A More Rigid Counterpart in Virtual Reality Alters Compliance Perception of Soft Silicon Cubes

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I. Introduction

Compliance perception plays an important role in both object identification and object manipulation [1], [2]. We learn through daily experiences to associate the felt softness of an object with the visual deformation that occurs when we interact with it. However, it remains unclear how these visual and haptic cues are combined to help us estimate an object's compliance and how these cues are weighted when discrepancies occur. To better understand the integration of visual and haptic cues involved in compliance perception, we designed a grasping task that introduced a sensory conflict using a virtual environment. In the virtual environment, the visual properties of the object can be modified without affecting its physical properties, enables the introduction of mismatches between what participants see and feel. For example, Bouzbib et al. [3] demonstrated that altering only visual deformation while keeping physical properties unchanged was sufficient to induce compliance to a rigid tangible object. This makes it possible to investigate how visual and haptic cues are integrated when discrepancies occur. We further explore how hand dominance may influence the reliance on visual or haptic information. We hypothesize that as the non-dominant hand is less proficient in fine haptic discrimination task, participants may rely more heavily on visual cues when using their non-dominant hand for object manipulation.
With this experimental paradigm, we aim to explore how people compare the reliability of visual and tactile cues and how this comparison influences the resulting sensory weights.

II. Methods

A. Setup

We compared two soft objects: a reference object (8 N/cm) and a softer comparison (7.5 N/cm), each composed of a silicone cube (HxWxL = 20x35x55 mm^3) and a force-sensing resistor connected to a microcontroller (FSR03CE) (Fig. 1.A). To achieve different stiffness, we adjusted the mixing ratio of the two-part elastomer Ecoflex silicone, with a ratio of 1:1 for reference object and 2:1 for comparison object. We replicated the physical scene using Unity3D. The virtual reality scene consisted of two cuboids on a virtual

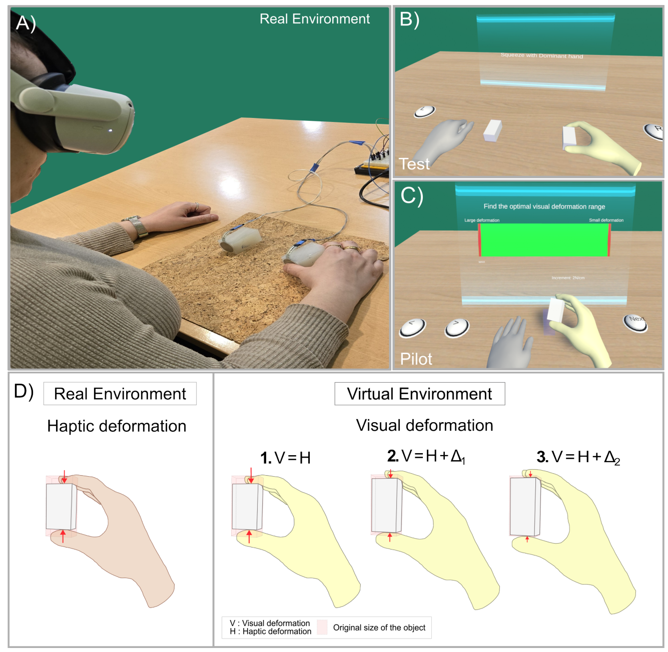

Fig. 1. (A) Real environment. The participant is interacting with the tangible soft object. (B) Virtual environment. The participant's avatar hand is compressing a virtual object. (C) Preliminary study. The consistency range is visually represented by a slider, red: inconsistent, green: consistent. (D) Visual conditions. 1: The deformation of the virtual object and the tangible object are similar, 2 and 3: The virtual object deform less than the tangible object.

table. The original virtual object sizes and position matched the physical ones. The virtual object deformed as a function of the applied force recorded with the sensor (Fig. 1.B-C).

B. Procedure

A total of 8 participants (4 males,4 females; mean age = 24) were recruited and compensated their participation. Participants compressed each object successively using either their dominant hand or non-dominant hand. They were asked to select the object they perceived as the most compliant. To control visual feedback, we replaced the participants' real hands with avatar hands, visible in the virtual environment. The visual deformation of the comparison object was manipulated in virtual reality: the visual deformation was either consistent with the physical deformation (condition V=H, stiffness=1.5 N/cm) or inconsistent (condition V=H+Δ_1, stiffness=3 N/cm and condition V=H+Δ_2, stiffness=4.5 N/cm) (Fig. 1.D). The visual deformation of the

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reference object remained consistent its physical deformation (stiffness=2 N/cm). A preliminary study was conducted to estimate the stiffness range (N/cm) for which the deformation of the virtual object was perceived as similar to the physical deformation of the tangible object. The Δ adjustments for the visual deformation conditions were derived from data collected in the preliminary study (Fig. 1.C). The dependent variable was the perceived *Compliance* while the two independent variables were the *Exploration procedure* (dominant hand or non-dominant hand) and the *Visual deformation* (V=H, V=H+Δ_1, V=H+Δ_2). Each of the six different conditions was repeated 10 times for each participant, 60 trials in total.

III. Results

The proportion of trials in which the haptically softer object was judged as the most compliant was measured across the different visual conditions and for both exploration with dominant and non-dominant hand (Fig. 2).

Visual condition effect. A significant effect of the visual condition was observed for both the dominant hand (Friedman test: X^2=7, $p = 0.030$) and the non-dominant hand (Friedman test: X^2=9.484, $p = 0.009$). Post hoc Wilcoxon rank test with Bonferroni correction revealed that for the non-dominant hand, this proportion was significantly higher in the congruent condition (condition V=H) compared to the incongruent condition, where the visual cues suggested a stiffer object (condition V=H vs V=H+Δ_1, - corrected $p = 0.034$). No significant difference was found for the dominant hand after correction.

Hand dominance effect. Although differences between visual condition were observed within each hand, no significant differences were found between the dominant and non-dominant hand for any visual condition (paired Wilcoxon signed-rank test, all $p > 0.05$), indicating that the observed visual bias was consistent across hands. However, a non-significant trend was noted in the condition V=H+Δ_1 ($p = 0.172$). This suggest a possible difference in visual reliance between hands under incongruent conditions.

IV. Discussion and Conclusion

Our study explored how visual information influences haptic perception of compliance during a bimodal grasping task. We tested whether participants could correctly identify the haptically softer object when visual and haptic cues were either congruent or incongruent and if this process differed when exploring with the dominant hand or non-dominant hand. Our results indicate a stronger influence of visual information on visuo-haptic judgment of compliance. When visual cues indicated a stiffer object, participants were significantly less likely to identify the haptically softer object as the more compliant object. This effect suggests a visual bias, whereby the perception of the compliance is shifted toward the visual stiffness, making the haptically softer object feels harder that it actually is. These findings align with previous research on multisensory integration, which suggests that the brain combines visual and haptic information in a statistically optimal manner, weighting each modality according to its relative reliability [4]. In our task, the stronger influence of the visual cue may reflect the fact the visual information was perceived as more reliable than haptic information, leading to a bias where the haptically softer object felt stiffer when paired with a visually stiffer cue.

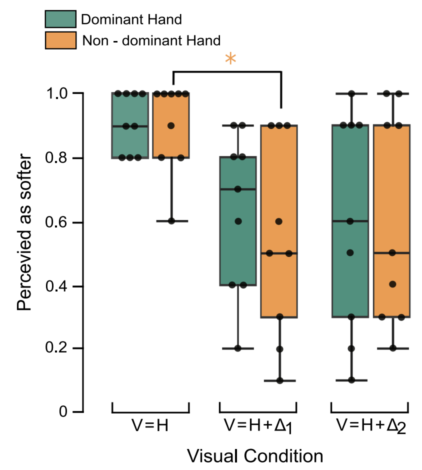

Fig. 2. Proportion of trials where participants judged the haptically softer object as the most compliant object, for each visual condition, shown separately for the dominant and non-dominant hand. Each dot represent an individual participant. Boxes represent the interquartile range (IQR) and the median (horizontal line). Asterisks indicated statistically significant differences between visual conditions based on Wilcoxon signed-rank tests (* $p < 0.05$)

We did find significant differences between visual condition within each hand, but no significant difference was found between dominant and non-dominant hand across conditions. Hand dominance may not affect the integration of visual and haptic cues in compliance perception. However, a non-significant trend was observed between the two hands in the V=H+Δ_1 condition. Participant may rely more on visual cues when using their non-dominant hand in condition of sensory conflict. This preliminary results indicated that sensory weights assigned to visual and haptic information could differ depending on whether the dominant or non-dominant hand is used.

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