

Perception of Compliant Environments through a Visual-Haptic Human System Interface

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Abstract—Perception of compliant environments through a human system interface with visual and proprioceptive feedback is investigated. Participants had to explore the virtual environment by gripping with two fingers. Haptically, compliance was generated by an admittance control scheme. Perception of compliance under conflicting multimodal information was analyzed using an adaptive staircase method. Inter alia, experiments showed that conflicts could be detected when compliances by both modalities differ more than 55%.

I. INTRODUCTION

A human system interface (HSI) enables a human operator to perceive and act in virtual or remote environments (see Figure 1). Perception and manipulation capabilities can be increased by feeding multimodal (e.g. visual and haptic) information of the target environment back (for an overview see [1]). Hence, haptic feedback is most crucial

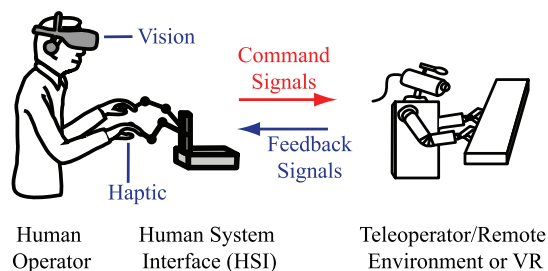


Figure 1. Multimodal human-robot interaction: Visual and haptic information are fed back increasing performance of telepresence and VR systems

since mechanical energy is exchanged over command and feedback signals. This closed feedback loop is susceptible to different kinds of disturbances and can even become instable (e.g. [2], [3]). Therefore, at the operator's site incongruences between visual and haptic information about the target environment can occur. However, humans can perceive even incongruent bimodal information without any conflict. Measurement of this perceptual process requires an HSI with high accuracy and extensive experiments using psychophysical procedures.

It is known that information of more than one modality is integrated to form a coherent percept (e.g. [4], [5]). Precondition of integration is spatial as well as temporal congruence of information (e.g. [4], [5]). However, if an intermodal conflict is below threshold of perception, integration still takes place (e.g. [6]), even though only one modality has been attended (e.g. [7]). In this context, Marks introduces the terms *stimulus* and *perceptual congruence* (see in [6], pp. 85-105): Stimulus congruence denotes that there are no differences in the physical stimulus parameters of an object. Even without physical congruence of stimulus parameters the discrepancy remains to some extent unnoticed: Perceptual congruence is psychological construct. Because a qualitative difference of the integrated percept depending on physical or perceptual congruent stimulus presentation has been observed, different mechanisms may be involved [?], [?]. Even decisional processes are discussed to contribute to the psychological phenomenon of perceptual congruence (see [?]). Therefore, attentional processes might influence integration and the extent of discrepancy, respectively (see e.g. [5], [8]). One branch of integration theory states that information of two or more modalities are combined by differently weighting them (e.g. [9], [10]). The relative contribution of each sense depends either on the appropriateness (e.g. [11]), the effectiveness (e.g. [12]) or the reliability (e.g. [13], [14]) of each modality, or on the direction of focusing attention (e.g. [15]). A wealth of research into visual-haptic integration exists and has concentrated either on size (e.g. [13], [16], [17]), shape (e.g. [18]–[20]) or texture perception (e.g. [21]–[23]), as well as on visual influence on proprioceptive localization (e.g. [24]–[26]), respectively. Bimodal perception of compliance information has evoked only few studies yet [27], [28]. Most of the research on integration indicates visual dominance over the haptic modality (for a review see [6], [11]), especially in spatial properties (e.g. [12]). Moreover, some factors, such as age (e.g. [29]), response modality (e.g. [30]), instruction (e.g. [31]) or noise (e.g. [13]), have been found to reduce visual influence. Some studies even show tactile dominance over vision (e.g. [21], [22], [32]) or at least in some tasks (e.g. [33]). Visual dominance there-

fore is no general phenomenon and depends on additional task relevant factors.

The contribution of this article is to identify the minimal allowable intermodal conflict, the just-noticeable difference or *JND* (see e.g. [34]), when perceiving object compliance through a visual-haptic HSI. Three hypotheses were tested. *Hypothesis 1*: Attending separately to information of two modalities arising from one source might introduce a high bias: The human perceptual system tries to integrate even conflicting information to provide a coherent percept, especially if information is derived from one source (see [4], [5]). Therefore, direct comparison of visual and haptic information should result in reduced detection performance (further referred to as method A). On the other hand, a low discrepancy threshold should result when attending to the object as a whole, and hence to compare between an object presented with bimodal congruent or increasing intermodally incongruent information (method further referred to as method B). *Hypothesis 2*: Most of the research on visual-haptic integration reports visual capture in intermodal conflict situations (see above). It is therefore expected that visual dominance should occur: The detection of intermodal discrepancies in object compliance should be impaired when the visual modality remains unaltered (as the target or reference modality) and hence the haptic modality varies. *Hypothesis 3*: As has been shown in different studies (see above), visual dominance seems not to be a general phenomenon and to depend on task relevant factors. It is expected that modality dominance is not constant over the whole stimulus range of object compliance: Low compliant objects provide scant visual compliance information, whereas high compliant objects might be easier perceived when relying on visual information. All three hypotheses were tested regarding influence of assessment method, reference modality (i.e. unaltered target modality), and reference compliance with respect to the perception threshold. This article is organized as follows: In Section 2 the HSI is introduced. Methodical matters are explained in Section 3. The results are presented in Section 4 and discussed in Section 5. A conclusion is presented in Section 6.

II. HUMAN SYSTEM INTERFACE

A. Hardware and Software

The human system interface (HSI) provides visual and proprioceptive (haptic) feedback. Furthermore, it measures finger positions and forces. See Figure 2 for a photo of the device and Figure 3 for a sketch of the haptic subsystem.

Proprioceptive information is exchanged via a haptic interface comprised of two SCARA robots providing a single degree of freedom each. The system interacts with index finger and thumb to allow gripping movements. High fidelity components like Maxon motors and Harmonic Drive Gears enable best possible control. Workspace is about 80 mm and maximum force is about 35 N. Position information is

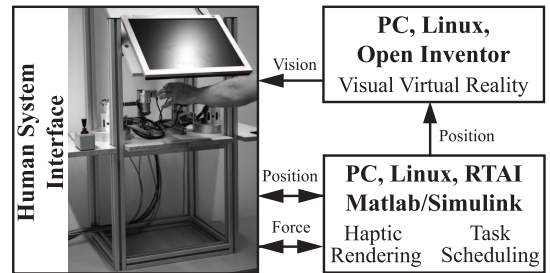


Figure 2. Human system interface and real-time processing unit: Visual and proprioceptive (haptic) information is fed back and positions are sensed.

measured by angle encoders and force is sensed by strain gauges attached on both robot links. Visual information is provided over a TFT screen. Thereby, the compliant environment is represented by a grey cube squeezed by two orange spheres (on opposed cube sides) representing finger positions (see Figure 4). The TFT screen is slanted by 40° and mounted in the line of sight to the hand enabling participants to look at the display as if there were looking at their hand¹. The system is connected to a PC running

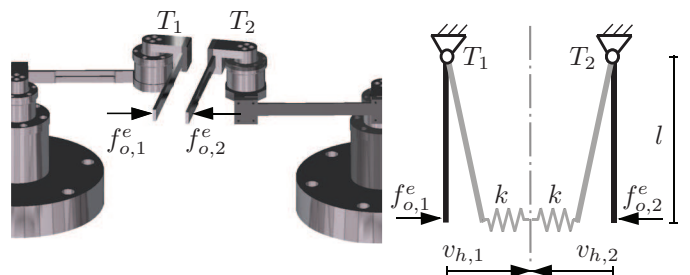


Figure 3. Kinematical structure of the haptic display: Two SCARA robots present compliance information for gripping movements.

RTAI-RealTime Application Interface for Linux. SCARA sensor signals are recorded by a "Sensoray 626" DAQ-Card providing 16 bit sensing resolution. Signal processing algorithms are implemented as Matlab/Simulink models with real-time code generated automatically. The system operates at 1 kHz sampling frequency. Measured positions are transferred to a second PC running the visual virtual reality programmed in Open Inventor.

B. Dynamics and Control

The identical robots of the HSI are controlled independently using the same admittance control scheme (see Figure 3 for kinematical configuration). In the following, the concept is explained using a single robot system without loss of generality. Furthermore, the explanation is restricted to translational movements only (kinematical transformation are ignored) since robot links are only moved little when performing the gripping tasks.

¹The tool transformation has no influence on the dynamics of the gripping movement, if participants are given a learning phase (e.g. see [35])

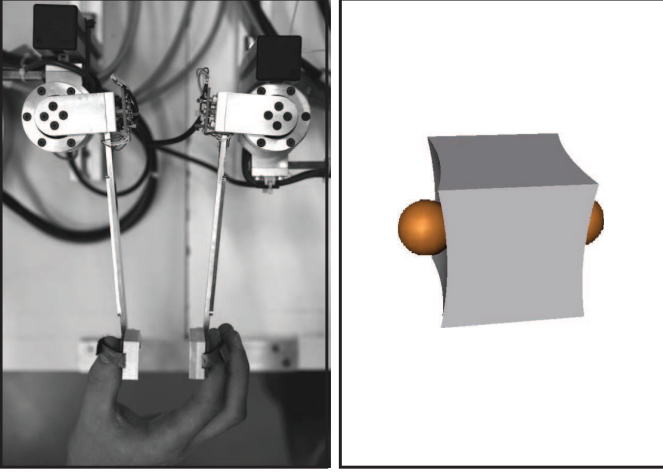


Figure 4. Haptic and visual feedback: The haptic feedback renders a compliant cube to be explored by thumb and index finger. In the visual feedback fingers are replaced by orange spheres.

For dynamics consider a mechanical robot with a single translational degree-of-freedom. The dynamical equation is given by

$$M_h \dot{v}_h + n_h = g_h - f_o^e \quad (1)$$

Where $M_h \in \mathbb{R}$ and $n_h \in \mathbb{R}$ denote mass and nonlinearities of the robot. Robot force $g_h \in \mathbb{R}$ depends on motor torque T and on link length l , respectively (Figure 3). The velocity of the tool tip is denoted by v_h . Input-output linearization [36] is achieved by commanding

$$g_h = f_h^m + n_h. \quad (2)$$

The resulting linear dynamics are

$$M_h \dot{v}_h = f_h^m - f_o^e. \quad (3)$$

Where f_h^m is the new motor force of the linearized HSI. A velocity controller, $C_v : U \rightarrow M$, realizes the command signal f_h^m according to

$$f_h^m = G_h(C_v(v_v - v_h)). \quad (4)$$

Where G_h represents the dynamics of the actuator, which can be reduced to the dynamics of the current control.

The HSI is serially connected to the human operator, whose fingers are described by the dynamics $Z_o : U \rightarrow M$. The velocity of the HSI and the velocity of the operator's fingers are opposite

$$v_h = -v_o. \quad (5)$$

The dynamics of the robot interacting actively with the human operator are described by

$$f_o = Z_o(v_o) + f_o^m. \quad (6)$$

Where f_o^m is the force actively intended by the human operator impeded by the force f_o that mediates the virtual reality (VR).

The dynamics of the VR is described by the admittance $Y_v : U \rightarrow M$, which represents pure stiffness yielding

$$v_v = Y_v(k, f_m^e) = k^{-1} \frac{df_m^e}{dt}. \quad (7)$$

Where k [N/mm] is the stiffness coefficient (compliance k^{-1}) whose perception is addressed in this publication. The control concept employing inner velocity control driven by a virtual reality with force reference is called admittance control. It is best suitable for rendering non-rigid environments like compliant environments (see [37] for detailed information). Minimum compliance (= maximum stiffness) that can be rendered is $k^{-1} = 0.2$ mm/N.

A block diagram of the human operator interacting with the haptic human system interface is depicted in Figure 5. Hollow arrows depict physical interactions, filled arrows are used for signal interactions. All subsystems are considered to be linear and time-invariant. The fidelity of the VR

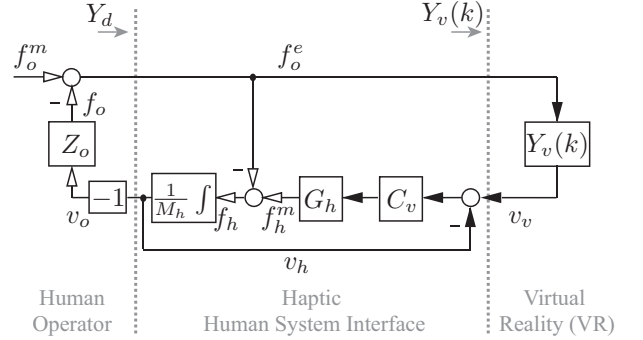


Figure 5. Admittance control: The haptic virtual reality is induced using different stiffnesses. High performance is achieved through light weighted robot.

depends on dynamics and control of the HSI. The robot is light weighted, dynamics of the motor current control are negligible, and velocities are small (i.e. friction effects negligible). Consequently, the transparency of the system can be assumed as nearly ideal and the displayed dynamics Y_d can be considered equal to the dynamics of the VR

$$Y_d = Y_v. \quad (8)$$

III. METHOD

A. Participants

32 students of the Technische Universität München and the Universität der Bundeswehr München took part in this study and were paid for participation. Half of the participants were assigned to group A (method A), the other half to group B (method B). Due to missing values, two (group A) and five participants (group B) had to be excluded from further analysis. The average age of participants amounted to 25 years (group A) and 26 years (group B). Eleven men and three women (group A) and six men and five women (group B) participated. All of them were right-handed and had normal or corrected to normal vision.

B. Stimuli

Seven stimuli with different reference compliances were selected covering a broad range realizable by the HSI. Reference compliance (k_{ref}^{-1}) amounts to 0.2, 0.4, 0.5, 0.8, 1.4, 2.5 or 4.9 mm/N.

Additionally, intermodal discrepancy should be assessed with either the visual or the haptic modality remaining unchanged and therefore being the reference modality: Reference compliance of the unchanged modality was one of the seven values, whereas compliance of the comparison or non-target modality was varied according to the procedure described in Section 9.

C. Design

Two methods of assessment has been defined: Method A demands comparing visual and haptic information directly within one trial and to decide whether sensory information deviates from each other, while participants have to sequentially method B compare a congruent with an incongruent stimulus. With both methods a total of 14 threshold values had to be assessed, namely each reference stimulus (7) and target modality (2) combination. In order to reduce overall testing time for participants, method of assessment was chosen to be a between-participants-variables and testing of the 14 experimental conditions was divided into two sessions with seven randomly chosen stimuli. Within one of each test sessions seven experimental conditions were randomly chosen with the following restrictions: Neither the same reference compliance nor the same reference modality were presented in succession.

Because the ability to be drawn into a book, film or VE, better known as *immersive tendency* (see [38]), has been known to play an important role in designing human-machine-interaction, discrepancy of bimodal information might be mediated by this personal factor. Therefore, an additional 12-item questionnaire was included to control for that variable ([38], translated by [39]): Immersive tendency was assessed by answering 12 items building the two factors, *tendency to get emotionally involved* and *degree of involvement* (see [39]).

An additional group specific question was included in the demographical questionnaire: Group A rated under which reference (unchanged) modality they felt easier to perform the task, whereas group B rated the sensory information they mostly had relied on during test sessions.

D. Experimental Procedure

Participants were seated in front of the HSI with their dominant hand grasping the device and while looking nearly perpendicular at the screen. They were carefully instructed according to their group membership to which they were randomly assigned. A short training had to be completed prior to each test session. Afterward, 7 experimental conditions (one test session) were randomly presented. Participants explored the stimulus depending on their group membership and responded by moving the

joystick.

The start and end of each trial was signaled by a sound. Duration of stimulus presentation depended again on group membership: Group A compared visual and haptic information for 4s with an intertrial-interval amounting to 4s. Group B tested the stimulus compliance for 2s with an interstimulus-interval of 2s and an intertrial-interval of 4s. Masking of environmental noise was regarded to be not necessary due to the HSI making no disturbing noise which might influence the participants' responses.

At the end of the second test session participants filled in questionnaires assessing their demographical data, their experience during testing (additional group specific question) as well as the immersive tendency questionnaire.

E. Procedure of measuring the JND%

Two different methods of measuring the perception threshold according to the group variable have been established (method A, B). However, both methods targeted the perception threshold or JND% is defined as

$$\text{JND}\% = \frac{S - S_{\text{ref}}}{S_{\text{ref}}}. \quad (9)$$

The psychophysical procedures to derive the JND% was chosen to be an adaptive staircase method targeting the 50% performance level (e.g. [40]). Starting stimulus as well as step size were adopted according to group membership (task scheduling, see Figure 2).

Group A. Participants were instructed to directly compare within one trial information from both modalities given the reference modality which was announced by the experimental instructor prior to measurement. Therefore, the experimental task was to make cross-modal comparisons and to choose between two response alternatives, namely "difference" vs. "no-difference".

Threshold measurement started with the comparison stimulus

$$k^0 = 2k_{\text{ref}} \quad (10)$$

while step size was adapted according to

$$k^1 = k^0 - xk_{\text{ref}}. \quad (11)$$

After the third transition point step size was reduced from $x_1 = 0.1$ to $x_2 = 0.03$. Congruent stimuli were interspersed with a probability of 10%. After having reached the threshold ten times, threshold measurement ended: The perception threshold was computed as the mean across all ten transition points. JND% was derived according to 9.

Group B. Participants explored two objects sequentially one of which characterized by a discrepancy and the other being the congruent one. Reference modality was not announced by the experimental instructor. The participants' task was to decide whether the second stimulus felt more or less compliant than the first or whether there was a difference between the first and second stimulus.

Threshold measurement started with the comparison stimulus yielding a discrepancy of

$$k^0 = k_{\text{ref}} + 0.8k_{\text{ref}} \quad (12)$$

while step size was varied according to 11. Until the third transition point has been reached, step size amounted to $x_1 = 0.1$ and was then reduced to $x_2 = 0.03$. Congruent comparison stimuli were interspersed with a probability of 5%. After having reached the threshold six times, the sequence ended. The perception threshold was defined by the mean of the six transition points. JND% was derived according to 9.

IV. RESULTS

A. Immersive tendency

Participants rated their immersive tendency on a 7-point-scale building the two factors *emotional involvement* and *degree of involvement* which were computed for each participant. Group A showed an average emotional involvement of 23.3 (standard deviation sd 5.8) and an average degree of involvement of 25.6 (sd 6.9), whereas mean emotional involvement amounted to 16.8 (sd 4.4) and mean degree of involvement to 24.6 (sd 8.7) in group B. All values did not statistically significant differ from those reported by Scheuchenspflug [39], indicating that the participants are a good sample of population.

In order to find out whether the two groups (A, B) differed from one another regarding the immersive tendency, because there seemed to be a difference in emotional involvement at least descriptively, a t-test for independent groups was computed. No difference in degree of involvement could be found ($t(21)=0.3$, $p=0.8$). However, both groups differed statistically significantly in their emotional involvement ($t(21)=3.0$, $p<0.05$): Group A rated to be higher emotionally involved than group B. However, only 29% of variance could be explained by this effect which therefore can be neglected.

Group A. No correlation between emotional involvement and performance could be observed. Only two variables when the haptic modality was the (unaltered) target modality showed a statistically significant (significance-level of 5%) correlation with degree of involvement: Reference compliance of 2.45 mm/N (Spearman $\rho = +0.7$) and of 0.42 mm/N ($\rho = -0.8$). A positive correlation indicates a higher JND% along with a higher degree of involvement, whereas a negative correlation indicates better performance (reduced JND%) with a higher degree of involvement.

Group B. Additionally, emotional involvement had no influence on performance, whereas degree of involvement statistically significantly influenced perception threshold: With the visual modality being the target modality and a reference compliance of 0.42 mm/N a positive correlation could be observed ($\rho = -0.7$).

B. Group specific question

Participants answered an additional question according to the modality which facilitated the given task (group A) and according to the modality participants mostly attended to (group B). To determine whether there was an influence on performance or a relation to immersive tendency separate correlation analyses for both groups (A, B) were computed.

Group A. Participants answered performing the task was easier when the reference modality was either the haptic (n=2) or the visual (n=4) modality or both together (n=8). There was neither a correlation with immersive tendency nor performance (according to 9).

Group B. Participants reported that they primarily attended the haptic modality (n=5), the visual modality (n=3), both modalities without preference (n=2). Rating of the attended modality affected statistically significantly (significance-level of 5%) performance when the visual modality was the (unaltered) target modality: Reference compliance of 0.5 mm/N ($\rho = +0.7$) and 0.42 mm/N ($\rho = +0.8$) indicating higher performance when attending to the haptic modality, medium performance for the visual and lowest performance when attending to both modalities. However, there was no correlation with immersive tendency.

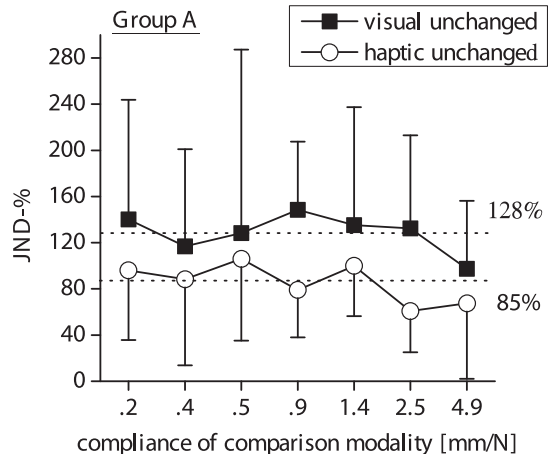


Figure 6. Group A compared visual and haptic compliance information of one object directly: Mean JND% is higher when the visual modality is the (unaltered) target modality.

C. Descriptive analysis: JND%

As has been described in Section 9, JND% were computed for each experimental condition within both groups and indicated the minimal perceivable discrepancy of intermodal information. The mean performance can also be seen in Table I.

Group A. As can be seen in Figure 6, reference modality affects performance: When the visual modality remains unchanged during testing, the threshold of detecting discrepancies increases. This indicates visual dominance. No

influence of reference compliance nor an interaction can descriptively be observed (see Figure 6).

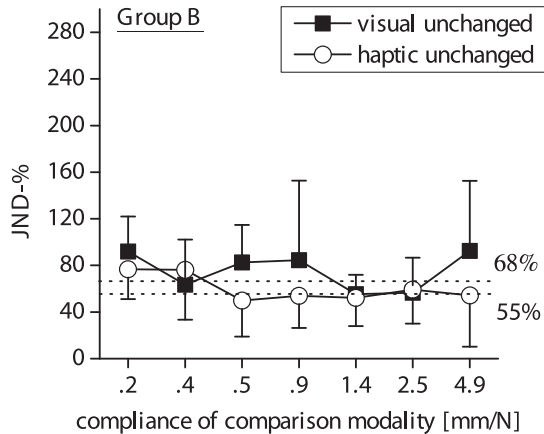


Figure 7. Group B compared two compliant objects differing in intermodal information sequentially: Mean JND% is higher in only some stimuli when the visual modality is the (unaltered) target modality.

Group B. Group B showed overall higher performance than group A (see Figure 7): Mean JND% is lower and standard deviation are smaller indicating that group B showed higher sensitivity. Again, there seems to be an influence of reference modality on JND%, but only in some reference stimuli. Most of the participants who had to be excluded were unable to perform the tasks when the visual modality remained unaltered and thus more likely when attending to the visual modality.

D. Testing the predictions

In order to determine the influence of reference compliance (0.22 to 4.88 mm/N) and reference modality (visual, haptic) depending on assessment method (A, B) on the ability to detect discrepancies in intermodal information, a 7x2x2 analysis of variance (ANOVA) with repeated measurements and method as between-participants-variable was computed (significance level of 5%).

Threshold was significantly different in both groups ($F(1,23)=9.5$, $p<0.05$; partial $\eta^2=0.29$): Group B showed higher sensitivity, i.e. detected smaller discrepancies in intermodal information. Additionally, target modality influenced the JND%: Performance was higher when the haptic modality was reference modality and therefore the visual modality was changed during the testing ($F(1,23)=8.6$, $p<0.05$; partial $\eta^2=0.27$). No interaction of target modality and reference compliance could be observed ($F(6,138)=0.7$, $p=0.6$). No other effects reached statistical significance.

However, effect size (partial η^2) of both main effects is very low and, as can be seen in Figure 6 and 7, the above reported influence of reference modality seems primarily due to performance of group A. Therefore, a 7x2 ANOVA with repeated measurements was computed for each group.

unaltered (target) modality	comparison	
	direct (group A)	indirect (group B)
vision	128%	55%
haptic	85%	55-68%

Table I
JND% DEPENDING ON TARGET MODALITY AND METHOD.

Again, main effect of modality was statistically significant in group A ($F(1,13)=10.3$, $p<0.5$); the effect now accounted for 44% of the variance. However, no influence of reference modality on performance could be observed in group B ($F(1,13)=1.2$, $p=0.3$). The only other though negligible effect that reached significance was the interaction between target modality and reference compliance ($F(6,60)=2.5$, $p<0.05$; partial $\eta^2=0.20$) indicating higher JND% when reference compliance is 0.5, 0.85 and 4.88 mm/N and the visual modality the reference.

V. DISCUSSION

Perception thresholds of discrepancies in visual-haptic compliance information have been assessed for different experimental conditions. Participants had either to directly compare visual and haptic compliance information (method A) or to sequentially compare two visual-haptic objects (method B). Chosen method affects the detection performance, as has been expected (*Hypothesis 1*). As can also be seen in Table I, direct crossmodal comparisons allow high discrepancies between modalities to be undetected (around 128% to 85%), whereas around 55% to 68% of intermodal discrepancy are allowable with sequential comparisons. Similar results are obtained by Srinivasan, Beauregard & Brock who showed that participants' ability to identify the less compliant of two easily distinguishable compliant stimuli decreased as the ratio between visual and haptic discrepant compliance information increased to around 0.5 [28].

This difference in discrepancy threshold due to assessment method reflects that detecting visual-haptic conflicts is very difficult as long as no congruent comparison is available: Therefore the perceptual system integrates the information in order to provide a coherent percept (e.g. [4], [5]). On the other hand, conflicts can be more easily detected when comparing with the congruent information. As has been expected (*Hypothesis 2*), reference modality influenced discrimination performance: When varying haptic information (visual modality is unchanged), the JND% is higher than with the haptic modality being the reference (see also [28]). This indicates that participants relied more on visual information when performing the discrimination task. Although this visual dominance can be observed for both groups (main effect), especially performance of group A contributes to this effect. Therefore, in group A 128% of differences between the visual comparison and the haptic reference information are necessary in order to be detected, whereas 85% of discrepancy in

intermodal information can be detected when the haptic modality remains unchanged (see Table I).

Visual dominance depended on reference compliance in group B, as had been expected (*Hypothesis 2*). However, effect size is rather low. Additionally, a positive correlation between directing attention and discrepancy threshold could be observed in some reference stimuli: Performance was impaired when participants attended to the wrong modality, i.e. vision. Moreover, the analysis of missing values revealed that expecting the wrong modality resulted in a non-convergence of the iterative psychophysical procedure. This cost of attending to the wrong modality has already been shown to decrease performance (e.g. [15], [41]). Whether the influence of attention accounts for the observed result has not been systematically addressed in this study. Further experiments have to clarify, whether this effect might account for this interrelation.

VI. CONCLUSION

This research addressed the minimal allowable visual-haptic conflict when perceiving object compliance. If the discrepancy between visual and haptic compliance information is below 55%, no intermodal difference in compliance can be perceived.

The results might especially be interesting for control and reduction of haptic information in telepresence systems.

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