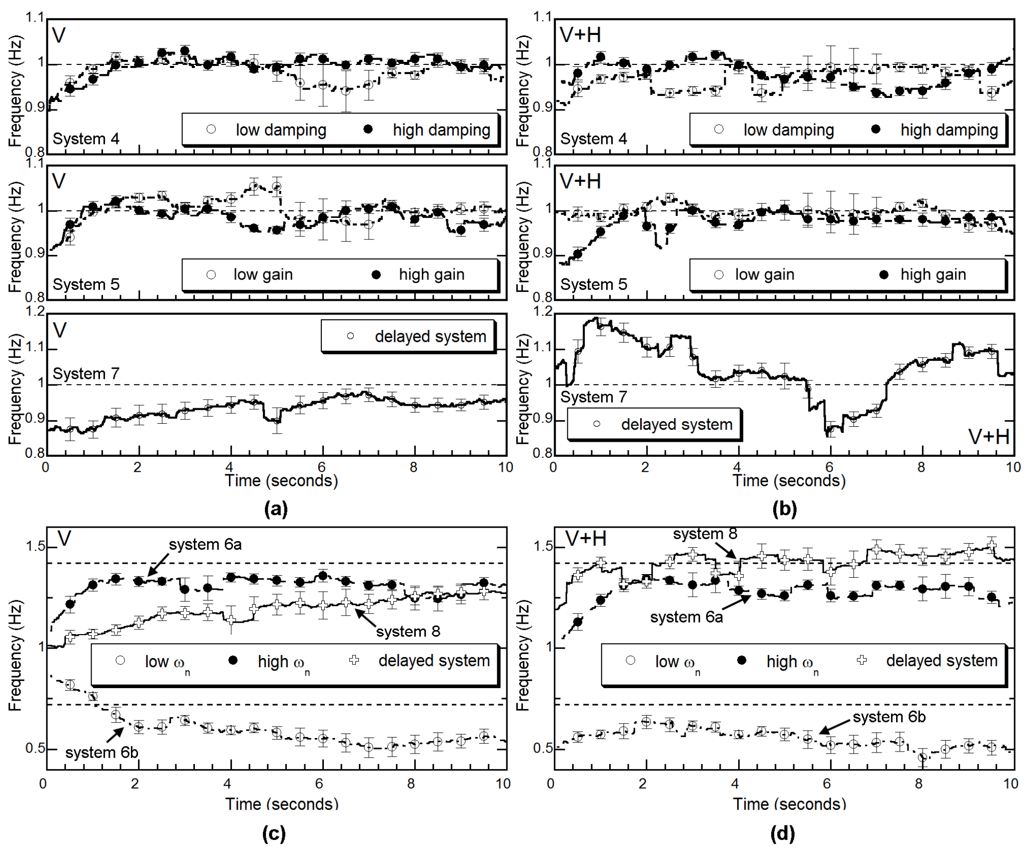

Figure 6. Average time-frequency profiles in C3 and C4. Panels on the left are with V feedback and panels on the right are with V+H feedback. Panels (a) and (b) are for target systems with the natural frequency same as the natural frequency of the nominal system and (c) and (d) are for target systems with the natural frequency different from the nominal system.

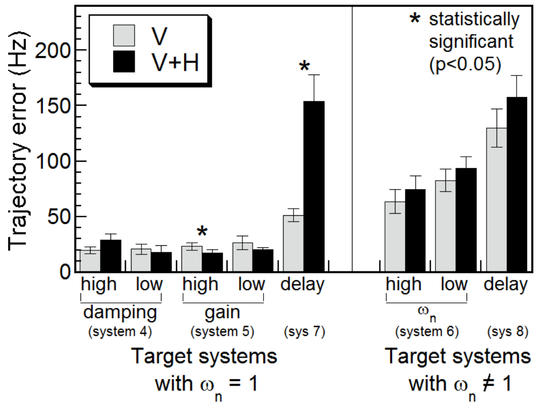

Figure 7. Average trajectory error in systems presented in C3 and C4 pooled across participants. Pairs of vertical bars on the right and left are for systems with different and same natural frequency, respectively, as the nominal system. An asterisk indicates the mean error is significantly different with the two feedback.

case than in the V case. Such a response is expected since haptic feedback is a bilateral modality and physical coupling of the human with the system dynamics always introduces such artifacts, since the human can no longer perform as a pure motion generator.

Once the participants were trained and got acquainted with the nominal system, they were unexpectedly presented with target systems having different parameter sets. When the gain or damping factor of the nominal system is modified while keeping the natural frequency identical to that of the nominal system (systems 4 and 5 of C3), the excitation frequency of the participants was not affected. This observation implies that participants are not only capable of exciting a linear second-order system at its resonance frequency, but this ability is robust with respect to changes in the magnitude cues when the natural frequency is kept unchanged. The more oscillatory response in the V+H case is again due to physical coupling, rendering infeasible the role of the human as a pure motion source.

When the participants were presented with target systems having higher or lower natural frequencies than the nominal system but with the same gain (C2), achieved by modifying stiffness and/or mass parameters, they were able to identify the target natural frequency and converge to this value within about 2 seconds. For this condition, systems having the same frequency response but resulting in different force feedback magnitudes are also tested, and no significant difference is observed between these parameter sets. This observation implies that the identification and adaptation processes are independent of force scaling for the range of values tested. These results are consistent with the study by Huang et al. [15], in which participants performed a similar system identification task, but unlike [15], the present study showed no significant difference in performance between the two sensory feedback modalities. The dissimilarity in the results could be that in the present study, the participants were first over-trained with the dynamics of the nominal systems, whereas in [15], the natural frequencies were changed in every trial.

When both the natural frequency and the gain of the target system are changed in catch trials (systems 6a and 6b in C3), the participants were still able to identify the change in the target frequency but their convergence to the target frequency was unsatisfactory. Given the earlier observations that participants can adapt to these target frequencies when the gain level is kept constant, and the fact that participants can robustly excite the system at its natural frequency for the gain range tested, it appears that gain level has an important effect during the adaptation to a new target frequency. This implies that participants are making use of magnitude amplification cues for adaptation to new target frequencies.

Finally, changes in phase cues are tested by introducing time delay to the target systems (C4). One system has the same natural frequency as the nominal system, while the other has a higher natural frequency. All systems have the same gain levels. The performance of the subjects is poor with delayed systems. This is an expected result since control of time delayed system is generally more challenging, and humans do not manipulate such systems very often in their everyday life.

To summarize, our results indicate that participants have a persistent ability to perform system identification of the dynamic systems which they control, regardless of the cues that are conveyed to them. In the future, we intend to further investigate human motor adaptation and the effects of parameters on the time rate of adaptation in order to improve the efficacy of virtual assistance methodologies for training and rehabilitation with haptic feedback.

Acknowledgements

This work was supported in part by the Office of Naval Research Grant number N00014-04-1-0517 and NSF IIS-0448341. The second author was supported by TUBITAK 107M604 grant.

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