Framework for human haptic perception with delayed force feedback

Fu, Wei; van Paassen, Marinus M.; Abbink, David A.; Mulder, Max

DOI
10.1109/THMS.2018.2885401

Publication date
2019

Document Version
Accepted author manuscript

Published in
IEEE Transactions on Human-Machine Systems

Citation (APA)
Fu, W., van Paassen, M. M., Abbink, D. A., & Mulder, M. (2019). Framework for human haptic perception with delayed force feedback. *IEEE Transactions on Human-Machine Systems*, *49*(2), 171-182. Article 8585042. https://doi.org/10.1109/THMS.2018.2885401

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Framework for Human Haptic Perception With Delayed Force Feedback

Wei Fu, *Student Member, IEEE*, Marinus M. van Paassen, *Senior Member, IEEE*, David A. Abbink, *Senior Member, IEEE*, and Max Mulder, *Member, IEEE*

***Abstract*—Time delays in haptic teleoperation affect the ability of human operators to assess mechanical properties (damping, mass, and stiffness) of the remote environment. To address this, we propose a unified framework for human haptic perception of the mechanical properties of environments with delayed force feedback. In a first experiment, we found that the delay in the force feedback led our subjects to underestimate all the three mechanical properties. Moreover, subjects perceived additional damping or stiffness properties that the environment did not possess. It was found that the extents of these changes in the perception depend on both time-delay magnitude and the frequency of the movement with which subjects interacted with the environment. This was due to the fact that subjects were not able to distinguish the delay-caused phase shift in the movement–force relation from changes in the three mechanical properties. Based on this, we proposed a framework that allowed for a prediction of the change associated with delayed force in perception of mass–spring–damper environments. The framework was corroborated by a second experiment, in which a combined mass–damper environment was tested. Our hypotheses that the delay would cause subjects to underestimate the mass but overestimate the damping and that the extents of the under- and overestimation would differ between individual subjects due to the difference in the interaction frequency were confirmed.**

***Index Terms*—Haptic perception, haptics, mechanical properties, teleoperation, time delay.**

I. Introduction

TELEOPERATION systems allow the human operator to accomplish tasks on a remote or hazardous site without the need for physical presence. This field has prompted the continuous development since the mid of the last century [1]–[4]. Providing haptic force feedback that directly reflects the environment properties is essential for maximizing the potential of teleoperation systems. It enables the human operator to sense mechanical properties—damping, mass, and stiffness—of the environment.

Manuscript received January 22, 2018; revised September 27, 2018; accepted December 2, 2018. *(Corresponding author: Wei Fu.)*

W. Fu, M. M. van Paassen, and M. Mulder are with the Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands (e-mail: W.Fu-1@tudelft.nl; M.M.vanPaassen@tudelft.nl; M.Mulder@tudelft.nl).

D. A. Abbink is with the Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: D.A.Abbink@tudelft.nl).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/THMS.2018.2885401

A system with poor transparency may adversely affect the operator's perception of the properties of the environment, limiting the performance on the task [5]. Designing high-transparency teleoperation systems is, therefore, of primary importance [6]. However, the information of damping, mass, and stiffness is inevitably distorted as the force feedback passes though different mediums (slave, communication channel, and master device) before reaching the operator. Effective mitigation of these distortions, in particular those caused by time delays, requires us to first understand *how* these mediums affect the perception of the mechanical properties.

Many studies attempted to understand the effect of time delays [7]–[12]. It seems that humans cannot separate the delays from the perception of the mechanical properties. Instead, the delay in the force leads to improper estimations of the environment properties [7], [8]. During continuous contact with an elastic force field, humans underestimate the spring stiffness when the delay exists [8], [11], [13]. However, such an underestimation disappears in the case of small delays (up to 30 ms) [10]. Apparently, the reported effects related to different time-delay magnitudes on the haptic perception of spring stiffness are inconsistent. Moreover, a detailed exploration of the effect of delays on perceived damping and mass properties is still lacking.

To this end, we aim to establish a clear understanding of the effect of the delayed force feedback on human perception of *damping, mass, and stiffness* properties of linear dynamic environments. This study consists of two user studies. In a first experiment, we investigate the variation associated with the time-delay magnitude in the perception. Attempts are also made to explore the correlation between the delay-caused perception changes and the frequency at which the interaction between the human operator and the environment occurs. The experiment allows us to reveal the fundamental principle that governs the perception change associated with delayed force feedback. On the basis of the principle revealed, we establish a framework that unifies the effect of delays on the perception of all three mechanical properties. It also provides a straightforward visualization that allows for a prediction of the perception change associated with delayed force feedback. With a second experiment, we tested its predictions and showed that knowledge of both the time delay and the interaction frequency is sufficient to describe the assessment of the mechanical properties perceived with delayed force feedback.

The remainder of the paper is organized as follows: Section II provides details about the first experiment. Section III gives the results of the experiment and the analysis of the results. In Section IV, we reveal the principle behind the change caused

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

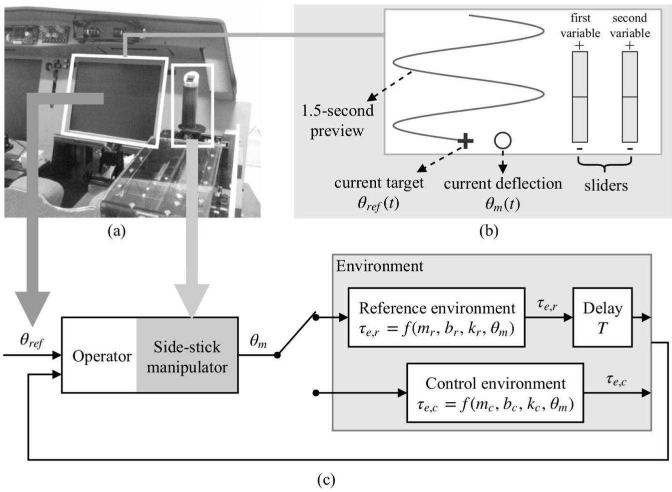


Fig. 1. (a) Devices used for the experiment. The LCD screen and the side-stick manipulator are marked by white boxes. (b) Contents shown on the LCD screen. The left-hand side part is the visual display for the tracking task. The preview curve moves downward as time progresses, and the two symbols "+" and "○" only move horizontally (see Section II-C). The two bars on the right-hand side are used for the adjustment of the parameters of the control environment (see Section II-D). (c) Schematic diagram of the experimental procedure.

by delays in the mechanical properties perceived. A unifying framework is proposed in Section V. Section VI elaborates on the second experiment that corroborates the proposed framework. Section VII discusses findings of this study, the limitation of this paper, and the future work. Section VIII concludes the contributions of this study.

II. Experimental Methods

An experiment was conducted to measure human haptic perception of damping, mass, and stiffness properties when force feedback was delayed. It was performed by 12 participants (10 male and 2 female), ranged in age from 24 to 55 years with a mean of 33.7, all right handed and without a history of impairments in moving the arm or hand. Participants were graduate students and academic staff members of TU Delft. All had sufficient knowledge about how each of these three mechanical properties feels, but were naive about the effect of the time delay on the perception of mechanical properties. The study was approved by the Human Research Ethics Committee of TU Delft, and informed consent was obtained from participants before the experiment.

In this experiment, the effect of the magnitude of the delay time was studied. We also studied the frequency dependence of the effect of delays, by asking subjects to apply sinusoidal excitation movements at different frequencies.

A. Procedure

Fig. 1(c) shows a schematic diagram of the experiment. The subject (the operator) haptically perceives one of two environments through a side-stick manipulator. One environment is a *reference* environment, and the other is a *control* environment. Both environments consist of a mass, damper, or spring load simulated with one degree of freedom in the lateral direction. Their forces in response to the manipulator movement can be expressed as

$$\begin{aligned}\tau_{e,j}(t) &= f(m_j, b_j, k_j, \theta_m)\\ &= m_j \cdot \ddot{\theta}_m(t) + b_j \cdot \dot{\theta}_m(t) + k_j \cdot \theta_m(t). \qquad (1)\end{aligned}$$

Here, the subscript $j \in \{r, c\}$, where r and c refer to reference and control, respectively. m, b, and k are the mass, damping, and spring coefficients. τ_e and θ_m denote the environment torque and the manipulator deflection angle. The force of the reference environment $\tau_{e,r}$ is delayed, whereas that of the control environment $\tau_{e,c}$ is not delayed.

The experiment has a "perceive and adjust" procedure. The subject initiates an experimental run by selecting one of the two environments. During each experimental run, the subject interacts with the selected environment using a prescribed sinusoidal manipulator movement. Such a manipulator movement will be realized by performing a tracking task. Each experimental run lasts for a fixed length of time. Details about the tracking task and the duration of the experimental run will be given later. After each run, the manipulator automatically moves back to the center, and the subject can adjust the mechanical properties of the control environment before he/she initiates another experimental run (see Section II-D for the tuning procedure). The subject is asked to repeat this procedure until the two environments are the same in the perceived damping, mass, and stiffness properties.

The simulated dynamics of the side-stick manipulator are the same for the two environments. Therefore, although the subject perceives the lumped dynamics of the manipulator and the environment, the dynamics of the manipulator will not affect the comparison between the two environments. The Appendix gives the manipulator dynamics and the information about the hardware in greater detail.

Section II-B gives the settings of the reference environment. The initial settings of m_c, b_c, and k_c of the control environment are taken to be identical to those of the reference environment. Their final values adjusted by subjects will be taken as the measurements, they will indicate the mechanical properties subjects perceived from the delayed reference environment.

Subjects were not informed that the force feedback from the reference environment was delayed. If our subjects are able to perceive the time delay and isolate it from the correct information of the mechanical properties, the three parameters of the control environment should remain at their initial settings. However, if the delay cannot be assessed separately, it will affect subjects' perception of the mechanical properties, and the three parameters will change.

B. Conditions

Three different reference environments were tested. To reduce complexity, each reference environment only possessed a single mechanical characteristic, i.e., damper, mass, or spring. Table I lists the settings of the three reference environments. All these settings chosen here are within the typical manipulator setting range for manual control tasks [14]. Note that in this paper, all the mechanical properties are expressed in a rotational coordinate system, the corresponding linear quantity can be derived using the distance from the effective grip point on the manipulator to the axis of rotation of the manipulator (90 mm, see the Appendix).

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE I
SETTINGS OF THE THREE REFERENCE ENVIRONMENTS

Environment	Damping b_r [Nm·s/rad]	Mass m_r [kgm^2]	Stiffness k_r [Nm/rad]
Damper	0.3	0	0
Mass	0	0.035	0
Spring	0	0	2.0

Two time delays $t_{d,i,(i\in\{1,2\})}$ ($t_{d,1} = 100$ ms, $t_{d,2} = 170$ ms) were studied. To investigate the frequency dependence of the effects of delays, we selected two frequencies for the prescribed sinusoidal manipulator deflection $\omega_{i,(i\in\{1,2\})}$ ($\omega_1 = 6$ rad/s and $\omega_2 = 8$ rad/s). A factorial combination of these two independent variables results in four conditions for each of the three reference environments. The duration of an experimental run was set to 7.35 s in the case of $\omega_i = 6$ rad/s and 5.5 s in the case of $\omega_i = 8$ rad/s.

C. Prescribed Manipulator Movement

To ensure that our subjects moved the manipulator at the desired frequency ω_i (and with that excited the environments at that frequency), they performed a preview tracking task [15] in each experimental run. The visual display of the tracking task was shown by an LCD screen in front of the subject, as can be seen from Fig. 1(a). Fig. 1(b) illustrates the tracking display in greater detail. The reference manipulator deflection is calculated according to

$$\theta_{\text{ref}}(t) = 0.37 \cdot \sin(\omega_i t). \tag{2}$$

In this paper, the manipulator deflection is given in radian. In the experiment, the first and last full cycle of this prescribed movement are used as fade-in and -out phases. The movement amplitude gradually increases from 0 to 0.37 during the fade-in phase, and decreases from 0.37 to 0 during the fade-out phase. To perform the tracking task, the subject needs to reduce the distance between the *current* manipulator deflection $\theta_m(t)$ [shown by "○" in Fig. 1(b)] and the current reference deflection $\theta_{\text{ref}}(t)$ (shown by "+"). The two symbols only move horizontally. The visual preview, shown as a winding curve, contains 1.5-s future information of the reference deflection. It moves downward as time progresses.

D. Tuning of the Control Environment

Rather than asking our subjects to adjust all three coefficients (b_c, m_c, and k_c) of the control environment, we reduce the complexity of the procedure through coupling the adjustments of m_c and k_c. This can be motivated from the frequency response function (FRF) of the control environment as

$$\begin{aligned} H_c(\omega) &= \frac{F_{e,c}(\omega)}{\Theta_m(\omega)} = m_c \cdot (j\omega)^2 + b_c \cdot j\omega + k_c \\ &= \underbrace{k_c - m_c \cdot \omega^2}_{\Re H_c(\omega)} + j \cdot \underbrace{b_c \cdot \omega}_{\Im H_c(\omega)}. \end{aligned} \tag{3}$$

Here, $F_{e,c}(\omega)$ and $\Theta_m(\omega)$ are the Fourier transforms of $\tau_{e,c}$ and θ_m. $\Re H_c$ and $\Im H_c$ are the real and imaginary parts of the complex-valued FRF.

Due to the tracking task, subjects will only excite the environment at a single frequency of ω_i. The force of the environment is determined by the FRF at this particular frequency. First, the real part of this complex number is determined by k_c and m_c combined, see (3). It generates a spring or inertia force in response to the movement, depending on its current sign [16]. When $\Re H_c(\omega_i)$ is positive, it generates a spring force of which the ratio to the displacement is $\Re H_c(\omega_i)$. The combination of k_c and m_c that yields a particular harmonic spring force is not unique. However, the harmonic spring forces generated by all combinations are equal to that generated by a pure spring with zero mass and a spring constant of $\Re H_c(\omega_i)$. A negative $\Re H_c(\omega_i)$ generates an inertia force that is directly proportional to the acceleration. Similarly, all combinations of k_c and m_c that generate a particular harmonic inertia force can be represented by a pure mass of $\Re H_c(\omega_i)/\omega_i^2$. Due to this characteristic and the fact that a system generates only one of the two forces (the spring and the inertia forces) at a single frequency, the adjustment of the mass and stiffness can be combined by means of the real part $\Re H_c$. Second, the damping is adjusted with the imaginary part $\Im H_c$, independent of the other two parameters. In the experiment, the computer calculates the three mechanical properties according to the following rule:

$$\begin{aligned} b_c &= \frac{\Im H_c(\omega_i)}{\omega_i} \\ k_c &= \begin{cases} \Re H_c(\omega_i), & \text{if } \Re H_c(\omega_i) \geq 0 \\ 0, & \text{if } \Re H_c(\omega_i) < 0 \end{cases} \\ m_c &= \begin{cases} 0, & \text{if } \Re H_c(\omega_i) \geq 0 \\ \dfrac{-\Re H_c(\omega_i)}{\omega_i^2}, & \text{if } \Re H_c(\omega_i) < 0 \end{cases}. \end{aligned} \tag{4}$$

In the experiment, $\Re H_c$ and $\Im H_c$ were labeled as the "first variable" and "second variable," respectively. Subjects could individually adjust these two variables, using two vertical sliders shown on the screen [see Fig. 1(b)]. Before the experiment, the relation between the two variables and the three mechanical properties was explained to subjects. All subjects received sufficient training for the adjustment of the mechanical properties.

III. RESULTS

In the experiment, our subjects performed the tracking task with considerable accuracy. The frequencies of the actual manipulator movement with regard to the two desired frequencies were 6.011 ± 0.032 and 8.019 ± 0.040 rad/s (mean ± std.), respectively. This indicates that the measurements accurately reflect the effects of the condition tested.

Each subject spent a similar amount of time on the adjustment of mechanical properties under all conditions. All finished the experiment with confidence that the two environments were perceived to be the same. The original mechanical properties of all the three reference environments were *under*estimated. In addition, the delay in the force feedback led our subjects to perceive each of the reference environments as having *one more* mechanical property. Additional spring stiffness was perceived from the delayed damper environment; an additional damping property was perceived from the delayed mass environment; and an additional property related to negative damping was perceived from the delayed spring. Different experimental conditions led to dif-

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
MECHANICAL PROPERTIES PERCEIVED BY SUBJECTS AND THE RESULTS OF STATISTICAL TESTS

Delayed Environment		Perceived mechanical properties, mean ± 95%CI				Factor Impact, DOF.: (1, 11)					
		t_d: 100 [ms] ω: 6 [rad/s]	t_d: 170 [ms] ω: 6 [rad/s]	t_d: 100 [ms] ω: 8 [rad/s]	t_d: 170 [ms] ω: 8 [rad/s]	$t_d * \omega$ F	$t_d * \omega$ Sig.	t_d F	t_d Sig.	ω F	ω Sig.
damper	b_c [Nms/rad]	.2499±.0089	.1475±.0075	.2126±.0116	.0437±.0124	106	.000	299	.000	210	.000
	k_c [Nm/rad]	0.931±.0357	1.547±.1044	1.586±.1455	2.253±.1071	.241	.633	84.5	.000	197	.000
mass	m_c [kgm^2]	.0275±.0015	.0176±.0013	.0236±.0008	.0070±.0013	17.7	.001	504	.000	111	.000
	b_c [Nms/rad]	.1205±.0066	.1814±.0060	.2073±.0070	.2811±.0084	2.13	.172	441	.000	598	.000
spring	k_c [Nm/rad]	1.690±.0586	1.011±.1030	1.423±.0939	0.435±.0825	23.9	.000	235	.000	64.9	.000
	b_c [Nms/rad]	-.195±.0087	-.285±.0119	-.180±.0106	-.233±.0055	32.6	.000	103	.000	51.8	.000

ferent extents of these changes in the perception. Table II lists the measurements of the mechanical properties perceived from each reference environment, i.e., the final values of b_c, m_c, and k_c of the control environment, along with the results from two-way repeated measures ANOVAs that indicate the effect of the factor tested. Note that in the table, the term 95% CI denotes the 95% confidence interval corrected for between-subject variability, and that a significance value of 0.000 means $p < 0.0005$.

A. Perception of Delayed Damper

The perceived damping b_c under all the four conditions is smaller than the reference damping of 0.3 N·m·s/rad. The effects of both the delay time t_d and the excitation frequency ω are significant: An increase in either t_d or ω causes more *under*estimation. This can be seen more straightforwardly from the left-hand side plot of Fig. 2(a). In addition, the red line drops faster than the blue line due to a significant interaction. This indicates that the change caused by t_d in the perception is more pronounced when ω increases.

The additional spring stiffness perceived by our subjects varies significantly with t_d and ω. As can be seen from the right-hand side plot of Fig. 2(a), higher t_d or ω significantly increase the level of the spring stiffness perceived.

B. Perception of Delayed Mass

The delayed mass was *under*estimated under all conditions. Greater underestimations occurred when either of t_d or ω increased, as can be seen from the left-hand side plot of Fig. 2(b). In addition, a significant interaction leads to the faster drop of the red line, indicating that the effects of the time delay is amplified when the frequency increases.

Under different conditions, different amounts of *additional* damping were perceived from the delayed mass. The increase in b_c due to a larger t_d or ω as shown in the right-hand side plot of Fig. 2(b) was significant.

C. Perception of Delayed Spring

The delay in the force feedback led our subjects to *under*estimate the spring stiffness of the reference spring environment. Moreover, subjects related a part of the environment response to negative damping. These two mechanical properties perceived varied significantly with both t_d and ω, as can be seen from Fig. 2(c). Moreover, a strong interaction was revealed: The slopes of the two lines in both plots are different. Again, this indicates that the effect of t_d depends on ω.

D. Discussion

The results clearly demonstrate that the time delay affects the human perception of all the three mechanical properties. It appears as if the delay "shifts" a part of the perception of the original property toward the perception of another. This shift in perception depends on both the time delay and the excitation frequency. In conclusion of the impacts of these two factors: Different time delay magnitudes have different effects on the dynamics perceived, and changes in perception are more pronounced with larger delays. In addition, the effect of the time delay varies with the frequency at which the environment is excited, demonstrating a clear frequency dependence.

IV. BLACK-BOX MODELING PRINCIPLE AND EVALUATION

In this section, we will investigate how the mechanical properties were estimated by our subjects, and reveal the principle behind the perceptual changes caused by the experimental variations. We will first carry out an analysis in the time domain, then visualize it in the frequency domain. The findings will then be verified by the experiment results.

A. Principle Behind the Perception Change

1) Investigation Into the Subjects' Strategy: After the experiment, we asked our subjects to explain their strategies for adjusting the mechanical properties. We found that all subjects were unaware of the delay in the force feedback from the reference environment. In order to match the damping of the two environments, subjects compared the forces that they perceived at around the center of the manipulator movement (i.e., the point where the deflection angle is zero, $\theta_m \approx 0$). They related the amount of this force to the damping level. Both the mass and stiffness levels were estimated at the extremes of the manipulator movement (the peaks of the deflection). At the extremes, the force pulling the manipulator back to the center (elastic force) was related to the stiffness level, whereas the force needed to change the direction of the manipulator velocity (inertia force) was related to the mass level. This indicates that our subjects estimated the mechanical properties on the basis of the correlation between the movement and force, in line with the findings reported in [7], [17]–[19].

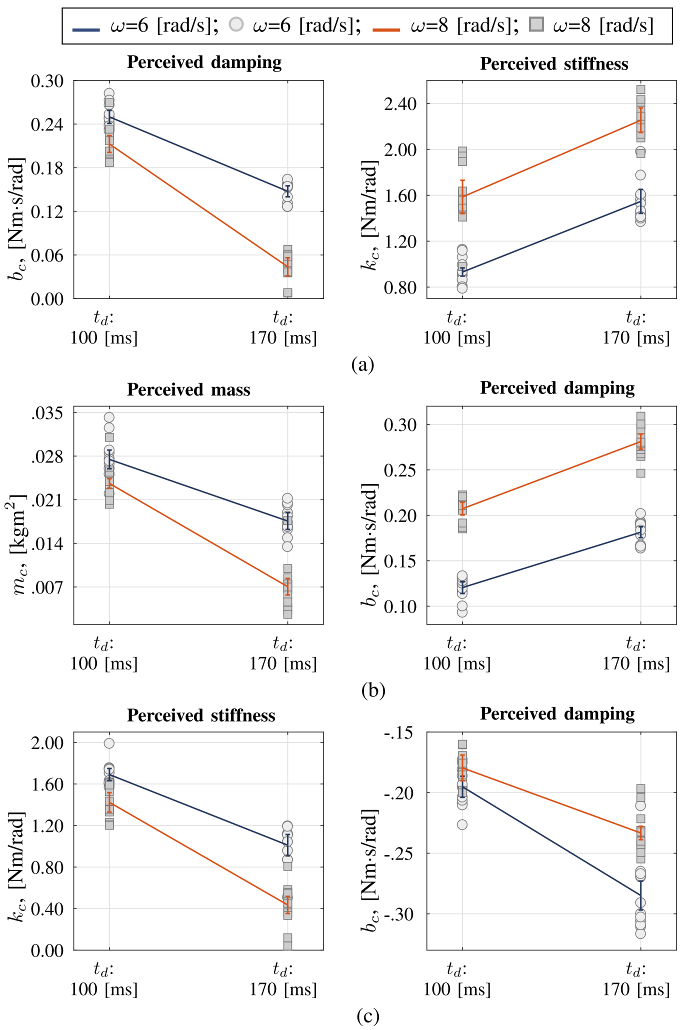


Fig. 2. Mechanical properties subjects perceived from the delayed reference environments. The data are shown with mean and 95% confidence interval corrected for between-subject variability (represented by the bars). The symbols (square and circle) represent the measurements from individual subjects. (a) Delayed damper environment. (b) Delayed mass environment. (c) Delayed spring environment.

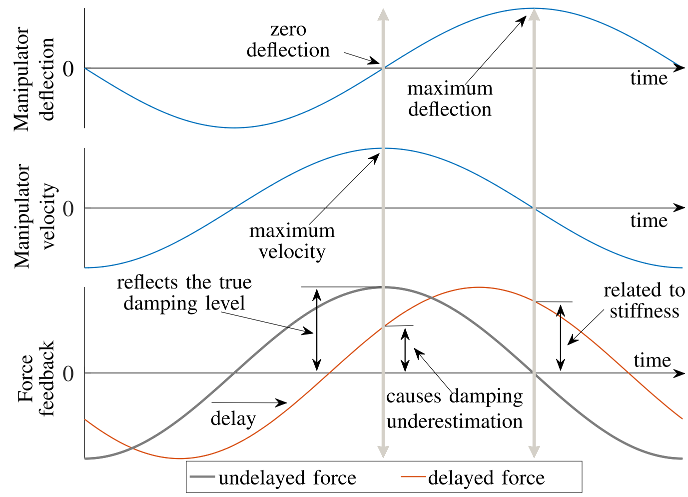


Fig. 3. Illustration of the relation between the manipulator deflection (top), manipulator velocity (middle), and the force feedback (bottom), for a pure damper environment. For a clear comparison, only one cycle is shown.

2) Time-Domain Analysis: For an undelayed environment, the forces felt at the deflection angles mentioned earlier, indeed, reflect the true levels of the corresponding properties. For example, consider a pure damper environment that possesses a damping of b and zero mass and zero stiffness. Here, we use b instead of an explicit numerical number for the damping. This is because the example shown in the figure is not limited to any particular value of damping.

When the human operator moves the manipulator with a sinusoidal profile, as prescribed during the experiment, the velocity profile of the manipulator is a cosine, which reaches the peak when the deflection angle is zero, see Fig. 3. When relating the force perceived at this point to the damping, one is actually estimating the ratio of this force to the velocity maximum. Because the force caused by the damping is proportional to the velocity, if the force feedback is not delayed, it will indeed be perfectly "in phase" with the manipulator velocity, as can be seen from the force profile shown as the gray curve in Fig. 3. Therefore, the damping estimation on this basis approximates the true level of damping.

However, due to the time delay, the force feedback from the damper environment *does not align*—is not "in phase"—with the manipulator velocity. As can be seen from the force profile shown as the red curve, the force at the center is smaller, so does its ratio to the maximum velocity. This reduced ratio results in an *underestimation* of the environment damping. In addition, the delay causes resistant forces at the two extremes of the manipulator deflection, leading subjects to perceive a *nonzero* environment stiffness. This explains the "shifts" in the perception observed earlier.

3) Frequency-Domain Analysis: From the aforementioned analysis, we conclude that our subjects based their estimation of the environment properties on the phase characteristics between their actions on the manipulator (the manipulator movement) and the force feedback they received. A time delay in the force feedback causes this phase characteristic to change, leading our subjects to perceive different mechanical properties. With regard to the example shown in Fig. 3, an undelayed environment that possesses a lower damping and a nonzero stiffness can generate exactly the same phase change. Hence, the perception changes observed in the experiment are due to the fact that subjects *cannot distinguish* between the phase changes caused by the delays and the phase changes resulting from changes in damping, spring, or mass properties. This principle can be interpreted as a "black-box estimation problem," where the candidate model is always a single mechanical system no matter what the actual structure of the system is. That is, humans are inclined to always interpret what they feel as a mass–spring–damper system, no matter whether the force feedback they obtain is delayed or not.

To better understand this, we describe the correlation between the position and force of a delayed mass–spring–damper system with the FRF as

$$H_{\text{delay}}(\omega, t_d) = \frac{F(\omega)}{\Theta(\omega)} = \underbrace{e^{-j\omega \cdot t_d}}_{\text{delay}} \cdot \underbrace{(m \cdot (j\omega)^2 + b \cdot j\omega + k)}_{H_0} \tag{5}$$

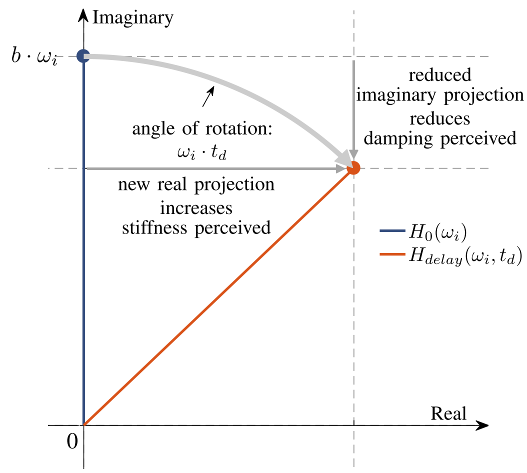


Fig. 4. Single-frequency Nyquist plots of a pure damper environment with undelayed force feedback (blue vector) and t_d-second delayed force feedback (red vector).

where t_d is the delay constant. In order not to cause confusion, note that we express the system dynamics with a *position*–force form, instead of the perhaps more commonly used impedance Z that describes the *velocity*–force relation.

When considered at a single frequency, the complex-valued FRF is a vector in the complex plane. Excited at this frequency, the system behaves like a single mechanical impedance, i.e., the characteristics of its force response are described by the FRF's projections on the two axes [16], which are as follows.

1) The force response at the velocity maximum—the force that our subjects used to estimate *damping*—is determined by the projection on the imaginary axis.
2) The force response at motion extremes—the force that our subjects used to estimate the *stiffness or mass*—is determined by the projection on the real axis. A positive real projection results in an elastic (spring) force; a negative one results in an inertia force.
3) The magnitudes of the aforementioned forces relate linearly to the size of the corresponding projections.

Now consider a pure damper environment ($b \neq 0$, $m = k = 0$), and draw the corresponding H_{delay} and H_0 at a single frequency ω_i on the complex plane—a single-frequency Nyquist plot—as shown in Fig. 4. As can be seen, the FRF of the undelayed environment (H_0, the blue vector) is located on the imaginary axis. So this system only generates a force in phase with the manipulator velocity, while at the extremes, the force is zero; it has a force profile similar to the gray curve in Fig. 3. The FRF of the delayed environment ($H_{\text{delay}}(\omega_i, t_d)$, the red vector) has a same magnitude, but is *rotated* by $\omega_i \cdot t_d$ radians in the clockwise direction, because of the time delay. Due to this, $H_{\text{delay}}(\omega_i, t_d)$ has a *smaller* projection on the imaginary axis and a *new* projection on the real axis.

The findings of the experiment show that our subjects did not separate the delay from the perception of the mechanical properties. This means the time-delayed dynamics H_{delay} rather than the original dynamics H_0 was used as the basis of the estimation of the environment properties. A reduction in the imaginary projection reduces the force at the velocity maximum, causing humans to perceive a lower damping. The additional projection on the positive real axis leads our subjects to feel an elastic force. As a result, the environment feels "more elastic," causing a perception of additional spring stiffness.

Similarly, all dependencies on the time delay magnitude t_d and excitation frequency ω, and their interactions, can also be explained. In the experiment, the variation in t_d or ω led to different phase shifts, causing different changes in the perception of the environment dynamics. Because the phase shift is the *product* of these two variables, the effect of each of these two factors is bound to increase when the other factor increases. Also, due to the trigonometric relation between the FRF vector and its projections on the two axes, the effects of these two factors are nonlinear.

B. Verification

The aforementioned principle can be verified using the experiment measurements. First, take the parameters listed in Table I and the settings of $t_{d,i}$ and ω_i into (5), $H_{\text{delay}}(\omega_i, t_{d,i})$ of the reference damper environment under different conditions can be obtained. This complex number yields the prediction of how the delayed damper will be perceived. Second, the FRFs of the control environments $H_c(\omega_i)$ yield the frequency-domain measurements of the perception of the delayed damper. The first row of Fig. 5 shows the comparisons between the predictions and measurements in the complex plane. As can be seen, the measurements from all subjects are close to the predictions.

The perceptual changes associated with the delayed mass and spring environments can similarly be explained, and the measurements also matched the predictions very well, as shown in the second and third rows of Fig. 5. The experiment measurements provide clear evidence of the "black-box modeling" principle, indicating that, while matching the perceptions of two environments, our subjects were actually matching the frequency responses of the two environments at the prescribed frequency ω_i.

V. Framework

In this section, we take a combined mass–damper environment as an example to illustrate how the principle discussed in the previous section can be extended to more general cases, e.g., cases where the environment consists of multiple mechanical properties. We start from a single excitation frequency, and then proceed to multiple frequencies. The extended principle provides a unified framework describing the effects of time delays on the perception of linear dynamic environments.

A. Single Frequency

Consider a combined mass–damper environment at a single frequency of ω_a. This environment possesses a damping of b and mass of m and zero stiffness. Again, values of the variables used for this example are not limited to particular numbers. Fig. 6 shows the single-frequency Nyquist plots of the undelayed dynamics of this environment ($H_0(\omega_a)$) and the time-delayed dynamics with a time delay T_a ($H_{\text{delay}}(\omega_a, T_a)$).

The FRF of the undelayed system (H_0) has projections on the negative real axis and positive imaginary axis. These two projections, respectively, determine the inertia force felt at the extremes of the manipulator deflection, and the damping force

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

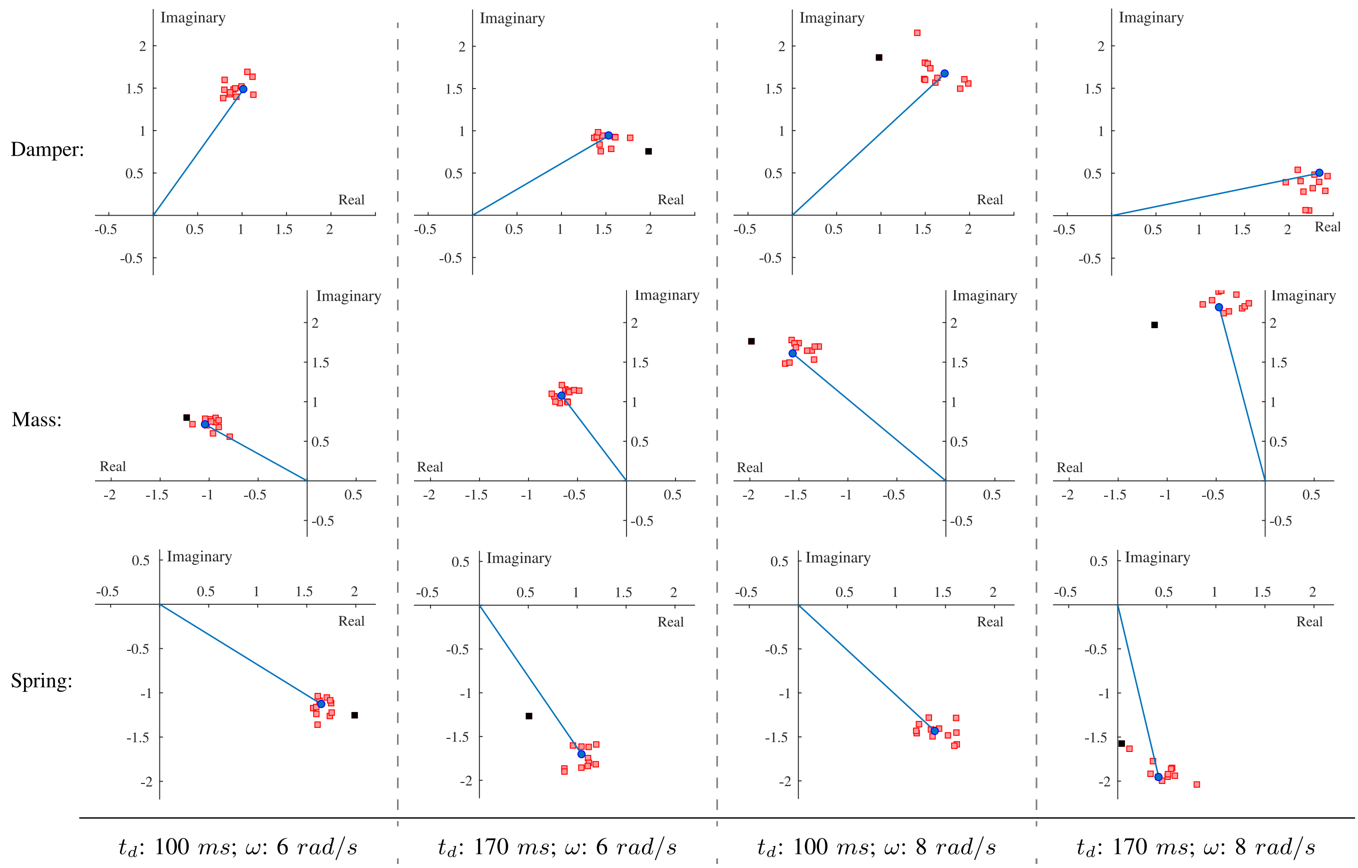


Fig. 5. Nyquist-plot predictions of the perceptions of the delayed reference environments, $H_{\text{delay}}(\omega_i, t_{d,i})$ (shown by blue line with dot), and the measurements of subjects' perceptions, $H_c(\omega_i)$ (shown by red squares ■). First row: the damping experiment; second row: the mass experiment; third row: the spring experiment. Outliers are marked by black squares (■).

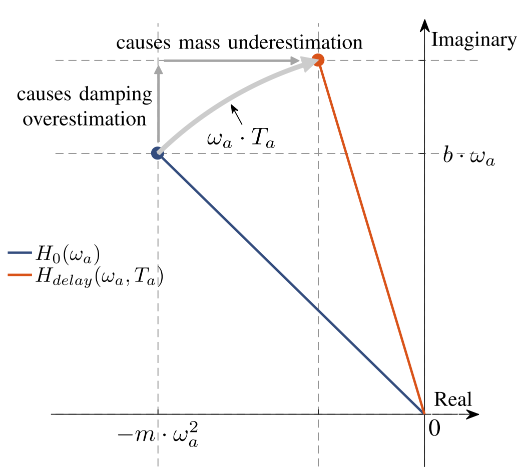


Fig. 6. Single-frequency Nyquist plots of a combined mass–damper system with undelayed force feedback (blue vector) and T_a-second delayed force feedback (red vector).

felt around the zero deflections. From the changed projections on the two axes, one can see that the delay causes this environment to be perceived as having a lower mass and higher damping, as compared to the reference. However, the change in the perception is not consistent over the entire frequency range. If the product $\omega_a \cdot T_a$ is further increased, for instance when increasing the excitation frequency ω_a, $H_{\text{delay}}(\omega_a)$ may move to the first quadrant of the complex plane. In this case, the projection on the real axis becomes *positive*, the original inertia behavior disappears completely, and an elastic force is exhibited instead. The original mass–damper environment will then be perceived as a *spring*–damper environment. With an even larger value of $\omega_a \cdot T_a$, the environment can exhibit an inertia behavior again. Such "switching" between different perceived mechanical properties occurs with increasing rotation angle $\omega_a \cdot T_a$ with a period of 2π rad.

B. Multiple Frequencies

Now, we proceed to a wider frequency range of 0–15 rad/s. The higher end of this range is slightly beyond the approximate (open-loop) natural frequency of human arm neuromuscular system [14]. Consider two different time delays: $T_1 = 60$ and $T_2 = 140$ ms. Fig. 7 shows the Nyquist plots of the corresponding $H_0(\omega)$ and $H_{\text{delay}}(\omega)$ of the mass–damper environment used earlier for this frequency range.

As can be seen, the time delays move the FRF of the original environment clockwise. We first analyze the effect of T_1: the red curve. At all the frequencies in the selected range, the projection on the real axis decreases in size, whereas the imaginary projection increases. As a result, the mass will be always *under*estimated and the damping will be always *over*estimated, no matter how the operator interacts with the environment.

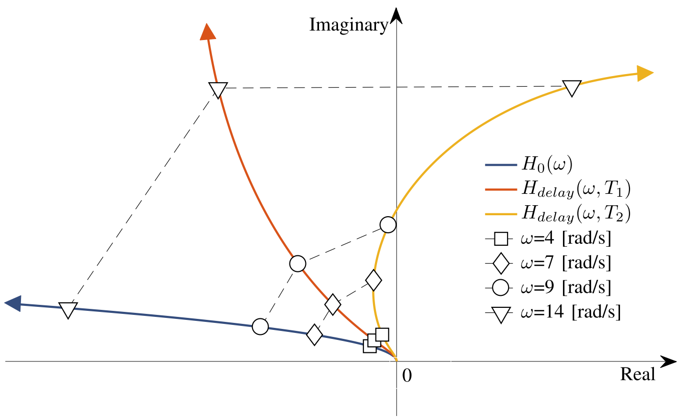


Fig. 7. Nyquist plots of a typical mass–damper system with undelayed (blue) and delayed force feedback (red and yellow). The delay times are $T_1 = 60$ ms and $T_2 = 140$ ms, respectively. The frequency range shown is 0–15 rad/s. The arrows of the curves indicate the increase of frequency. At frequencies of 4, 7, 9, and 14 rad/s, respective responses are marked and connected to facilitate comparison.

However, the extents of the under- and overestimation vary with the frequency. This is due to the fact that the delay-caused phase shift becomes larger as the frequency increases, shifting a larger proportion of mass into the damping. The perception will in fact depend on how the human operator interacts with the environment. Slow interaction movements will result in less distortion of the mechanical properties perceived, whereas fast movements cause more pronounced changes.

The trend of changes in the perception also depends on the delay time, as demonstrated by the larger time delay T_2. The corresponding FRF is shown as the yellow curve in Fig. 7. This curve intersects the imaginary axis at around 9 rad/s. When the interaction occurs below this frequency, the changes in the perceived mass and damping still follow the tendency discussed before while being more pronounced. However, the system begins to exhibit a spring behavior at higher frequencies, as the real-axis projection becomes positive. If the operator interacts with the environment with only fast movements, the inertia force is hardly presented. The elastic force makes the environment perceived to be similar to a spring. Moreover, with larger delays this spring behavior will appear earlier, because the FRF enters the first quadrant at lower frequencies. One can also imagine that the imaginary projection starts decreasing at higher frequencies or in the case of a larger delay time. Due to this, the viscous damping behavior exhibited by the delayed environment becomes weaker.

Similar analyses can be carried out to assess the effect of delays on the perception of damping, mass, and stiffness properties of all linear environments. The black-box modeling principle, in combination with the Nyquist-plot visualization, forms a framework that intuitively provides information of all delay-caused changes in the perception. In conclusion, the effect of delayed force feedback on human perception of environment mechanical properties is not consistent. Knowledge of the frequency range of excitation and the delay time is necessary to assess the full effect. But even when such knowledge exists, using fixed values to approximate the mechanical properties perceived by a human operator is still difficult, especially when the delay is large. Nevertheless, the *general trend* of how the delay affects the perception can be predicted. In order to corroborate the proposed framework, a second user study is carried out in the following section.

TABLE III
Parameters of the Reference Environment

Damping b_r [Nms/rad]	Mass m_r [kgm^2]	Stiffness k_r [Nm/rad]	Delay T [ms]
0.07	0.03	0	80

VI. Framework Verification

A second experiment was conducted to evaluate the proposed framework. The experiment followed a same "perceive and adjust" procedure. Subjects interacted with the two environments with the same side-stick manipulator. The dynamics of the manipulator are given in the Appendix. The reference environment was a typical mass–damper environment, of which the mass property would be perceived to be more dominating than the damping property. The force feedback from this environment was delayed by 80 ms. Table III gives details about this environment.

The control environment was a mass–spring–damper system from which the force feedback was not delayed. The initial settings of the mass, spring, and damper coefficients (m_c, b_c, and k_c) of this environment were the same as the reference environment. Subjects were asked to adjust the dynamics of the control environment until its three mechanical properties approximate to those of the delayed reference environment. In this experiment, instead of the two complex components, subjects directly adjusted the mass, spring, and damper coefficients using three vertical sliders shown on the screen. Moreover, unlike the first experiment in which the interaction was fixed at a particular frequency, in the second experiment, subjects were allowed to freely move the manipulator to explore the environments, but were asked to avoid hitting the manipulator's end stops and not make violent movements. The duration of each individual interaction with an environment was not limited. No feedback of the manipulator movement was given on the display.

Fig. 8 shows the Nyquist plot of the delayed reference environment, along with the dynamics without the time delay. The frequency range shown here is 0–15 rad/s. We believe this frequency range is sufficient for the assessment of the effect of time delay, since humans cannot generate movement beyond the bandwidth of their neuromuscular systems [14]. As can be seen from the figure, we expect subjects to perceive the delayed reference environment as having less mass but higher damping, as compared to the original undelayed dynamics. In addition, no stiffness would be perceived since the delayed environment does not exhibit any spring behavior within this frequency range.

The final values of m_c, b_c, and k_c of the control environment will indicate the mechanical properties perceived from the reference environment. As discussed earlier, the behavior exhibited by a delayed environment depends on the frequencies at which the excitation mainly occurs. Since the manipulator

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

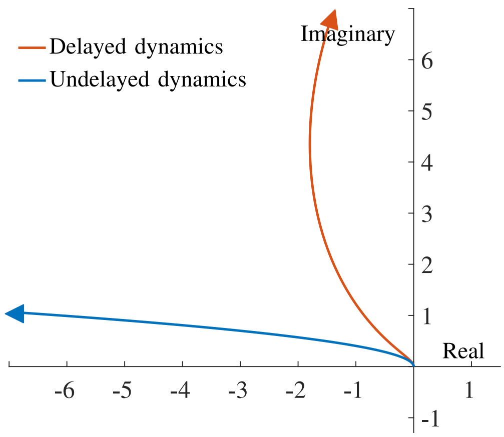


Fig. 8. Dynamics of the delayed reference environment and the dynamics without the delay.

TABLE IV
MECHANICAL PROPERTIES PERCEIVED BY SUBJECTS

	Subject					
	1	2	3	4	5	6
b_c [Nms/rad]	0.271	0.165	0.206	0.106	0.135	0.150
m_c [kgm^2]	0.014	0.019	0.017	0.023	0.021	0.020
k_c [Nm/rad]	0.000	0.000	0.000	0.000	0.000	0.000

movements applied by different subjects may differ, we expect the perception differs between individual subjects.

Six subjects (5 male and 1 female, between the age of 26–56 years with a mean age of 32.2), graduate students, and academic staff members of TU Delft participated in the experiment. They were all right-handed and did not have any history of impairment in moving the arm or hand. All subjects had sufficient knowledge about how each of the three mechanical properties feels, but were naive about the effect of the time delay on the perception of mechanical properties. In addition, subjects did not know the force feedback from the reference environment was delayed. This user study was approved by the Human Research Ethics Committee of TU Delft. Informed consent was obtained from all subjects before the experiment.

A. Result

Table IV lists the final values of m_c, b_c, and k_c of the control environment adjusted by subjects. Except for the stiffness property, the mass and damping properties perceived by different subjects of the delayed reference environment are considerably different. As expected, all subjects *under*estimated the mass and *over*estimated the damping. Moreover, no spring behaviors were perceived.

The differences in the mechanical properties perceived can be accounted for by the differences in the frequency of excitation between subjects. Although subjects were encouraged to use whatever movements they would like to interact with the environments, the manipulator movements applied by all subjects were still dominated by clear sinusoidal profiles. Fig. 9 gives an example that shows the manipulator movement generated by one subject during a single interaction with the reference environment.

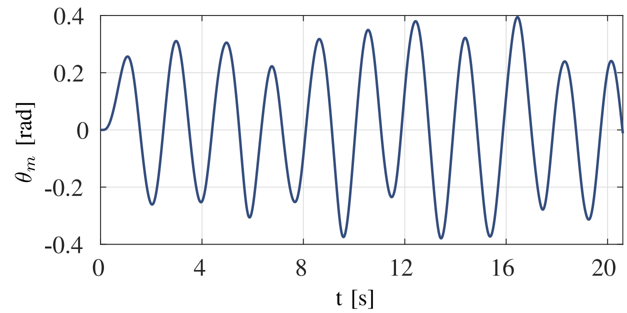


Fig. 9. Manipulator deflection angle θ_m generated by a subject during a single interaction.

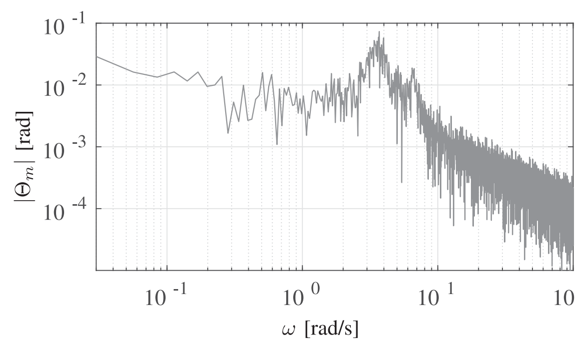


Fig. 10. Magnitude of the Fourier transform of the manipulator deflection angle generated by a subject during the entire experiment.

A similar human behavior was also mentioned by Nisky *et al.* in [20]. It seems that humans are inclined to use a sinusoidal profile to establish their impressions about a mechanical property. According to an interview carried out after the experiment, subjects attempted to interact with the control environment with similar manipulator movements to what they generated for the reference environment. The two environments were then compared in terms of the correlation between the movement and the force.

Due to this, we hypothesize that the frequency responses of the two environments would be the closest at the frequencies at which the environments were excited the most. Fig. 10 shows the power spectrum of the manipulator deflection angle generated by a subject during the entire experiment. The peak of the power spectrum occurs close to 4 rad/s. This is the frequency at which the majority of the interaction took place, i.e., the approximate frequency of the sinusoidal profile. Noticeable energy can also be seen at frequencies below 0.1 rad/s, which account for nearly static manipulator deflections. According to our subjects, such slow movements were applied at the beginning of the experiment to obtain the static spring force that was used to determine the spring stiffness of the environments.

Our hypothesis can be verified by plotting the difference in the frequency response between the two environments on top of the power spectrum of the manipulator deflection angle. The absolute value of the frequency-response difference can be ob-

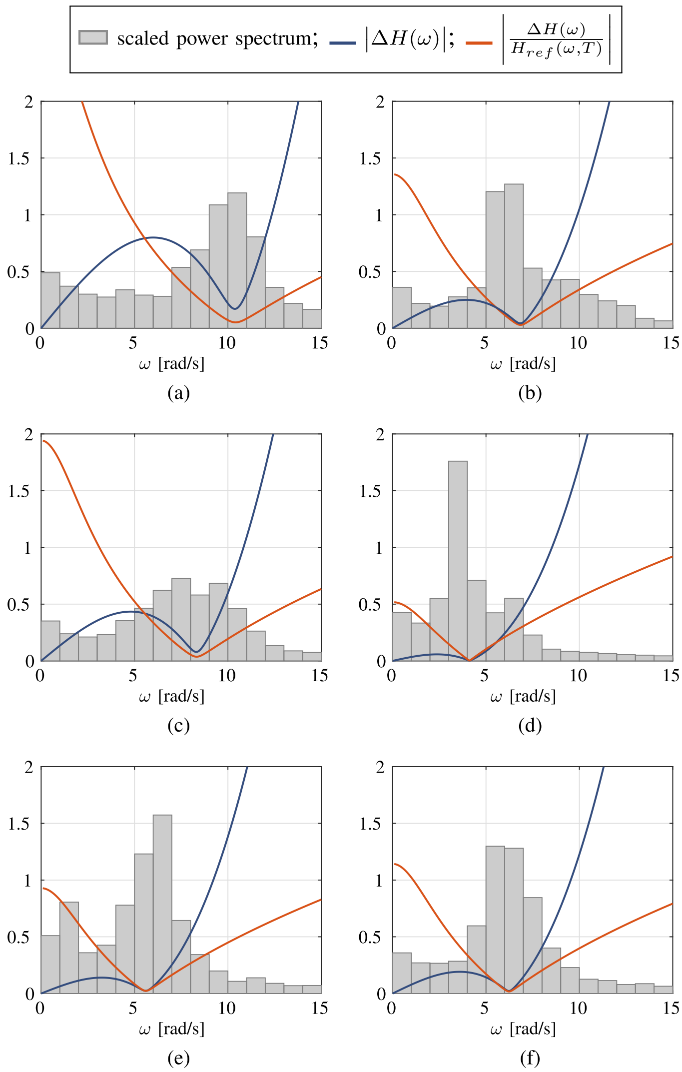


Fig. 11. Difference in the frequency response between the delayed reference and control environments, plotted on top of the scaled power spectrum of the manipulator movement. (a) Subject 1. (b) Subject 2. (c) Subject 3. (d) Subject 4. (e) Subject 5. (f) Subject 6.

tained from

$$|\Delta H(\omega)| = |H_{\text{ref}}(\omega, T) - H_{\text{con}}(\omega)|. \quad (6)$$

Here, H_{ref} and H_{con} denote the FRFs of the delayed reference environment and the control environment, respectively.

Now, consider the frequency range of 0–15 rad/s. For a better illustration, the power spectrum is scaled up and shown with its average over each frequency bin of 1.0 rad/s, as can be seen from Fig. 11.

In general, the characteristics of $|\Delta H(\omega)|$ for all subjects are similar. $|\Delta H(\omega)|$ starts from zero as both environments do not generate any static spring force. It then increases as the energy of the excitation reduces. As expected, the minimum value of $|\Delta H(\omega)|$ occurs at roughly the same frequency at which the power spectrum of the manipulator movement reaches the peak. The quick increase in the dynamic difference at higher frequencies is due to the fact that the noticeable difference in the mechanical properties increases as the system magnitude increases [18], [21]. To take this into account, the ratio of the dynamic difference to the system magnitude ($|\frac{\Delta H(\omega)}{H_{\text{ref}}(\omega,T)}|$) is also shown in Fig. 11.

To avoid numerical singularity, the lower end of the frequency range used to calculate the ratio is set to 0.1 rad/s. As can be seen, the slope at higher frequencies becomes lower and corresponds better to the characteristics of the power spectrum. The minimum of this difference ratio occurs at the same frequency as the absolute difference, coinciding with the peak of the power spectrum.

B. *Discussion*

The experimental findings confirm our hypothesis and demonstrate the validity of the framework proposed in Section V. Clearly, the mechanical properties of an environment will be perceived differently when the human operator excites the environment at different frequencies. Although the exact change in the perception varies with the frequency of excitation, in this experiment, we have demonstrated that the *general trend* of how the perception will change is readily appreciable using our framework.

We also found that humans may assess different mechanical properties at different frequencies. In the experiment, subjects assessed the stiffness of the environments with nearly static manipulator movements. According to subjects, this is due to the fact that, in this case, the spring force was less “polluted” by the forces generated by the damping and mass properties. Since the damping and inertia forces are stronger at higher frequencies, at lower frequencies, subjects can estimate the stiffness with higher accuracy. This can be accounted for by the perception threshold, which increases as the magnitude of the system dynamics increases [18], [21]. However, in cases where the damping and mass are negligible compared to the spring stiffness, accurate estimation of stiffness can also be obtained using faster movements. It remains unclear whether in such cases subjects will still select static movements for the assessment of the stiffness or be different in the movement frequency as they did to assess the mass and damping properties. A possible correlation may exist between the excitation movement and the dynamics of the environment. This question needs to be answered in future research.

It is of interest to note that the manipulator movement that our subjects employed to explore the properties of the environments resembles a sinusoid. This was also reported in [7] and [20] during the interaction with springlike environments. The reason for such behaviors is beyond the scope of this study, but certainly needs to be addressed in further research.

VII. General Discussion

Our framework is based on examining the FRF of the lumped dynamics of the environment and the time delay. This uses the fact that humans do not separate the time delay from the perception of the mechanical properties. Instead, the dynamics of the time delay and the mechanical properties are lumped together and perceived as a single mechanical system. This is consistent with the findings of previous research [7], [8], [10], [12]. A similar phenomenon also exists in the motor control in tracking tasks [22]. It is suggested that the central nervous system compensates for delays in a sensory channel by means of a representation that resembles a mechanical system.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Our findings related to the perception of stiffness are in line with previous work [8], [13], [23], in which the underestimation is also observed during continuous interaction with the environment. In addition, we find that changes in the perception of all three mechanical properties respect the *same* principle. However, as a result of the threshold for perceiving a difference in the mechanical properties, not all delays can cause a change in the perception. For a noticeable change in the stiffness, a minimum delay of 36ms is reported [24]. Delays below this noticeable level, as tested in [10], are therefore unlikely to cause significant effects.

In the present study, our subjects interacted with the environments using a side-stick manipulator. Such a setup of the manipulator led the lower arm to be the body part that was mainly involved in the interaction. We found that subjects were inclined to consider the movement to be the cause and the force to be the result, as also suggested by Nisky *et al.* in [9]. However, if the estimation would be on resulting movement in response to an applied force, as is hypothesized in [9] to match the control strategy for the shoulder joint, a different elaboration of the black-box estimation framework might be needed.

Clearly, due care should be taken when trying to evaluate the mechanical properties of a remote environment when force feedback is delayed. The effect of a time delay can be easily assessed using our framework. With knowledge of the frequency of excitation applied by the human operator, the mechanical properties perceived can be approximated by means of fitting the dynamics of the delayed environment with a mass–spring–damper system at the frequencies where the excitation mainly occurs.

Such an approximation can be fairly accurate in the case of self-exploration tasks, as humans are inclined to employ a sinusoidal profile to interact with the environment. In tasks that involve tracking, the mechanical properties perceived by the human operator is determined by the reference signal of the tracking task. If the reference signal possesses considerable energy over a relatively wide frequency range, the accuracy of the approximation depends on the magnitude of the time delay. The approximation can still be accurate when the delay is small, as demonstrated in [10]. However, when time delay increases, quantifying its effect using a model with a limited order is not possible any more. As shown by both experiments carried out in this study, there need not be a consistent change in the perception of each mechanical property in the presence of a delay. The change depends on the *product* of the delay time and the excitation frequency. Nevertheless, our framework still provides clear insights into the general changing trend in the perception of the mechanical properties.

As discussed earlier, the FRF of the time-delayed dynamics switches over the four quadrants with a frequency "period" of $\omega = 2\pi/T_{\text{delay}}$ rad/s. One can imagine that the FRF of the time-delayed dynamics can even spiral across all the four quadrants when the delay time is sufficiently large. In this case, a slight change in the excitation frequency will lead the environment to exhibit completely different behavior. Due to this, assessing the mechanical properties of the environment becomes very difficult for a human operator. As a result, the human operator will probably stop perceiving the environment as a mechanical system. It is therefore of interest for future research to understand the delay magnitude from which this situation starts to occur.

Furthermore, the framework proposed in this study is based on the assumption of the continuous interaction between the human operator and the environment. However, discontinuous interaction, during which the boundary of the force field is frequently crossed, can have different effects on the perception of mechanical properties [7], [8]. Extension of the framework, which takes this effect into account, should be made to include this effect.

VIII. Conclusion

In this paper, we investigated the effects of delayed forced feedback on the haptic perception of damping, mass, and stiffness properties of dynamic environments. In a first experiment, we observed that all mechanical properties were underestimated with time delays, and subjects perceived different mechanical properties than simulated. These changes in perception were accounted for by the fact that our subjects could not separate phase differences due to delayed force feedback from phase differences due to different environment mechanical properties. This key finding led us to define a unified framework—based on a visualization of the FRF of the lumped (environment and delay) dynamics—which can accurately predict all effects due to time delays. Our framework is verified by the second experiment, in which participants could explore a mass–damper environment with freely-selected movement patterns. The experimental findings showed that the delayed force caused an underestimation of the mass but an overestimation of the damping, as predicted by the framework. The framework also explains how perception of these two mechanical properties varied between individual subjects, depending on the frequency content of the movement pattern.

Appendix

The manipulator is configured with an admittance architecture. It is driven by an electrohydraulic servomotor. Position of the manipulator and moment on the manipulator are led through presample filters (bandwidth = 200 Hz) before being digitized at 2500 Hz and read into the laboratory computer. The manipulator's control system is executed at 2500 Hz, and effective position following bandwidth is around 40 Hz. The manipulator is supplied with a handle, diameter 35 mm, with grooves for placement of the fingers. When a hand is correctly placed on the handle, the center of the hand lies 90 mm above the manipulator rotation axis. The equivalent (simulated) dynamics of the manipulator can be expressed as

$$H_m(s) = \frac{\Theta_m(s)}{F_m(s)} = \frac{1}{m_m \cdot s^2 + b_m \cdot s + k_m}. \tag{7}$$

The manipulator dynamics were configured to guarantee the stability of the overall system. In the first experiment, m_m was set to 0.01 $\text{kg} \cdot \text{m}^2$ for the delayed-spring experiment (the experiment in which the reference environment was a spring), and 0.06 $\text{kg} \cdot \text{m}^2$ for both delayed-mass and -damper experiments. b_m was 0.3 N·m·s/rad for the delayed-spring experiment, and 0.05 N·m·s/rad for both delayed-mass and -damper experiments. The effort to move the manipulator was minimized by setting stiffness k_m to be $m_m \cdot \omega_i^2$. With such settings, the prescribed excitation frequency ω_i becomes the eigenfrequency of the manipulator. Thus, the manipulator itself only generates a damping force during the experiment, since the responses of the stiffness and mass are counteracted by each other. Note that the dynamics of the manipulator were identical for each reference environment and its corresponding control environment, although different settings were used for different reference environments.

In the second experiment, the dynamics of the manipulator were set to $m_m = 0.035\,\mathrm{kg}\cdot\mathrm{m}^2$, $b_m = 0.05$ N·m·s/rad, and $k_m =$ 0 N·m/rad, respectively. Again, the dynamics of the manipulator were identical for the reference environment and the control environment.

Note that in the experiment, the manipulator could only move laterally (left-hand side and right-hand side). The movement in the longitudinal direction (forward and backward) is fixed at the center.

References

[1] W. R. Ferrell, "Delayed force feedback," *Human Factors*, vol. 8, no. 5, pp. 449–455, 1966.

[2] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May 1989.

[3] G. Niemeyer and J. J. Slotine, "Stable adaptive teleoperation," *IEEE J. Ocean. Eng.*, vol. 16, no. 1, pp. 152–162, Jan. 1991.

[4] S. Hirche, T. Matiakis, and M. Buss, "A distributed controller approach for delay-independent stability of networked control systems," *Automatica*, vol. 45, no. 8, pp. 1828–1836, 2009.

[5] J. G. W. Wildenbeest, R. J. Kuiper, F. C. T. van der Helm, and D. A. Abbink, "Position control for slow dynamic systems: Haptic feedback makes system constraints tangible," in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, Oct. 2014, pp. 3990–3995.

[6] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robot. Automat.*, vol. 9, no. 5, pp. 624–637, Oct. 1993.

[7] A. Pressman, L. J. Welty, A. Karniel, and F. A. Mussa-Ivaldi, "Perception of delayed stiffness," *Int. J. Robot. Res.*, vol. 26, no. 11/12, pp. 1191–1203, 2007.

[8] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "A regression and boundary-crossing-based model for the perception of delayed stiffness," *IEEE Trans. Haptics*, vol. 1, no. 2, pp. 73–84, Jul.–Dec. 2008.

[9] I. Nisky, P. Baraduc, and A. Karniel, "Proximodistal gradient in the perception of delayed stiffness," *J. Neurophysiol.*, vol. 103, no. 6, pp. 3017–3026, 2010.

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

[11] R. Leib, A. Karniel, and I. Nisky, "The effect of force feedback delay on stiffness perception and grip force modulation during tool-mediated interaction with elastic force fields," *J. Neurophysiol.*, vol. 113, no. 9, pp. 3076–3089, 2015.

[12] S. Hirche, A. Bauer, and M. Buss, "Transparency of haptic telepresence systems with constant time delay," in *Proc. IEEE Conf. Control Appl.*, Aug. 2005, pp. 328–333.

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

[14] M. M. van Paassen, J. C. Van Der Vaart, and J. A. Mulder, "Model of the neuromuscular dynamics of the human pilot's arm," *J. Aircr.*, vol. 41, no. 6, pp. 1482–1490, 2004.

[15] K. Van der El, D. M. Pool, H. J. Damveld, M. M. van Paassen, and M. Mulder, "An empirical human controller model for preview tracking tasks," *IEEE Trans. Cybern.*, vol. 46, no. 11, pp. 2609–2621, Nov. 2016.

[16] D. Findeisen, *System Dynamics and Mechanical Vibrations: An Introduction*. New York, NY, USA: Springer, 2013.

[17] W. Fu, M. M. van Paassen, and M. Mulder, "On the relationship between the force JND and the stiffness JND in haptic perception," in *Proc. ACM Symp. Appl. Perception*. ACM, 2017, Art. no. 11.

[18] W. Fu, A. Landman, M. M. van Paassen, and M. Mulder, "Modeling human difference threshold in perceiving mechanical properties from force," *IEEE Trans. Human–Mach. Syst.*, vol. 48, no. 4, pp. 359–368, Aug. 2018.

[19] R. Leib *et al.*, "Stimulation of PPC affects the mapping between motion and force signals for stiffness perception but not motion control," *J. Neurosci.*, vol. 36, no. 41, pp. 10545–10559, 2016.

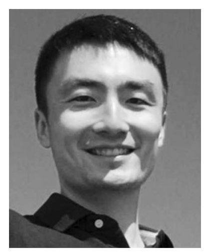
[20] I. Nisky, F. A. Mussa-Ivaldi, and A. Karniel, "Analytical study of perceptual and motor transparency in bilateral teleoperation," *IEEE Trans. Human–Mach. Syst.*, vol. 43, no. 6, pp. 570–582, Nov. 2013.

[21] W. Fu, M. M. van Paassen, and M. Mulder, "Modeling the coupled difference threshold of perceiving mass and stiffness from force," in *Proc. IEEE Int. Conf. Syst., Man., Cybern.*, Miyazaki, Japan, Oct. 7–10, 2018.

[22] R. Leib, A. Karniel, and F. A. Mussa-Ivaldi, "The mechanical representation of temporal delays," *Sci. Rep.*, vol. 7, no. 1, 2017, Art. no. 7669.

[23] B. Knorlein, M. D. Luca, and M. Harders, "Influence of visual and haptic delays on stiffness perception in augmented reality," in *Proc. 8th IEEE Int. Symp. Mixed Augmented Reality*, Oct. 2009, pp. 49–52.

[24] M. Rank, Z. Shi, H. J. Müller, and S. Hirche, "The influence of different haptic environments on time delay discrimination in force feedback," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.* Springer, 2010, pp. 205–212.



Wei Fu (S'18) received the M.Sc. degree in automation from the Faculty of Automation, Northwestern Polytechnical University, Xi'an, China, in 2015. He is currently working toward the Ph.D. degree in aerospace engineering at the Faculty of Aerospace Engineering, TU Delft, Delft, The Netherlands.

His research interests include human–machine systems, haptic perception, haptic interface design, teleoperation, and automatic control.

Marinus M. (René) van Paassen (SM'15) received the M.Sc. (*cum laude*) and the Ph.D. degrees in aerospace engineering from TU Delft, Delft, The Netherlands, in 1988 and 1994, respectively.

He is currently an Associate Professor with the Faculty of Aerospace Engineering, TU Delft. His research interests include human–machine systems, haptics, and cognitive systems engineering.

Dr. van Paassen is an Associate Editor for the IEEE Transactions on Human–Machine Systems.

David A. Abbink (SM'14) received the M.Sc. and the Ph.D. degrees in mechanical engineering from TU Delft, Delft, The Netherlands, in 2002 and 2006, respectively.

He is currently a Full Professor with the Faculty of Mechanical, Maritime and Materials Engineering, TU Delft, and the Head of the Delft Haptics Lab, Delft, The Netherlands. His research interests include human motor control, bilateral telemanipulation, haptic assistance, and human factors.

Max Mulder (M'14) received the M.Sc. and the Ph.D. degrees (*cum laude*) in aerospace engineering from TU Delft, Delft, The Netherlands, in 1992 and 1999, respectively.

He is currently a Full Professor with the Faculty of Aerospace Engineering, TU Delft. His research interests include manual control cybernetics and ecological information systems.

Dr. Mulder is an Associate Editor for the IEEE Transactions on Human–Machine Systems.