Masking Effects for Damping JND

Markus Rank[1], Thomas Schauß[1], Angelika Peer[1], Sandra Hirche[1], and Roberta L. Klatzky[2]

[1] Institute of Automatic Control Engineering, Technische Universität München, Munich, Germany {m.rank,schauss,angelika.peer,hirche}@tum.de,
[2] Psychology Dept. and Center for the Neural Basis of Cognition, Carnegie Mellon University, Pittsburgh, USA klatzky@cmu.edu

Abstract. Two psychophysical experiments are conducted to identify masking effects for the perception of damping. The results indicate that the just noticeable difference for damping increases with the magnitude of additional masking stimuli. This is the case for environments consisting of a damping/stiffness and environments consisting of a damping/inertia. This has implications for the design and evaluation of haptic human-system interfaces, telepresence systems and haptic rendering algorithms.

Keywords: Psychophysics, masking effects, damping perception, telepresence, teleoperation.

1 Introduction

A simple model that can capture a wide range of haptic environments is a combination of inertia, stiffness, and damping. The perceptual limit of each isolated component is well-researched [1, 4, 7]. In real environments, generally more than one of these components is present, e.g., a damped inertia. It is unknown how well humans can discern a specific haptic property when it is combined with another one. In tactile perception, e.g., a masking signal is capable of affecting another signal, such that the discrimination of the second signal is strongly affected [2]. Similarly, interactions of force and torque were found in haptic perception [8], indicating that unrelated stimuli can also affect discrimination abilities in the haptic domain. Knowledge about interactions and masking effects can play an important role in the design of mechanisms, e.g., a hinge of a laptop that should convey a specific haptic impression to the user. In the field of telepresence, perceptual limits have been taken into account to analyze *perceived transparency* [3]. Hereby, the error between displayed and remote environment is evaluated in a human-oriented way. In this context, interactions between different environment parameters can be used to define perceptual limits more exactly.

We present two experiments to study masking effects in haptic environments. As a model for this environment we consider a mass-spring-damper system. As examining the just noticeable difference (JND) for each environment parameter masked by the other two environment parameters would result in a huge number of conditions, we examine only the JND for damping. Damping was chosen for two reasons: On the one hand, it can be assumed that the largest masking effect between two stimuli is achieved if they are as similar as possible. The frequency responses of stiffness and inertia differ from that of damping by a phase shift of only $\pm 90°$, whereas the phase shift between stiffness and inertia is $180°$. On the other hand, damping is of significant importance for controller design, as higher damping can enlarge stability margins.

Suitable stimuli for the main experiment are determined in a pilot study which is presented in the next section. In Sec. 3 the main experiment which examines JNDs with masking effects is presented. Results of this experiment are given in Sec. 4. The paper is concluded by a summary and outlook.

2 Pilot Study for Stimulus Selection

Two different damping levels $d_1 = 10$ Ns/m and $d_2 = 20$ Ns/m which are above the absolute detection threshold and small enough to prevent fatigue were chosen. These stimuli are easily discriminable, as JNDs for viscosity are reported between 13.6% [1] and 34% [4]. In this pilot study, we separately determine parameter values for stiffness and inertia that will be used in the main experiment to mask damping. For each parameter, we further distinguish between two cases: In the first case, humans should perceive the overall environment as a combination of damping and stiffness or damping and inertia, where neither dominates the other. For this case, the values for stiffness and inertia are denoted as k_1 and m_1. In the second case, humans should perceive an environment consisting mainly of stiffness or inertia. Damping should still be perceivable but should be subordinate. In this case, stiffness and inertia are denoted as k_2 and m_2.

To find these values, participants were asked to modify an environment consisting of damping and a minimal inertia $m_0 = 0.5$ kg, which was necessary to ensure system stability. The participants could add stiffness or inertia by using a turning knob. In the conditions where stiffness had to be added, one full turn of the knob corresponded to 10 N/m; for inertia, one turn was equivalent to a change of 1 kg. Subjects were asked to produce two different conditions: One, where the impression of stiffness or inertia was slightly subordinate to damping (k_{sub}, m_{sub}), and a second, where stiffness or inertia was the slightly more dominating stimulus (k_{dom}, m_{dom}).

The study was performed by 10 subjects including two of the authors. One of the subjects was female and all were PhD students. Their mean age was 27.0 years. All gave their informed consent to participate in the study. Prior to the experiment, all participants were familiarized with the setup and the conditions by exploring environments consisting of pure inertia, pure damping, and pure stiffness. All participants completed the experiment in less than 20 minutes.

2.1 Experimental Setup

The haptic environments were rendered on a ServoTube linear actuator (Copley Controls Corp.) equipped with an optical encoder of 1 μm resolution. The device

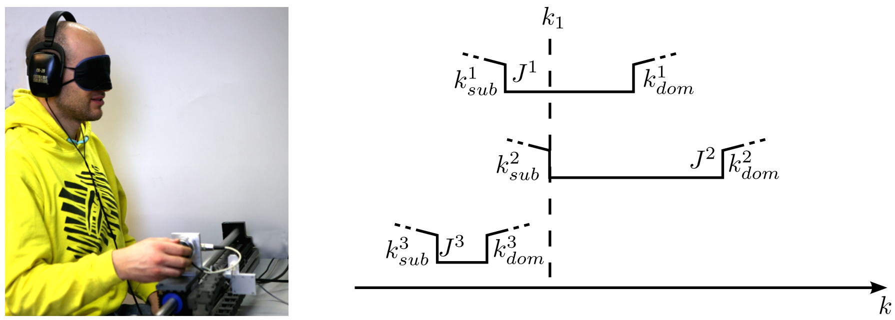

Fig. 1: A linear haptic interface (left) was used to determine the interval boundaries for k_1, which is identified using optimization techniques (right). Different cost functions $J^{1\cdots3}$ are associated with individual participants.

was controlled by a PC, running Ubuntu Linux with the CONFIG_PREEMPT_RT kernel patch and equipped with a Sensoray 626 DAQ card. The haptic environments were realized using a position-based admittance control scheme and rendered in real-time with a sample rate of 1 kHz. Participants' ears were covered by EX-29 headphones playing pink noise to cancel out the sound from the haptic device, and their sight was blocked by eyemasks to eliminate visual cues. The experimental setup is illustrated in Fig. 1 (left).

2.2 Results and Stimulus Selection

In principle, every value of stiffness in the interval $[k_{sub}, k_{dom}]$ is perceived as approximately equally dominating by the individual subject. Due to the large between-subject variance, it is not possible to find one value k_1 that is within $[k_{sub}, k_{dom}]$ for all subjects. Therefore, the number of participants that felt k_1 as equally dominating as damping is to be maximized. In addition, as this solution may not be unique, we minimize the mean distance between k_1 and the individual intervals $[k_{sub}, k_{dom}]$. The corresponding optimization problem can be written as

$$\arg\min_{k_1} \sum_{i=1}^{n} \sum_{j=1}^{2} J_j^i \quad \text{with} \quad J_j^i = \begin{cases} 0 & \text{if } k_1 \in \left[k^i_{sub,j}, k^i_{dom,j}\right] \\ c_{step} + k_1 - k^i_{dom,j} & \text{if } k_1 > k^i_{dom,j} \\ c_{step} + k^i_{sub,j} - k_1 & \text{if } k_1 < k^i_{sub,j} \end{cases}$$

where $k^i_{sub,j}$ and $k^i_{dom,j}$ are the subordinate and dominant value of stiffness that is set by participant i for damping d_j, and c_{step} is a constant of large value (here 1000) to penalize solutions where $k_1 < k^i_{sub,j}$ or $k_1 > k^i_{dom,j}$. The number of participants is denoted as n. An analogous problem can be formulated to determine the inertia m_1. Examples of perceptual intervals and the corresponding cost functions are depicted in Fig 1 (right). Using this procedure, a stiffness $k_1 = 19.0$ N/m and an inertia $m_1 = 2.8$ kg were determined.

The values k_2 and m_2 should be perceived as dominating over damping. Hence, the maximum value for stiffness k_{dom} and inertia m_{dom} that were reported by the participants was taken. One dataset was excluded for k_2 as an outlier because it was outside a band of two standard deviations around the mean. Following this procedure, $k_2 = 42.4$ N/m and $m_2 = 5.3$ kg were determined.

3 Damping Discrimination Experiment

The main experiment was designed to determine the discriminable differences of damping in haptic environments that simulate damping along with inertia or stiffness. The aim of this design was to identify potential masking properties of those distractive stimuli. In total, 10 conditions were tested: JNDs for the damping parameters $d_{1,2}$ alone and with masking stimuli of either $m_{1,2}$ or $k_{1,2}$. To assure stability of the low-level position-based admittance controller, a minimum inertia m_0 of 0.5kg was always present.

The experiment was performed by 8 paid subjects from different disciplines with a mean age of 28.5 years. All of them gave their informed consent before participation. Two of them had experience with haptic devices, three were female and all were right-handed. Before starting the main experiment, all participants were familiarized with the stimuli and procedure: pure inertia, damping, stiffness, and combinations of damping together with inertia and stiffness were presented, each followed by information about the specific environment.

In each experimental trial, the control condition and a stimulus condition was presented for 4 seconds each. The order of the two conditions was randomized. The two conditions were separated by a one-second break during which the device returned to the initial position. The participant was notified of the break by a beep displayed over the headphones. Participants had to decide which block was more damped. In addition, they were allowed to respond that they did not know. Based on the participants' answer, the stimulus was modified after each trial using an adaptive-staircase threshold estimation procedure [5]. The adaptive estimation of the damping JND for one control condition took 20-30 trials. All 10 conditions were presented twice, once starting the staircase from below and once from above the control condition. The order of control conditions was fully intermixed. Five staircase procedures were combined into one experimental session which was completed in about 30 minutes. After three JND estimation procedures, a break of 5 minutes was inserted. In total, four experimental sessions were performed, separated by a break of at least 30 minutes to avoid fatigue. The experimental setup was the same as described in Section 2.1.

4 Results

Percentual damping JNDs (relative to the control conditions) for different masking stimuli are depicted in Fig. 2. In order to determine effects of both types of masking stimuli, two 3-factor, repeated-measures ANOVAs for $r \times d \times m$ and $r \times d \times k$ were performed, where r is the repetition (1,2). The main effect of

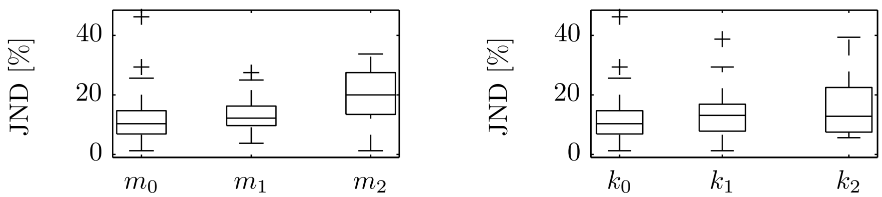

Fig. 2: Damping JNDs differ depending on inertia (left) and stiffness (right).

inertia m shows a significant influence ($F(2, 14) = 5.37$, $p < .05$, $\eta_p^2 = .43$) as does stiffness k ($F(2, 14) = 6.26$, $p < .05$, $\eta_p^2 = .47$). The main effect of d, Greenhouse-Geisser corrected for sphericity, is not significant in either ANOVA ($F(1.00, 7.00) = 1.79$, $p = .22$ and $F(1.00, 7.00) = 1.44$, $p = .27$). The effect of repetitions, also Greenhouse-Geisser corrected, is insignificant as well ($F(1.00, 7.00) = 0.66$, $p = .45$ and $F(1.00, 7.00) = 1.74$, $p = .23$). No interactions were found in either ANOVA.

Polynomial trend analyses showed significant linear trends relating the damping JND to both inertia and stiffness while quadratic trends were not significant[3]. For inertia, 85% of the main effect was accounted for by the linear trend ($SS_m = 1017.9$, $SS_{m,\text{linear}} = 862.9$, $p < .05$)[4]. For stiffness, 99% of the main effect was accounted for by linearity ($SS_k = 239.5$, $SS_{k,\text{linear}} = 236.9.9$, $p < .05$).

The results indicate that damping JNDs depend on the overall composition of the environment. In the cases where inertia or stiffness dominate the perception of the environment, the discrimination of damping apparently becomes harder.

5 Implications

In [3] the concept of *perceived transparency* is introduced which extends the classical transparency evaluation in a human-oriented way by including perceptual limits. Whether or not communication time delay and control parameter settings in a two-channel teleoperation system could be perceived by the human user through the effects of those parameters on the displayed inertia, damping, and stiffness is predicted in [3]. The novel findings suggest, that these predictions could be overly conservative in general, as only perceptual limits for individual parameters are considered. Perceptual limits and masking effects can also extend a new method for the analysis of four-channel teleoperation systems [6], which approximates the transparency error using a mass-spring-damper model.

The design of mechanisms with multiple predefined haptic properties is another application for which our results are relevant. For a mechanism with large

---

[3] As the different levels of inertia and stiffness are only approximately equally spaced, the linear trend is approximate. The significant linear trend indicates at least a monotonic relationship between damping JND and value of m/k. As linear regressions fit to the exact values of m and k only minimally improved the fits, the noise introduced by unequal spacing appears to be minimal.

[4] SS stands for *Type III Sum of Squares.*

inertia, e.g., a certain tolerance in the damping components is permissible. More generally, interactions among the desired haptic properties can and should be considered. Similarly, haptic rendering algorithms cannot always reflect all environmental properties sufficiently. For stiff environments, e.g., a certain amount of damping is necessary to assure stability. Therefore, damping could be adjusted in a way that ensures stability while not being perceivable to the operator.

6 Summary and Outlook

Two psychophysical experiments were conducted to investigate the impact of masking on the JND of damping. The discrimination abilities for damping deteriorated with additional stiffness as well as inertia. This phenomenon can be utilized in the design and evaluation of human-system interfaces, haptic rendering algorithms, telepresence systems, and mechanical systems in general.

The next steps towards understanding the underlying mechanism causing the changes in JND is a time-series analysis of the force and position data that were recorded during the experiments. Furthermore, combinations of motion and force, such as work cues may contribute to damping discrimination.

Acknowledgments This work was supported in part by a grant from the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction". The authors furthermore thank the Alexander von Humboldt Foundation.

References

1. Beauregard, G., Srinivasan, M., Durlach, N.: The manual resolution of viscosity and mass. In: ASME Dynamic Systems and Control Division. vol. 1, pp. 657–662 (1995)
2. Gescheider, G., Bolanowski, S., Verrillo, R.: Vibrotactile masking: Effects of stimulus onset asynchrony and stimulus frequency. Journal of the Acoustical Society of America (1989)
3. Hirche, S., Buss, M.: Human perceived transparency with time delay. In: Advances in Telerobotics, Springer Tracts in Advanced Robotics, vol. 31, pp. 191–209. Springer Berlin / Heidelberg (2007)
4. Jones, L., Hunter, I.: A perceptual analysis of viscosity. Experimental Brain Research 94(2), 343–351 (1993)
5. Kaernbach, C.: Adaptive threshold estimation with unforced-choice tasks. Perception & Psychophysics 63(8), 1377–1388 (2001)
6. Schauß, T., Peer, A.: Parameter-space transparency analysis of teleoperation systems. In: IEEE Haptics Symposium (HAPTICS). pp. 111–116 (2012)
7. Tan, H., Srinivasan, M., Eberman, B., Cheng, B.: Human factors for the design of force-reflecting haptic interfaces. Dynamic Systems and Control 55(1), 353–359 (1994)
8. Wu, B., Klatzky, R.L., Hollis, R.L.: Force, torque, and stiffness: Interactions in perceptual discrimination. IEEE Transactions on Haptics 4(3), 221–228 (2011)