Markus Rank*
Institute of Automatic Control Engineering
Technische Universität München
D-80290 Munich, Germany

Zhuanghua Shi
Hermann J. Müller
Department of Psychology
Ludwig-Maximilians-Universität München
D-80802 Munich, Germany

Sandra Hirche
Institute of Automatic Control Engineering
Technische Universität München
D-80290 Munich, Germany

Perception of Delay in Haptic Telepresence Systems

Abstract

Time delay is recognized as an important issue in haptic telepresence systems as it is inherent to long-distance data transmission. What factors influence haptic delay perception in a time-delayed environment are, however, largely unknown. In this article, we examine the impact of manual movement frequency and amplitude in a sinusoidal exploratory movement as well as the stiffness of the haptic environment on the detection threshold for delay in haptic feedback. The results suggest that the detection of delay in force feedback depends on the movement frequency and amplitude, while variation of the absolute feedback force level does not influence the detection threshold. A model based on the exploration movement is proposed and guidelines for system design with respect to the time delay in haptic feedback are provided.

1 Introduction

One of the benefits for humans operating telepresence systems is that it enables them to work in remote locations, for example, underwater or in space. However, communication-induced artifacts that occur in long-distance teleoperation, such as time delays and packet loss, impair the transparency of the system (Hirche & Buss, 2007). In particular, with long geographical distances, there will be inevitable communication latencies affecting the subjective experience of presence and task performance (Kaber, Riley, Zhou, & Draper, 2000; MacKenzie & Ware, 1993; Frank, Casali, & Wierwille, 1988; Lane et al., 2002; Sheridan & Ferrell, 1963; Jay, Glencross, & Hubbold, 2007).

Studies on the influence of delayed feedback on task performance date back to the 1960s. Using a servo-controlled "minimal manipulator," Sheridan & Ferrell (1963) found that performance decreased with increasing time delay in the visual feedback of a manipulation task. In the early 1990s, MacKenzie & Ware (1993) extended the classical Fitts' Law to a situation of delayed visual feedback. They found time delay to prolong task completion time by a multiplicative factor. Similar effects have also been observed in delayed haptic environments (Alhalabi, Horiguchi, & Kunifuji, 2003; Wang, Tuer, Rossi, Ni, & Shu, 2003). Recently, Jay et al. (2007) examined the impact of delayed haptic and visual feedback from the partner in a collaborative virtual environment with two operators. They found both visual

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*Correspondence to m.rank@tum.de.

and haptic delay to impede task performance in terms of both loss of contact with the target object and acquisition time; however, haptic delay had a greater impact on performance than visual latency.

While many studies of time delay have examined issues related to task performance (MacKenzie & Ware, 1993; Frank et al., 1988; Lane et al., 2002; Sheridan & Ferrell, 1963; Jay et al., 2007; Kaber et al., 2000), there are relatively few studies on delay perception per se in telepresence environments. Arguably, however, knowing humans' capabilities of perceiving delays is useful for providing system designers with guidelines for the development of multimodal communication protocols as well as for human-centered evaluations of existing applications with respect to system fidelity and the experience of telepresence. Psychophysicists have shown that the threshold for perceiving asynchrony between events can vary from 20 ms up to 200 ms, depending on stimulus settings and sensory modality (Hirsh & Sherrick, 1961; Fraisse, 1984; Vogels, 2004). However, haptic delay perception in real telepresence scenarios may be different since it arises from a complex environment and differs from the simple discrete events used in typical psychophysical studies. In particular, force feedback is continuous rather than discrete in many applications. Additionally, communication delay as the most common source of delay manifests itself as a latency between the operator's action and the system feedback, and is thus quite different from the asynchrony between two sensory modalities (Hirsh & Sherrick, 1961; Fraisse, 1984; Vogels, 2004). Thus, haptic delay perception in telepresence environments depends on how the operator issues action commands and what information is fed back. For the visuomotor feedback loop, it has been shown that delays between manual motor commands and visual feedback can be detected once they exceed 30 to 40 ms (Poulton, 1974; Ellis, Young, Adelstein, & Ehrlich, 1999). With a head mounted display (HMD), detection of head tracking latency has been found to be even lower, less than 20 ms (Adelstein, Lee, & Ellis, 2003; Mania, Adelstein, Ellis, & Hill, 2004). The low threshold for detecting head tracking latencies has been suggested to result from secondary effects such as image slip, rather than from direct time perception.

In the aforementioned study of Jay et al. (2007), continuous haptic delay could be perceived to be starting from around 50 ms in a collaborative virtual environment. Thus, in general, detection thresholds for delays may vary substantially (Adelstein et al., 2003; Allison, Harris, Jenkin, Jasiobedzka, & Zacher, 2001; Mania et al., 2004; Jay et al., 2007), depending on the specific setups used in a particular study. Yet, to the best of our knowledge, what factors influence detection thresholds for time delay and haptic delay perception in general has never been systematically investigated.

In order to address this gap in the literature, in the present study, we examine factors potentially influencing delay perception in a continuous haptic environment. Specifically, we study the impact of the frequency and amplitude of sinusoidal manual movements as well as of environmental stiffness on delay detection in a spring-type force field environment. The results reveal that high movement frequencies or amplitudes lead to lower detection thresholds, while latency discrimination is uninfluenced by the spring coefficient. The remainder of this article is organized as follows: in Section 2, we describe three hypothetical mechanisms for haptic delay detection; these are then tested in two experiments reported in Sections 3 and 4; finally, Section 5 discusses the implications of the results for telepresence systems.

2 Theoretical Models of Delay Perception

It is commonly accepted that perception and action are closely linked (Warren, 2006). When a user in a telepresence system performs actions and produces forces in the remote environment, his or her activities alter the state of the environment (e.g., changing the position of an object). Changes of the external environment are in turn received by the user through multiple sensory modalities. With delayed haptic feedback, different features from the environmental feedback could lead to detection of the delay. Factors involved in delay perception could include: an internal clock, feedback from own exploration, or an internal comparison of the force feedback with the predicted, undelayed force profile of the environment. Consequently, there are (at least) three hypothetical mechanisms (henceforth referred to as H1, H2, and H3) that may be involved in delay detection in continuous haptic feedback environments.

H1. Time delay of haptic feedback is detected solely from the temporal domain and the detection threshold is independent of the system's force feedback profile $f(t)$ and the excitation movement $x(t)$.

This hypothesis originates from temporal perception theory (Fraisse, 1984), according to which time delay, as a special type of duration, is estimated from an internal clock. Assuming that a simple manual movement does not influence the internal clock, the detection threshold T_d of the haptic delay feedback is independent of the operator's manual movement and force feedback, that is, it is constant.

$$T_d = \text{const.} \tag{1}$$

Henceforth, we will refer to this hypothesis as the constant model.

H2. The threshold for detecting delayed haptic feedback depends on the characteristics of the active exploration movement.

It has been demonstrated that the detection of asynchrony between head motion and visual feedback is dependent on the turning speed of the head (Allison et al., 2001), that is, higher speeds result in lower detection thresholds for visual delays. Here, we state H2 in a more general way, namely, that the detection of time delay in a haptic system depends on the characteristics of the exploration movement $x(t)$ within a given environment,

$$T_d = T_d(x(t)). \tag{2}$$

We refer to this as the exploration model.

H3. The detection of delay in haptic feedback is inferred from the deviation of the delayed feedback force and the expected undelayed force.

In virtual environments with an HMD, the user may infer head tracking latency based on the spatial discrepancy between the delayed and nondelayed object positions (Adelstein et al., 2003), that is, the displacement of an object from its originally expected position introduced by the latency between head motion and visual feedback. In impedance-type haptic environments, a similar mechanism, based on deviations of force feedback $f(t)$ from the expected undelayed force dynamics $f^*(t)$ of the system, may support the detection of delayed feedback.

$$T_d = T_d(f(t), f^*(t)). \tag{3}$$

This hypothesis is defined over the relationship between two force profiles and will therefore be referred to as the force discrepancy model.

For experimental validation, we chose a linear spring as our haptic environment. The delayed spring force $f(t)$ is described by the equation

$$f(t) = -kx(t - \tau), \tag{4}$$

where k is the spring coefficient, x the deflection from the equilibrium position of the spring, and τ the artificially introduced delay. In order to observe and detect the time delay in the system, we instructed the participants in the study to make a sinusoidal excitation movement

$$x(t) = A\sin(\omega t), \tag{5}$$

with amplitude A and frequency ω. Accordingly, the velocity profile of this movement is

$$\dot{x}(t) = A\omega\cos(\omega t). \tag{6}$$

In this experimental framework, we have three degrees of freedom: A, ω, and k. In order to test hypotheses H1–H3, two experiments were conducted in which A, ω, and k were varied in a systematic manner. The constant model predicts a detection threshold independent of the movement, while the other two models predict an influence of A and ω. Intuitively, a larger amplitude introduces a longer movement distance where detection of delay can take place as well as larger forces in the delayed environment. Furthermore, fixed time delay in combination with higher movement frequencies provoke a higher overall phase shift between the movement and the feedback force. Certain events within the force feedback such as direction changes or the maximum feedback force thus shift out of phase with the movement. High movement frequencies as well as large amplitudes therefore potentially help in detecting the time delay at lower absolute levels. As discussed earlier, the deviation of the perceived location from the expected position from undelayed vision (e.g., image slip) has been established to be a key factor in visual feedback delay detection (Adelstein et al., 2003). Considering similar mechanisms for delayed force feedback perception (H3), the deviation of delayed force feedback from the nondelayed reference, $\Delta f(t)$, could be a useful feature for haptic delay detection. We assume here that the reference force can be represented as the ideal prediction. With Equations 4 and 5, $\Delta f(t)$ can be derived as

$$\Delta f(t) = kA(\sin(\omega t) - \sin(\omega(t - \tau))). \qquad (7)$$

Figure 1 depicts the evolution in time of the undelayed reference, the delayed sensory feedback, and the deviation between them. Analogous to the image slip mechanism in visual perception, the maximum force difference between expected nondelayed system behavior and sensory feedback could be a key factor in the detection of the time delay. It can be easily derived that the force difference reaches its maximum at time $\frac{1}{2}\tau$ after the zero-crossings of the predicted (nondelayed) force reference, which is expressed by

$$\Delta f_{\max} = \Delta f(t)|_{t=\frac{1}{2}\tau} = kA2\sin\left(\frac{1}{2}\omega\tau\right) \approx kA\omega\tau. \quad (8)$$

The last step in the calculation holds for small values of $\omega\tau$, which is a valid assumption for the range of parameters considered in the experiments.

Notably, the maximum force error is dependent on the product of A and ω, predicting that choosing values of A and ω such that their product is constant ($A\omega$ = const.) would result in the same detection threshold. Additionally, $A\omega$ is the value for the peak velocity of the movement, as can be derived from Equation 6. As the velocity is a potential key factor in hypothesis H2, a significant influence of $A\omega$ would simultaneously support hypotheses H2 and H3. Varying the environmental parameter k with unchanging movement profiles can help to differentiate the latter two

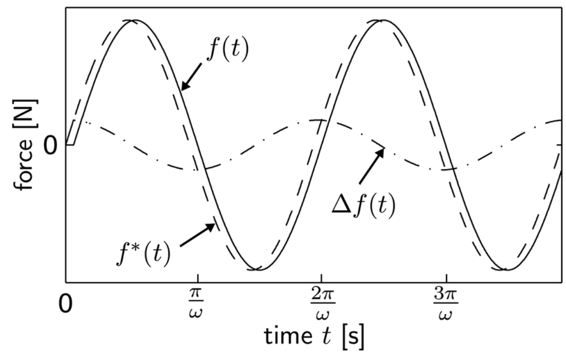

Figure 1. *The difference of the undelayed force reference $f^*(t) = A\sin(\omega t)$ (dashed) and the actual delayed sensory feedback $f(t)$ (solid) forms a force error $\Delta f(t)$ (dash-dotted) with peak amplitude $\Delta f_{max} \approx kA\omega\tau$.*

models. H3 predicts decreasing perceptual thresholds with increasing stiffness, while H2 predicts nonchanging perceptual sensitivity for haptic delay with respect to the environmental properties.

3 Experiment 1

Experiment 1 was designed to examine the influence of the amplitude A and frequency ω of the sinusoidal excitation movement on the detection of delay in haptic feedback.

3.1 Participants

Fifteen university students (3 male, 12 female, age range 21–37 yr) participated in the experiment. All were right-handed and had normal or corrected-to-normal vision; none of them reported any history of somatosensory disorders. Informed consent was obtained from all participants prior to the experiment.

3.2 Apparatus and Stimuli

The haptic stimuli were rendered using a ServoTube linear motor module (Copley Controls Corp.). A rubber-coated handle was used for user interaction with the device. Force and torque information was measured with a 6 DOF force-torque sensor (JR3, Inc.).

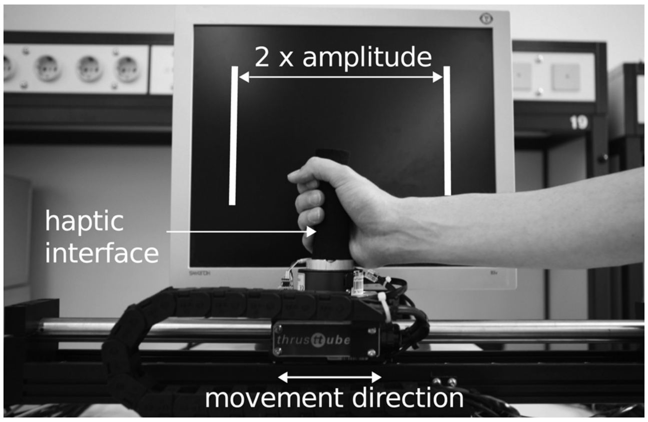

Figure 2. *The experimental apparatus consists of a linear actuator device with a rubber-coated handle and a TFT screen used for visual stimulus presentation. The experimental task was to move the handle in a sinusoidal movement with a specific frequency and amplitude, indicated by tone rhythms and vertical bars on the screen.*

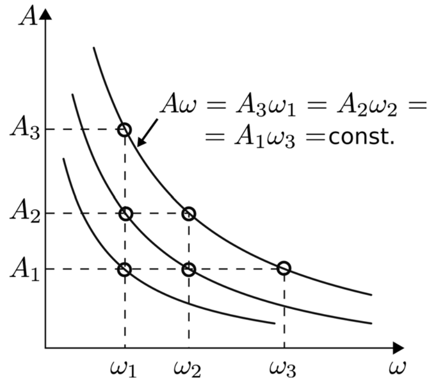

Figure 3. *Six pairs of movement amplitudes and frequencies were chosen in such a way that ω, A and Aω have three different levels. Aω on the same hyperbola means Aω = const.*

The device was controlled by a PC (AMD Phenom Quad-Core Processor, 2.2 GHz, 4 GB RAM), equipped with a Sensoray 626 DAQ Card running Gentoo Linux. The haptic environment including the delay was realized using an impedance control scheme and rendered in real time using the real time application interface (RTAI). Visual information was displayed on a 22 in LCD monitor with a refresh rate of 60 Hz. White background noise was played as background during the experiment using KOSS QZ99 headphones to mask the noise from the haptic device. Participants sat in an upright position centered toward the equilibrium point of the virtual spring, and the force field was rendered in the participant's transverse plane within a comfortable manual reachable range. Participants' responses were collected using a joystick. The setup is depicted in Figure 2.

In order to examine the influence of the frequency ω, amplitude A, and force discrepancy which is directly dependent on $A\omega$, six experimental conditions were selected in an orthogonal way; these are illustrated in Figure 3. The stimulus pairs were placed on three isoclines $A_i\omega_j = \text{const}$. The three movement amplitudes $A_{1,2,3}$ were set to 11.25 cm, 15 cm, and 20 cm, and the frequencies $\omega_{1,2,3}$ were set to 0.75 Hz, 1.0 Hz, and 1.33 Hz, respectively. The spring stiffness k was kept constant at 65 N/m. The overall experimental setup allowed stable interaction up to a delay of 150 ms.

3.3 Method and Procedure

Since Experiment 1 mainly focused on the detection threshold for haptic latency, we selected a synchrony/asynchrony judgment as the experimental task. We applied an adaptive double staircase method to keep testing brief and so avoid fatigue effects. With this method, two staircase sequences are randomly intermixed for each condition, one starting from a surely detectable delay level of 100 ms and the other from an undelayed setting. A modified version of the accelerated stochastic approximation method was implemented for each staircase sequence (Kesten, 1958). In the case of a "delayed" judgment, the haptic latency was reduced on the subsequent trial in the same sequence of the respective staircase, while the haptic latency was increased when a nondelayed judgment was made. The change in the magnitude of the time delay between two consecutive trials within the same staircase sequence was calculated following the adaptation rule

$$\tau_{n+1} = \tau_n - \frac{20}{1 + m_{\mathrm{rev}}}(Z_n - 0.5), \tag{9}$$

where τ_n denotes the magnitude of temporal delay on trial n and m_{rev} the number of reversals between the response categories. Z_n represents the user's response on trial n as $Z_n = 1$ for a force delayed judgment and

$Z_n = 0$ for a force undelayed decision; the initial step size was $\tau_1 = 20$ ms. The procedure stopped when (i) both staircases had converged after five response reversals and (ii) the mean difference of the last three trials between two sequences was less than 20 ms. Otherwise, the sequence was terminated after 40 trials. The synchrony/asynchrony detection threshold was then estimated by taking the mean values of the last six trials, three trials for each staircase sequence.

Before recording data, all participants were familiarized with delays in the linear spring force field in a preexperimental practice block. During practice, three different haptic latencies (0, 70, and 100 ms) were presented randomly, along with the value of the latency on the screen. Additionally, a dot on the screen moving in the desired sinusoidal way with a given frequency and amplitude indicated the required movement trajectory. The participant was asked to move the haptic device so as to follow the moving visual dot. In addition, two vertical bars marked the movement boundaries and rhythmic click sounds indicated the reversal time of the dot. In the formal experiment, there was no indication of the delay level and no visual guidance of the movement on the screen. We removed the guidance cue since a pilot study had shown that tracking the visual movement was a rather attention-demanding task, potentially interfering with the required temporal judgment. However, the click sounds were preserved to help users move in the right rhythm. The experiment was divided into six blocks; each block contained one of the six experimental conditions shown in Figure 3. At the beginning of each block, three practice trials (without visual guidance) with random latencies were presented before starting a double staircase procedure. The participants explored the system for 10 s and then indicated whether or not there was a force delay in the system by pushing the joystick to either the left (delayed system) or the right (undelayed system). The whole experiment took approximately 1 hr to complete.

3.4 Results

In total, 12 valid data sets were further analyzed; three participants' data had to be excluded due to failure of convergence of the double staircase sequences in two or more blocks. In 90% of all cases, the staircase procedure converged within 30 trials. An analysis of the movement trajectories revealed that all participants in the experiment made reasonably sinusoidal-shaped movements, although the amplitudes and frequencies deviated slightly from the desired motion trajectory (see Figure 4). The mean values of real amplitudes and frequencies are summarized along with mean threshold values and standard errors in Table 1.

The estimated mean thresholds for two factors are shown in Figure 5. All data sets (i.e., threshold estimates) were examined by a univariate analysis of

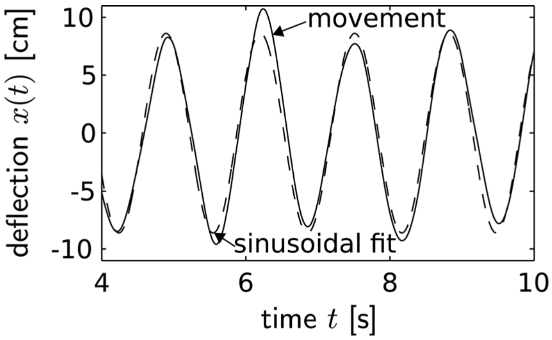

Figure 4. *An example of a manual movement with a given frequency and amplitude. The dashed curve denotes the best sinusoidal fit to the actual movement which is plotted as a solid line.*

Table 1. *Key Measures of the Actual Movement and Detection Thresholds with the Corresponding Standard Errors Observed in Experiment 1**

$\frac{1}{2\pi} \cdot \omega \left[\frac{1}{s}\right] / A$ [cm]	$\hat{\omega}/\hat{A}$	$T_d \pm SE$ [ms]
0.75/11.25	0.71/8.89	46 ± 4.5
0.75/15	0.70/10.45	47 ± 7.3
0.75/20	0.68/13.19	37 ± 6.3
1/11.25	0.93/8.62	41 ± 5.0
1/15	0.92/10.74	37 ± 4.2
1.33/11.25	1.24/8.65	36 ± 5.8

*In column 2, the mean of the actually observed movement amplitude $\hat{A}$ and frequency $\hat{\omega}$ are summarized; the last column presents mean thresholds with standard errors.

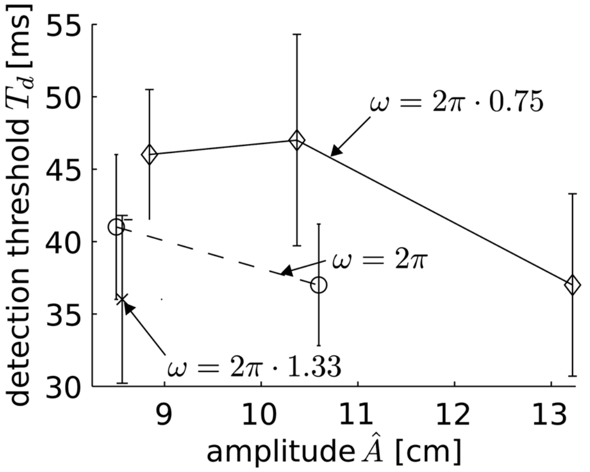

Figure 5. *Mean detection thresholds as a function of actual movement amplitude $\hat{A}$ and instructed frequency ω. Solid stars correspond to frequency $\omega = 0.75$ Hz, dashed circles to $\omega = 1$ Hz, and the cross to $\omega = 1.33$ Hz. Error bars indicate 1 SE.*

variance (ANOVA) with amplitude A and frequency ω as fixed factors, and subjects as the random factor. The analysis revealed the main effects of amplitude A and frequency ω to be significant, $F(2, 22) = 4.38, p < .05$ and $F(2, 22) = 4.79, p < .05$, respectively. A further contrast test for the factor of amplitude showed that the threshold was only significantly lower for $A = 20$ cm compared to the other two amplitude levels, $F(2, 56) = 3.83, p < .05$. Another contrast test for the factor frequency revealed that the thresholds decreased significantly when the movement frequency increased, $F(2, 56) = 5.87, p < .01$. A separate univariate ANOVA was conducted for the factor of $A\omega$, which revealed the main effect to be significant, $F(2, 22) = 6.42, p < .01$. A contrast test showed that the largest value of $A\omega$ resulted in the lowest threshold.

In order to further examine the relationship between the detection thresholds and the actual movements, we conducted a linear regression for the mean thresholds with $\hat{A}$ and $\hat{\omega}$,

$$T_{\mathrm{d}} = 84.5 - 2.32\hat{A} - 23.67\hat{\omega}, r^2 = 0.833, \qquad (10)$$

and a linear regression for the mean thresholds with $\hat{A}\hat{\omega}$,

$$T_{\mathrm{d}} = 63.75 - 2.69\hat{A}\hat{\omega}, r^2 = 0.815. \qquad (11)$$

Both linear regressions suggested that the independent movement parameters $\hat{A}$ and $\hat{\omega}$ and their product $\hat{A}\hat{\omega}$ are potentially influential factors for haptic feedback delay.

3.5 Discussion

Experiment 1 demonstrates that the detection threshold for haptic feedback delay depends on the participant's movement frequency ω and movement amplitude A. This is clearly inconsistent with the constant model (H1), according to which delay detection involves purely temporal perception. The detection threshold for haptic-feedback delay decreases when the movement frequency or amplitude increases ($r^2 = 0.833$), suggesting that participants infer the time delay through characteristics of their own movements—consistent with the exploration model (H2). However, the results are also in line with the force discrepancy model (H3), since $A\omega$ is directly related to the maximum force discrepancy from Equation 8 and the linear regression in Equation 11 revealed a high linear correlation between the detection threshold and the parameter $A\omega$ ($r^2 = 0.815$). Experiment 1 does not permit a decision between these two hypotheses.

4 Experiment 2

Recall that the environment in Experiment 1 had fixed properties, which made Equation 8 solely depend on the movement parameters $A\omega$. Therefore, to decide between hypotheses H2 and H3, we conducted a second experiment in which the stiffness parameter k was systematically varied. While the perceptual threshold predicted by H2 does not depend on k, H3 presumes that increasing stiffness results in a better discrimination performance.

4.1 Participants

Ten participants took part in Experiment 2 (two of them had taken part in Experiment 1; four male, six female, age range 21–29 yr). All had normal or corrected-to-normal vision and were right-handed; none of them reported any history of somatosensory disorders. Informed consent was obtained from all participants prior to the experiment.

4.2 Apparatus and Stimuli

The hardware setup was the same as in Experiment 1. In Experiment 2, two pairs of A and ω values were selected: ($A_1 = 20\,\text{cm}, \omega_1 = 0.75\,\text{Hz}$) and ($A_2 = 15\,\text{cm}, \omega_2 = 1\,\text{Hz}$), making $A\omega = \text{const.}$ In addition, three discriminable levels of spring stiffness were examined: $k_1 = 40\,\text{N/m}$, $k_2 = 50\,\text{N/m}$, and $k_3 = 65\,\text{N/m}$. The values of k_1 and k_2 were selected to be lower than k_3 (used in Experiment 1) in order to avoid fatigue during the experiment.

4.3 Method and Procedure

Instead of requiring participants to make a simple two-alternative forced-choice response, we used a two-interval two-alternative forced-choice (2I2AFC) paradigm in Experiment 2. We chose this method because some of the participants in Experiment 1 reported that they found it hard to remember the baseline (non-delayed) condition, making them adopt a conservative response strategy during the experiment. On each trial, two intervals were presented, one standard interval with nondelayed force feedback and one comparison interval with delayed force feedback. By providing a standard stimulus on each trial, the 2I2AFC procedure helps to reduce response bias and variability among subjects. The order of the standard and comparison (target) stimuli was randomized across trials. Each stimulus was presented for 7 s, with a transition phase between them. In the transition phase, the system latency was linearly transferred from one state to another to avoid cues arising from abrupt changes of system latency. After participants explored the two stimuli, they were prompted to respond to the question "In which interval of the trial did you experience a delayed force feedback?" to which they made a 2I2AFC decision. The adaptive double-staircase method was modified according to the changed experimental paradigm. While the detection threshold was defined at 50% in Experiment 1, it was raised to 75% in the 2I2AFC paradigm of Experiment 2. Therefore, the adaption rule for the step size was changed to

$$\tau_{n+1} = \tau - 2\frac{20}{1 + m_{\text{rev}}}(Z_n - 0.75), \qquad (12)$$

with the same terms as in Equation 9. After every three experimental blocks, there was a break permitting participants to take a rest. The remaining procedure, including the familiarization with time delay in the haptic feedback, was the same as in Experiment 1, and the whole experiment took about 2 hr to complete.

Table 2. *Key measures of the actual movement and detection thresholds with the corresponding standard errors observed in Experiment 2**

$\frac{1}{2\pi} \cdot \omega \left[\frac{1}{s}\right] / A\,[\text{cm}] / k\left[\frac{\text{N}}{\text{m}}\right]$	$\hat{\omega}/\hat{A}$	$T_{\text{d}} \pm SE$ [ms]
1/15/40	1.06/14.8	24 ± 4.5
1/15/50	1.08/14.8	25 ± 6.5
1/15/65	1.12/14.4	28 ± 9.3
0.75/20/40	0.84/18.5	34 ± 9.3
0.75/20/50	0.85/18.4	31 ± 4.5
0.75/20/65	0.84/18.7	37 ± 9.5

*In column 2, the actually observed movement amplitude $\hat{A}$ and frequency $\hat{\omega}$ are summarized; the last column presents mean thresholds with standard errors.

4.4 Results

One data set was excluded from further analysis due to the participant having failed to follow the required movement frequency. The mean discrimination thresholds, along with their standard errors, are summarized in Table 2.

Estimated from the actual movements, the mean values of the product factor, $\hat{A}\hat{\omega}$, were 15.9 and 15.6 for two movement pairs ($A_1 = 20\,\text{cm}, \omega_1 = 0.75\,\text{Hz}$) and ($A_2 = 15\,\text{cm}, \omega_2 = 1\,\text{Hz}$), respectively, that is, not significantly different from each other (paired t-test: $p > .1$). The individual threshold estimates were further examined by a univariate ANOVA with fixed factors ω (same as for A) and stiffness k and subjects as the random factor. This analysis revealed the factor ω (i.e., pair of $A\omega$) to be significant, $F(1, 8) = 9.46$, $p < .05$, while the factor k (stiffness) failed to reach significance, $F(2, 16) = 0.798, p > .1$. There was no significant interaction, $F(2, 16) = 0.245, p > .1$.

4.5 Discussion

Although the value of $A\omega$ was kept constant for the two parameter pairs ($A_1 = 20\,\mathrm{cm}, \omega_1 = 0.75\,\mathrm{Hz}$) and ($A_2 = 15\,\mathrm{cm}, \omega_2 = 1\,\mathrm{Hz}$), the detection thresholds were different. In the condition with the higher frequency $\omega = 1\,\mathrm{Hz}$, the detection thresholds were lower. This adds further support to the exploration model (hypothesis H2). When the movement amplitude A and the movement frequency ω were fixed, the detection thresholds remained constant at the same level regardless of changes in stiffness k. This suggests that the force discrepancy model (hypothesis H3) is not valid for delay detection in spring-type environments. The fact that environmental stiffness did not influence the detection threshold supports the argument that the force discrepancy provoked by haptic latency is not the key factor for latency detection within the force range examined in the present study. Note that the validity of this conclusion may be restricted to a certain range of the force feedback. For example, in free-space motion without any force feedback, the time delay of the system cannot be detected solely through active movement. On the other hand, very stiff environments become unstable with a small delay in the haptic loop. Thus, the user may infer (or recognize) the delay from an unstable state of the system.

Compared with Experiment 1, there is another interesting finding: The thresholds obtained in Experiment 2 were generally lower than those in Experiment 1. This may be due to the differential judgment method used in the two experiments, that is, a discrimination task in Experiment 2 versus a detection task in Experiment 1. By providing nondelayed force feedback on every trial, the discrimination task was easier than the detection task. Furthermore, because most trials in the double-staircase sequences in Experiment 1 were of the delayed force feedback type, some temporal visuomotor adaptation might also have contributed to the higher threshold estimates. It has been demonstrated that participants may adapt relatively quickly (within 5 to 20 min) to delayed visuomotor feedback and recalibrate temporal perception (Cunningham, Billock, & Tsou, 2001; Cunningham, Chatziastros, von der Heyde, & Bülthoff, 2001; Stetson, Cui, Montague, & Eagleman, 2006). Nevertheless, this did not influence the testing of the two alternative hypotheses.

5 General Discussion

Time delay is a critical issue for haptic telepresence systems operating over long distances. Challenges to be dealt with include technical issues such as system instability and, on the side of the human operator, impaired temporal perception. In order to better understand how time delay influences the operator, it is important to know first of all what factors affect the perception of time delay itself. In this article, we aimed to quantify the impact of manual movement frequency and amplitude as well as of the stiffness of the haptic environment on the detection of delay in haptic feedback. We found that:

1. The detection thresholds for time delay in force feedback are negatively correlated with movement frequency and movement amplitude.
2. Movement amplitude and frequency influence the delay detection separately.
3. Within a comfortable force range, scaling the feedback force does not affect temporal discrimination of the haptic delay.

The finding of the detection threshold being movement-dependent permits us to conclude that perception of delay in a continuous haptic environment is not based purely on an internal clock mechanism, as assumed by hypothesis H1. Instead, the interrelations between human detection thresholds and exploration movements support the dynamic perception-action theory (Warren, 2006). The results of the present two experiments suggest further that influential factors in the dynamic perception of time delay derive mainly from the operator's action (consistent with the "exploration model"), rather than changes in absolute force in the external environment (the "force discrepancy model").

The close relationship between detection thresholds and the operator's own actions points to important factors to be taken into consideration in design guidelines for haptic communication protocols: the operator's movement dynamics and the penetration depth into structures of the remote environment. A haptic task that requires only slow movements can tolerate longer delays in the feedback than a highly dynamic task requiring fast movements. In consequence, the dynamics of the local haptic interface and its workspace influences the maximum allowable time delay given by the detection threshold. With larger inertia and damping of the local haptic interface, the achievable human movement frequency decreases—resulting in a higher detection threshold for time delay. Similarly, the workspace dimensions of the local haptic interface limit the maximum movement amplitude—with detection thresholds showing a tendency to increase with smaller workspaces. Using the regression in Equation 10, guidelines for the maximum allowable time delays in spring-type environments can be derived based on the maximum movement frequency and amplitude.

The second finding, that scaling the remote force within a reasonable range does not influence the sensitivity of temporal perception, is especially interesting for the application in micromanipulation tasks. In this application area, small forces arising in a microscale environment must be augmented for the user to provide a perceptible haptic impression (Ando, Korondi, & Hashimoto, 2001). For the case of delayed haptic feedback, our finding suggests that the scaling factor can be chosen irrespective of haptic latency. Note, however, that we only validated this hypothesis for a limited range of stiffnesses. In extreme scenarios, such as stiff contact with a rigid object, an infinitesimally small time delay may result in an unstable system, which completely changes the characteristics of the system. The human operator may then be able to infer the time delay from increasing oscillations in the force feedback.

Though not in the main focus of this investigation, other studies reveal a general trend toward reduced task performance with increasing time delay in the force feedback (Jay et al., 2007). It is thus reasonable to believe that results from time delay perception experiments obtained in the current work can be partially transferred to task performance.

The failure of the simple force discrepancy model to make accurate predictions may be taken as a hint that the absolute force discrepancy is not the key factor for the detection of time delay. Possibly however, Weber's fraction of the force discrepancy could be an additional influential factor, since many perceptual limits follow the classical Weber law. Weber's law states that the JND of force discrimination increases linearly with the absolute force. Calculating the Weber fraction $\Delta f_{\max}/f(t)$ from Equations 8 and 4 reveals that it is independent of k, as this parameter cancels out in division, leaving only A and ω as determining factors. In other words, a perceptual threshold for time-delay perception considering the Weber fraction makes identical predictions to the exploration movement hypothesis in spring-type force environments. Further experiments would be necessary to decide between these newly derived alternatives.

Several questions for further research arise from the present findings. For example, it is currently unknown what factors would be important for delay perception in other haptic environments, such as environments with inertia and damping characteristics. In addition, it is appealing to explore the relationship between the movement frequency distribution of an arbitrary explorative movement and the time delay perception threshold, since human motion in teleoperation is not limited to sinusoidal trajectories.

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