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Visual-Haptic Perception of Compliance: Direct Matching of Visual and Haptic Information

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Abstract – *Visual-haptic perception of an object's compliance demands integration of haptic position and force information as well as visual position information. In this investigation the role of active exploration on visual perception as well as the influence of visual-haptic information was addressed. Participants were instructed to directly match a compliant stimulus displayed either by vision (static passive or active), haptics, or both. Active testing of the visually displayed cube resulted in no difference in visual thresholds, suggesting that exploration method did not influence visual position discrimination. However, the threshold of visual matching of the cube's indentation was smaller than for haptic compliance matching, not only unimodally but bimodally, in which case the alternate modality was present and adds noise resulting in an increase in bimodal thresholds.*

Keywords – *Visual-Haptic Perception, Compliance, Human System Interface, Sensory Fusion, Psychophysics*

I. INTRODUCTION

Mechanical environments can be perceived by processing force- and position-based information (i.e. position, velocity, acceleration). Considering human visual-haptic perception of compliance, position-based information can be detected by both modalities while force information can only be detected by the haptic modality. The obtained information has to be mathematically processed to obtain an estimate of the explored compliance. An analysis of the underlying perceptual process of information integration will contribute not only to a psychological understanding of compliance perception but also to the design and control of human system interfaces used to access artificial environments. A sound analysis requires a visual-haptic human-system-interface (HSI) with high accuracy in displaying mechanical environments and extensive experiments using psychophysical procedures.

Information derived by different senses has to be integrated into a single percept of the manipulated object. Most research in this area has concentrated on the intersensory integration of a single object attribute (e.g. [1–4]), e.g. position (see e.g. [1]). In addition, intrasensory integration, i.e. within one modality, has also been addressed (e.g. [5–7]): Research indicates qualitative differences when integrating intra- or intersensory information (e.g. [3]). However, studies concerning more complex variables such as compliance have, as yet, rarely been undertaken (see e.g. [8–14]). When a person explores a compliant object, the haptic system provides information about arm and finger displacement along with signals as to force (kinesthesis), as well as information about the indentation of the fingertip (cutaneous or tactile information) (e.g. [15, 16]). The visual system adds information about the finger positions over time (see Figure 1). These inputs give rise to a percept of the object's compliance. When there is redundant information from both modalities, i.e. both arise from the same physical event, integration presumably occurs (e.g. [17]). However, the way in which haptic and visual information are combined to determine compliance, and whether additional cognitive factors influence integration, is not as yet known.

Tan and colleagues found evidence that people tended to rely on force cues to discriminate levels of compliance, but were affected by position cues as well [9]. They computed the just-noticeable difference (JND) relative to a given standard stimulus (the so-called Weber-fraction or JND%, see e.g. [18]) when people discriminated compliance with varying pinch force over a constant displacement and when people discriminated force with varying pinch displacement. These JND% were lower than when compliance was discriminated

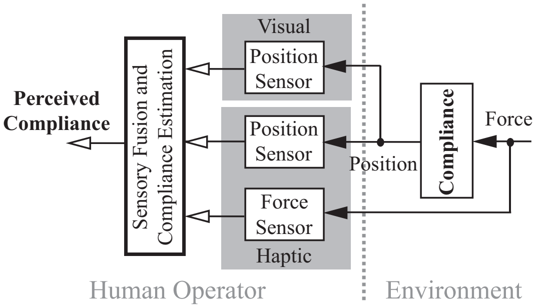

Figure 1. Visual-haptic perception of compliance information: Redundant position information and haptically perceived force information are combined to generate the final estimate.

by applying force over randomly varying displacements. The increased JND% seems to result from the perceptual system computing the perceived compliance when both force and position signals vary (see [9]). While more than 20-30% differences in compliance appear necessary for discrimination to be successful (e.g. [9–13]), differences in finger distance of around 5% (e.g. [1, 19, 20]) and 8-10% difference in force information can be discriminated (e.g. [9, 10, 21]).

On the other hand, visual perception of object compliance might primarily be based on visual position information, because there exist no visual receptors to decode visual force information (see Figure 1). Visual discrimination ability for position information has primarily been addressed by comparing length or size of objects: Deviations of around 3% can be detected (e.g. [22–24]). Similar results have been found when people discriminate line length (e.g. [25]). Furthermore, an influence of line orientation on the accuracy of discrimination has repeatedly been shown (e.g. [23–25]): A difference of approximately 10% between lengths of vertically oriented lines can be visually perceived (e.g. [25]). Force information, and thus object compliance, cannot be directly derived by the visual system. However, an estimate of an object's compliance could be obtained even by mere visual observation and thus involve expectancies about visual deformation of a compliant object ([26], see also e.g [27]).

Some preliminary results on visual-haptic perception of compliance have been reported, showing that easily discriminable stimuli became harder to discriminate with decreasing visual reliability [8, 28]. Multisensory perception has often been reported to result in a more reliable percept than unimodal [1]. However, intermodal discrepancy can remain unnoticed (e.g. [28]) and result in a single, altered percept [29]. In a task where people were to compare two multi-modal (visual and haptic) stimuli, one with congruent compliance cues and another where one modality was discrepant, the detectability of the discrepant information was found to depend on the modality. Specifically, detection was lower when the visual modality was held constant across the stimuli and haptic cues were made discrepant, than in the reverse situation (for further details see [28]). In addition, the method of threshold assessment also influenced the overall magnitude of the detectable intermodal discrepancy. On this basis, it appears that a threshold assessment method which allows the participants directly to match perceived compliance could offer valuable clues to intermodal interaction. The present study was designed with this goal. Participants directly matched compliant stimuli signaled by vision, haptics, or both. On each trial, a standard stimulus was presented, and the participant adjusted a comparison stimulus to match it in compliance.

The contribution of this study is three-fold. First, it addressed the role of active exploration in a visual position discrimination task (i.e. of actively indenting a visually displayed cube without receiving force or relevant haptic position information): As could be shown e.g. in multisensory texture perception, even auditory information can allow participants to get information about a texture's roughness (e.g. [30, 31]). Based on the results by Tan et al. showing increased thresholds when position varies [9], information about the process of indenting, when added to visual information about indentation, should add noise, resulting in an increase of the discrimination threshold (*Hypothesis 1*). Furthermore, we expected that when compliant cubes had to be discriminated by static indentation without active exploration, participants would rely on static position information, and therefore the value obtained should be comparable to the JND% observed in visual position perception (see [25]). Secondly, the study investigated intermodal interactions, by having subjects adjust stimuli rendered haptically and visually. On these trials, the comparison stimulus matched the standard stimulus in one modality (called the reference modality), and the task was to adjust the second modality of the comparison stimulus so that the stimuli matched completely. According to reported results on intermodal discrepancy thresholds (see [28]) and the phenomenon of visual dominance (e.g. [32]) an influence of reference modality is also expected with the present matching paradigm (*Hypothesis 2*): Smaller errors should occur with the visual modality matching and the haptic modality being the reference (which remains unaltered during the visual matching) than with the reverse. A third issue is how the thresholds obtained in the bimodal condition compare to unimodal thresholds. Keeping in mind that integration often occurs by combining information from more than one sense by weighting them e.g. according to their reliability (see [1]), a difference between unimodal and bimodal assessed threshold is expected (*Hypothesis 3*). Specifically, the threshold for a given comparison modality is expected to be greater in the bimodal condition than the unimodal, if the presence of the unaltered reference modality in the bimodal condition adds irrelevant cues to the judgment.

In order to answer these questions, an experiment was conducted. The article is organized as follows: The Human System Interface used for the experiments is explained in detail in Section II. The method (Section III) and results (Section IV) are then described. Section V provides a discussion of the research conducted, and conclusions are drawn in Section VI.

II. HUMAN SYSTEM INTERFACE

A human system interface is used that provides visual and haptic feedback at high accuracy. The visual subsystem consists of a TFT screen mounted in the line of sight of the hand showing the visual virtual reality. The haptic subsystem consists of two SCARA robots providing two degrees of freedom each (see Figure 2). The system interacts with index finger and thumb to allow the exploration of the compliant environment by gripping movements. Workspace is about 80 mm and maximal force is about 35 N. Position information is measured by angle encoders and force is measured by strain gauges. Haptically, the compliant environment is generated using an admittance control scheme. Visually, the environment is presented by a compliant cube with yellow spheres representing the finger tips. Within psychophysical experiments participants are able to adjust the compliance of the comparison stimulus with a potentiometer: A 360 degree turn of this rotary knob corresponds to a 50% change of compliance. The matched comparison compliance was recorded when the participant ended the trial by commanding the joystick. The system works under realtime conditions and is programmed by Matlab/Simulink. For a detailed description refer to [28].

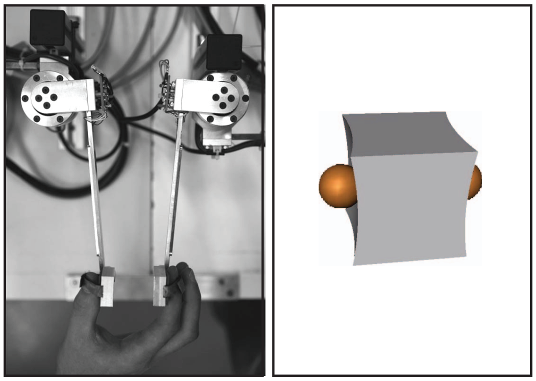

Figure 2. Haptic and visual feedback: Haptic feedback generated by an admittance control scheme. In the visual feedback fingertips are represented as yellow spheres.

III. METHOD

A. Participants

Twenty-three students of the Technische Universität München and the Ludwigs-Maximilian-Universität München took part in this study and were paid for participation. Three participants had to be excluded from further analysis because of missing data. The remaining 20 students (15 women and 5 men) were 24 years on average. All of them were right-handed and had normal or corrected to normal vision.

B. Stimuli

Cubes of 80 mm edge length with a standard compliance amounting to 0.85 mm/N were chosen to represent the compliant stimuli and displayed by the HSI (see Section II). Additional dummy cubes with a different standard compliance (see below) were included in testing, in order to prevent response perseveration. Virtual cubes were either displayed unimodally, i.e. visually or haptically, or bimodally, i.e. visual and haptically. No visual cues were given during the unimodal haptic presentation as well as no haptic cues during the unimodal visual presentation. An additional haptic standard compliance of 0.5 mm/N was chosen to represent the compliant cube of the dummy trials. Unimodal visual stimuli were presented in two ways, with and without active exploration. In the active condition, participants were allowed to indent the visual cube by moving the grasp device while no haptic force feedback as well as no haptic position information was given: The grippers could be closed, causing the cube to be visually indented to the pre-defined standard indentation depth (Va). In the passive condition, visual discrimination was done with watching the static indented cube (Vp). Additionally, a visual standard indentation depth of 13 mm was selected for the dummy trials.

Due to the method of threshold assessment (see Section D) there were two bimodal conditions: Either the haptic or the visual modality provided a basis for comparison while the other modality served as a constant reference. Therefore five modality conditions were realized: unimodal haptic (H), unimodal visual active (Va) as well as unimodal static passive (Vp) and the two bimodal conditions, visual reference with haptic comparisons (vH) as well as haptic reference with visual comparisons (hV).

C. Design

Thresholds of each reference modality (H, Va, Vp, vH, hV) were assessed from above (down-series, i.e., the comparison started detectably above the standard) and below the threshold (up-series). Each series was repeated 5 times. Thresholds were assessed in three modality-specific blocks: Unimodal haptic (H), unimodal visual (Va, Vp) as well as bimodal (vH, hV) stimulus presentation. Five dummy trials were included in each block; order of series or modality condition within one block was randomized. Order of blocks was counterbalanced across participants using latin squares. All 65 threshold assessments had to be completed by each participant.

D. Procedure of assessing the PSE and the threshold

Unimodal Matching. As the psychophysical method of assessing the unimodal threshold, the method of adjustment was chosen, also called method of average error (see e.g. [18]): Participants tested a standard stimulus and were instructed to adjust the compliance of the comparison stimulus with a rotary knob until it matched the compliance of the standard stimulus. In order to minimize any tendency for stereotypic responses, each of the ten repeated adjustments started from variable start levels (80, 75, 70, 65, and 60%) and participants adjusted the compliance by rotating the knob in one direction. The trial ended when indicated by the participant and the adjusted value was recorded. From the matching data, two measures are extracted. One is the mean of the matched comparisons, the PSE. The difference between the PSE and the standard, or the constant error, measures bias in responding. The second measure is the variability around the PSE, as measured by the population SD of the matched comparisons. As a measure of dispersion around the mean, this can be treated as a measure of the difference threshold. When normalized by the standard and multiplied by 100, it is treated here as a just noticeable difference or JND%.

The visual task was either to match the visual indentation while being allowed to actively indent the visual displayed cube or to match the visually indented cube without active exploration. Although participants were instructed to adjust the visually perceived compliance the task was a visual position matching task with or without active exploration

Bimodal Matching. The procedure of assessing the bimodal thresholds was adapted from the unimodal one. The participant was given a bimodal standard stimulus, which had congruent visual and haptic cues, and a comparison stimulus with a reference modality that matched the standard and an adjustable modality that was clearly discrepant. His or her task was to adjust the discrepant modality with the rotary knob until it matched the compliance of the standard. Again, each threshold assessment was repeated ten times, five times from above the standard compliance and five times from below while start levels of the adjusting modality were variable (160, 155, 150, 145, and 140%). Bimodal trials ended with the participant indicating that the adjusted level matched that of the perceived congruent one. The bimodal PSE and its standard deviation SD (threshold) were computed as described above.

E. *Experimental Procedure*

Participants were seated in front of the HSI with their dominant hand grasping the device and looking nearly perpendicular at the screen. They were carefully instructed during a short training. Each trial started with testing the standard stimulus (unimodal matching) or the congruent bimodal stimulus (bimodal matching); switching between standard and comparison was possible. They were allowed to re-adjust the selected comparison stimulus, although they were instructed to decide as accurately as possible and by matching the standard stimulus with the least adjustments possible. In order to prevent visual or haptic matching, the robot arms were set to the start position and exploring the standard or comparison was only possible after a delay of 2s. The delay between standard and comparison mode amounted to 1s (interstimulus-interval). The intertrial-interval lasted for 2s.

After having completed all three blocks, participants were asked to fill in a questionnaire assessing their demographic data as well as their immersive tendency (subscale of a presence questionnaire by [33], translated by [34]) to control for any personal factors that might eventually influence the data.

F. *Statistical Analysis*

PSE and threshold (SD around the PSE) were computed as described in Section D. The SD was used as the performance measure to test the hypothesis. Results (SD and normalized SD, also called JND%) are descriptively analyzed in Section IV.B and testing the hypotheses in Section IV.C. In order to test hypothesis 1, a t-test with dependent groups (exploration method active or passive) was computed on the dependent variables (SD around the PSE as well as PSE) using the visual unimodal data only. Afterwards, hypothesis 2 was tested with a two-factorial ANOVA with repeated measurements on the two factors ”comparison modality”(active vision, haptics) and ”number of modalities” (uni-, bimodal).

IV. RESULTS

A. *Questionnaire data*

Participants rated their immersive tendency on a 7-point-scale for each of two factors, *emotional involvement* and *degree of involvement*, which were computed for each participant. Average emotional involvement was 27.7 (standard deviation sd = 6.5) and average degree of involvement 17.7 (sd = 5.5); these values did not statistically significantly differ from those reported by Scheuchenpflug [34], indicating that the participants are a sample of a comparable population. No correlation between emotional involvement and the SD around the PSE could be observed. In order to determine the influence of preferred modality, participants answered an additional question concerning their preference for either the visual, the haptic or both modalities during the bimodal threshold assessment. Performing the task was rated to be easier when either the haptic (n=2), the visual (n=13) modality was changed or without preference (n=5). Neither immersive tendency nor performance (SD) was correlated with the individual preference rating (according to III.E).

B. Descriptive Analysis

Visual matching. The PSE varied little across conditions, corresponding to an average constant error of CE%, as normalized relative to the standard. *Visual matching*. PSE and thresholds (SD) of visual indentation were assessed with active exploration or by mere visual observation. As can be seen from Figure 3 there is essentially no difference in PSE or threshold between the two conditions. The normalized SD (JND%) amounted to 11.5% with passive static and 12.9% with active exploration.

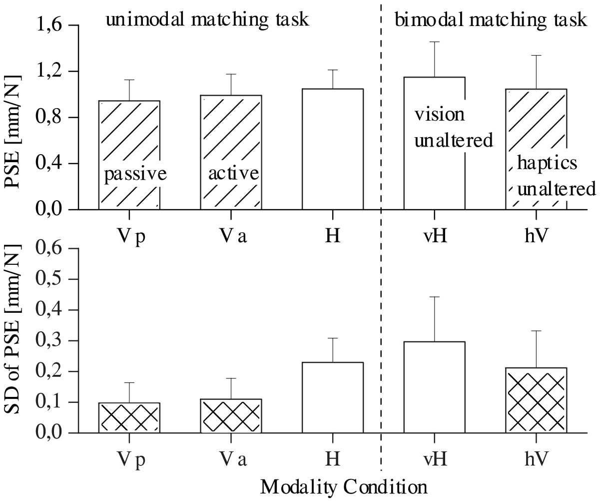

Figure 3. Mean PSE and its standard deviation when testing object compliance either unimodally (visually or haptically) or bimodally while one modality remained unchanged

Haptic and bimodal matching. There are only small differences between the PSE depending on modality condition. However, differences in thresholds (SD) can be observed (see Figure 3): Bimodal matching results in an increase of the standard deviation compared to unimodal matching; furthermore, haptic unimodal matching results in a higher SD than visual. The normalized SD (JND%) amounted to 27.0% with unimodal haptic matching and increased to 34.9% with additional visual information (vH). The addition of haptic information resulted in an increase of the normalized standard deviation of active visual matching to 24.9% (hV).

C. Testing the hypotheses

As has already been descriptively observed, the difference in SD between active and static passive matching of visual indentation tested with a t-test was not statistically significant ($t(19) = 0.73, p = 0.475$). This indicates that active exploration has no effect on either PSE or its standard deviation SD.

A two-factor ANOVA tested the influence of ”comparison modality” (visual, haptic) and ”number of modalities” (unimodal, bimodal). The visual active condition was selected to represent the unimodal visual results. The main effect of ”comparison modality” was statistically significant ($F(1, 19) = 44.89, p < 0.05$; partial $\eta^2 = 0.703$). Haptically adjusting the comparison stimulus yielded a higher threshold than visual matching. Additionally, ”number of modalities” significantly influenced the threshold ($F(1, 19) = 7.00, p < 0.05$; partial $\eta^2 = 0.269$) indicating an increase in threshold in the bimodal matching tasks. The interaction term turned out not to be statistically significant ($F(1, 19) = 1.18, p = 0.291$).

V. DISCUSSION

Using the psychophysical method of adjustment, individuals' matching of compliance (and visual indentation) discrimination was measured when participants explored cubes haptically or visually, in unimodal and bimodal conditions. The effect of actively vs. passively perceiving a visually displayed compliant cube was also assessed; participants either tested the cube by visually indenting it or only by observing the (static) indentation depth. A difference between these testing methods was expected (*Hypothesis 1*): Static passive exploration should result in a JND% comparable to those observed in visual position discrimination (approximately 10% according to [25]); active exploration could increase this value due to added noise. The data showed, however, that about 11.5% deviation when passively matching the static standard indentation depth or compliance could be detected, and no statistical difference in the threshold (SD) obtained by active matching was found.

Visual dominance was expected. Therefore, when matching visual compliance with added haptic information, the threshold should be smaller than when displaying additional haptic information while adjusting the visual modality (*Hypothesis 2*). Also expected was an increase in threshold when matching the bimodal standard compared to matching the unimodal one, due to noise from the additional unaltered modality (*Hypothesis 3*). The results showed that haptic matching led to a higher threshold, and this effect did not differ, according to whether matching was unimodal or whether congruent visual information was also present. In fact, the presently obtained JND% as derived by normalizing the SD is similar to that reported in the literature for haptic matching of non-virtual stimuli [8–14] and for visual position discrimination [25].

In addition, the present bimodal thresholds are relatively low compared to the results reported in [28]. This indicates again a difference of assessment method on the minimal detectable intermodal threshold (see also [18]).

VI. CONCLUSION

Integration of visual as well as haptic information when exploring an objects' compliance is demanding. As has been shown for haptic perception of compliance, force and position information have to be combined and result in an increase of the JND% [9]. On the other hand, only position information can be sensed by the visual system: We found that visual exploration method, i.e. static passive matching vs. active visually indenting, did not influence performance in terms of SD or JND%. The observed JND% is comparable to those reported for position discrimination in [25], amounting to approximately 12%. Additionally, we found that visual matching of indentation was superior in both unimodal and bimodal conditions; presumably this is attributable to not being forced to compute a compliance estimate as in haptic mactcing tasks (see [9]). Furthermore, bimodal matching resulted in an increase of thresholds compared to unimodal matching: When one modality remains constant while another is compared, the threshold increases relative to matching on the comparison modality alone. The size of this increase is comparable, whether the comparison modality is vision or haptic. This indicates that the additional alternate modality - although congruent - adds noise, and the added noise does not depend on the modality being matched.

VII. ACKNOWLEDGMENT

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