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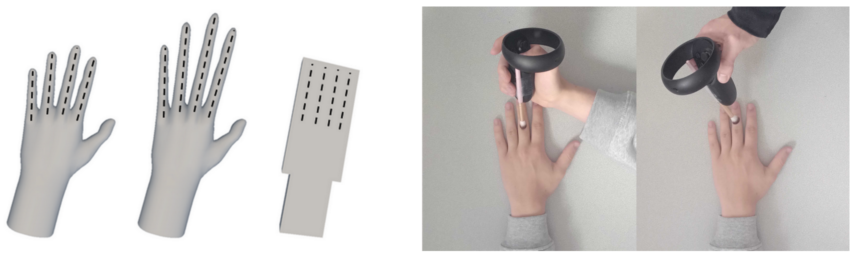

Figure 1: We assessed the sense of body ownership towards different dysmorphic hands, induced by two visuotactile stimulation techniques (right part of the figure, from left to right): self-touch (users inducing themselves the tactile stimulation) and external-touch (experimenter inducing it). The left part of this figure shows all the hand appearances that we studied, from left to right: anthropomorphic, longer-finger and block, hatched lines show matching tactile stimulation areas.

ABSTRACT

In Virtual Reality, self-touch (ST) stimulation is a promising method of sense of body ownership (SoBO) induction that does not require an external effector. However, its applicability to dysmorphic bodies has not been explored yet and remains uncertain due to the requirement to provide incongruent visuomotor sensations. In this, paper, we studied the effect of ST stimulation on dysmorphic hands via haptic retargeting, as compared to a classical external-touch (ET) stimulation, on the SoBO. Our results indicate that ST can induce similar levels of dysmorphic SoBO than ET stimulation, but that some types of dysmorphism might decrease the ST stimulation accuracy due to the nature of the re-targeting that they induce.

Keywords: Virtual Reality, Embodiment

Index Terms: Virtual Reality—Human-centered computing—Human computer interaction (HCI)—Interaction paradigms;

1 INTRODUCTION

Virtual Reality (VR) technology allows to provide users with various artificial sensory information, giving them the possibility to exceed the boundaries of reality, e.g., experiencing the feeling of being present inside virtual environments (VEs) or being embodied into virtual bodies that can be anthropomorphic but also that can exhibit dysmorphic characteristics [1]. In this study, the term "dysmorphic" covers all the virtual body types that differ from the users' real bodies in terms of body morphology and structure. Hence we consider virtual bodies as being dysmorphic even if (i) they are anthropomorphic such as in [50, 62], (ii) they differ from a human body in terms of proportion [24, 33], or (iii) of structure [22, 38, 60]. Using dysmorphic virtual bodies not only has potential for entertainment, but also in other applications such as increasing users' task performance [2, 33, 60], reducing their experienced pain [31, 42], impacting their behavior [44, 62], changing their perception of the environment [19, 30, 36, 47], or of themselves [34, 50].

However, using such dysmorphic virtual bodies raises questions regarding the Sense of Embodiment (SoE), and more specifically regarding the Sense of Body-Ownership (SoBO) which is often defined as the feeling of owning the virtual body or body-part [23]. Indeed, dysmorphic limbs in particular, due to their morphological difference from users' usual experiences, are less likely to be accepted by the brain as being part of their body [28, 40, 52, 53]. Evidence exists that a decreased SoBO can negatively impact user's immersion and emotional responses [17], and reduce the previously mentioned effects [18, 34, 50, 56, 57].

Different techniques exist to induce the SoBO towards an artificial or virtual limb. They often consist in providing synchronous sensory information of different natures to the real and artificial limb. Visuomotor stimulation, consists in matching the motor control of the real limb to the visual movement of the artificial limb [13, 54, 58]. Visuotactile stimulation is another technique consisting in matching a tactile stimulation of the real limb with visual stimulation of the artificial limb [8, 63]. It should be mentioned that visuotactile and visuomotor are not exclusive and, in line with SoBO's Bayesian causal inference model [45], they can be combined to strengthen its elicitation [10, 26]. In previous research, these two techniques were used separately [4, 49] or conjointly [10, 22, 24] to induce SoBO towards a dysmorphic body.

While visuotactile is theoretically an effective method to induce SoBO, it most often requires the involvement of external stimulation (delivered by either an experimenter or a robotic effector [20]) to provide tactile stimulation to the real body part. In the following, we will refer to this as an External-Touch visuotactile stimulation (shortened as ET stimulation). The requirement of using an external effector hinders ET potential of replication outside laboratories, and therefore, it cannot provide a fully satisfactory practical solution

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to administer SoBO towards a virtual body. On the other hand, previous research showed that Self-Touch visuotactile stimulation (shorten as ST stimulation), where users are both the receiver and the provider of the tactile stimulation, could elicit SoBO, and even reach higher scores than classical ET stimulation [20]. By replacing the requirement of an external experimenter, letting users perform the action themselves, we believe ST could offer a more practical solution to induce SoBO via tactile sensation than ET.

Interestingly, in the case of dysmorphic bodies, ST stimulation faces additional theoretical limitations. Indeed, the difference of body structure between the real and the virtual bodies or body parts might introduce mismatches between the real and the virtual contact position or duration. These discrepancies might prevent (i) the elicitation of the SoBO [9], (ii) the capacity to offer realistic ST interactions, or (iii) the design of body-based interactions through body augmentations [15, 16, 38]. To tackle the limitation of mismatching body contact, some studies [34, 44] introduced the potential use of haptic retargeting techniques [5, 11, 32, 64], consisting in applying an offset between the tracked body-part and its virtual counterpart.

However, to the best of our knowledge, the application of retargeted ST was only tested with limited tactile sensation as a single contact point (i.e., a discrete stimulation) and with virtual bodies with small morphological differences from the real body. As a consequence, it is yet unclear how continuous retargeted ST can induce SoBO towards dysmorphic bodies with higher shape divergence from the real body, nor how continuous ST compares with ET stimulation. Indeed, according to the Bayesian computation of multiple sensory channels' theory [23, 45], SoBO can vary depending on the received sensory information, and it remains unclear how a retargeted ST stimulation (leading both to matching visuotactile feedback and a mismatching visuomotor one) can induce a strong SoBO.

In this paper, we studied how ET and ST could impact the induction of the SoBO over three types of virtual hand appearances: (i) an anthropomorphic, and two dysmorphic, (ii) a hand presenting longer fingers than usual human hands, and (iii) a block-shaped hand. The SoBO was evaluated via a subjective measure (questionnaire) and two objective measures: a *self-pointing* and a *button-pressing* task.

2 Related Work

In this Section, we focus on studies that induced SoE over virtual dysmorphic bodies (i.e. bodies that differ morphologically from the user's real body). Since, in most cases, these studies relied on visuomotor feedback, as a result of tactile stimulation which could reduce the SoBO towards a dysmorphic virtual body or body part, we then present the SoBO in detail and how ET and ST can impact it. Finally, we list the studies that successfully induced a SoBO over a dysmorphic virtual body or body part.

2.1 Dysmorphic Embodiment in VR

VR offers the unique possibility to embody users into virtual dysmorphic bodies, differing at a different intensity from their bodies, such as a different anthropomorphic body [50, 62], a body with dysmorphic limbs [22, 24, 33, 46], or a fully dysmorphic body [4, 27].

Embodying such dysmorphic virtual bodies was shown to impact users' perception and behavior. Indeed, modifying users' bodies could impact their perception of distances [57], as well as objects' sizes [19, 30, 35, 56]. Interestingly, the appearance of a virtual body could also influence users' (i) perception of their real body [34, 39, 50], but also (ii) behaviour following the dysmorphic embodiment, their actions being adapted to the virtual body they were embodied in [7, 44]. Some studies also pointed to the potential effect of virtual appearance manipulation to reduce pain perception [31, 42]. The Proteus Effect [12, 61], in which embodied users temporarily adopt behaviors related to stereotypes associated with the altered appearance of their avatar was also shown to induce change in behaviour [62] and self-identification [50]. Homoncular Flexibility suggests that it is possible for users to learn to control virtual bodies different from their own. For example, users' movements can be remapped to give them control of a third arm [60] or a virtual tail [49]. It was also shown that controlling such impossible bodies could increase users' performance in some tasks, e.g. users were better at hitting a target when embodied with a third arm than in a two arms condition [60], they also typed quicker with longer fingers [33] and were better at a tapping task with longer arms [33].

However, to induce such effects, it is critical to elicit SoE towards the virtual dysmorphic body. In particular, the SoBO over dysmorphic bodies or body-parts is of particular importance. Indeed, it was found that a reduced SoBO is correlated with a reduction of most of the aforementioned perceptual or behavioral changes. For example, a reduced SoBO led to smaller pain reduction [42], perception changes of oneself [34, 50], or of the environment [47, 56, 57], as well as to reduce the emotional responses induced by a virtual immersive experience [17].

2.2 The Sense of Body Ownership

We now briefly present the current theories about how SoBO's supposed induction and its different applications, in particular in the case of dysmorphic bodies. The SoBO is the sensation that a non-bodily object (e.g., artificial limbs) is part of one's own body [23]. This effect was studied for the first time in the so-called Rubber-Hand Illusion (RHI) [8], during which an experimenter strokes simultaneously the participant's hand and a rubber hand, while only the rubber hand is visible to the user. The simultaneous visual and tactile strokes are sufficient to elicit a subjective SoBO (i.e. SoBO measured with a subjective questionnaire) toward the rubber hand, as well as to modify participant's perception of their own body when asked to point toward their real hand participants experienced a *proprioceptive drift*, i.e. they tended to point to a different location in between the position of their real hand and the rubber hand.

Commonly, the SoBO is induced by presenting congruent stimulation of the real and artificial limb, from different sensory channels. While the traditional RHI used visual and tactile, it was later shown that visual and motor (visuomotor stimulation) [13, 55, 58], tactile and motor (hidden ST stimulation) [14], or visual, tactile and motor (visible ST stimulation) [20] were also effective to elicit SoBO. Later, the RHI was also proved to be an effective method to elicit SoBO towards a virtual hand in VR [63]. Moreover, SoBO induction seems to be stronger when combining several sensory channels instead of only two of them [10]. These findings are in line with the Bayesian causal inference model according to which SoBO results in a Bayesian computation of multiple sensory channels [23, 45]. While most of the previous studies focused mainly on SoBO induction from a theoretical perspective, few took into consideration the different factors that could hinder or facilitate the integration of SoBO induction mechanisms in user experiences, especially in VR. From this perspective, ST stimulation [20] in addition to inducing higher SoBO than ET, presents the advantage to get rid of the requirement of an external effector, simplifying the required setup.

2.3 The Sense of Body Ownership towards Dysmorphic bodies

Various studies reported successful induction of SoBO over various dysmorphic bodies, such as a longer arm [24], a virtual tail [49], a hand with six fingers [22], an additional hand [10], animal bodies [27] or robotic arms [4], one study even reported a weak SoBO, but significantly higher than the control condition, towards a table [3]. In contrast, a large reduction of SoBO was also found when trying to induce ownership towards roughly sculpted hands [52], an arrow [63] or a stick [53]. These results emphasize the non-triviality of inducing SoBO towards dysmorphic hands, which requires counterbalancing the differences between the dysmorphic hand and the users' previous experiences [28, 40, 52, 53]. This highly depends on various parameters (for more discussion of these parameters and their impacts on SoBO, we refer the reader to Kilteni et al.'s work [23]), and most notably on the stimulation technique or the dysmorphic hand appearance.

Visuotactile stimulation for SoBO induction has been for a long time reserved to ET, however, its lack of usability lessens its potential for VR use. Therefore, in this paper, we aim to explore novel usages of ST [20], which offers a more flexible way to provide a visuotactile stimulation, in particular for SoBO induction of dysmorphic bodies.

However, in the case of dysmorphic body parts, the morphological difference between the real and the visual hand might provoke mismatches of contact position or contact timing, and consequently reduce the SoBO [9]. In addition, this mismatch might hinder the design of ST interactions based on augmented bodies [15, 16, 38], and limit the capacity to handle natural ST interactions, forcing the VR applications' designers to prevent intentional or accidental self-touch contacts in order to preserve immersion. Haptic retargeting is a technique designed in order to overcome visual and tactile contact position discrepancies [5, 6, 11, 25, 32, 64], essentially consisting in introducing an offset between the real control and its virtual display, in order to match visual and tactile contact positions. Even if mostly employed to match tactile and visual props, this technique has been utilized in previous studies to match visual and tactile feedback of dysmorphic bodies for ET [22, 24, 52] and ST [34, 44] stimulation. However, this technique has been used combined with ST stimulation only with limited tactile sensation (single contact point) and morphological difference between the real and virtual body which was still anthropomorphic.

Thus, more research is required to study the potential use of retargeting for congruent continuous ST stimulation of dysmorphic bodies, especially on its impact on SoBO compared to ET stimulation. Indeed, compared to ET, the acceptance of the redirected ST stimulation might be decreased by the additional conflicting tactile and sensory information introduced. In order to uncover this uncertainty, our paper studies the potential of ST stimulation for SoBO induction of dysmorphic hands, using retargeting algorithms.

3 Experiment

We conducted an experiment that aimed to compare the influence of ST and ET stimulation techniques in the induction of SoBO towards dysmorphic bodies. To this end, we immersed participants in a VE with different hand appearances (one anthropomorphic and two dysmorphic hands), which were stimulated by both ST and ET. For each condition, the SoBO was evaluated via a questionnaire and behavioral changes during simple tasks' execution.

3.1 Independent Variables

In this experiment, we assessed two independent variables: hand appearance and tactile stimulation. For the *hand appearance* variable, which impacted the appearance of the participants' left virtual hand, we evaluated three different virtual hands: one anthropomorphic and two dysmorphic, as illustrated in Figure 1. In each condition, the virtual hand was displayed in a plain grey color in order to prevent the hand likeliness in terms of texture or color to influence the results. The anthropomorphic condition, which was meant to be used as a control condition, fit in proportion with the participants' real left hand. We used two dysmorphic hand appearances to investigate different levels of dysmorphism intensity (i.e. structural divergence with an anthropomorphic hand) on the results. The first dysmorphic appearance (longer-finger condition) consisted of a virtual hand with fingers 1.5× longer than the participants' finger length, except the thumb which fit the participants' length. The finger-extension ratio was chosen after pilot experiments to ensure that the dysmorphism would easily be noticed by participants. This condition was intended to be of low dysmorphism, with a body structure close to an anthropomorphic body structure. The second dysmorphic appearance (block condition) which was meant to be of high dysmorphism, presented participants with a virtual block-shaped left-hand, which size was about the same as the participant's hand size.

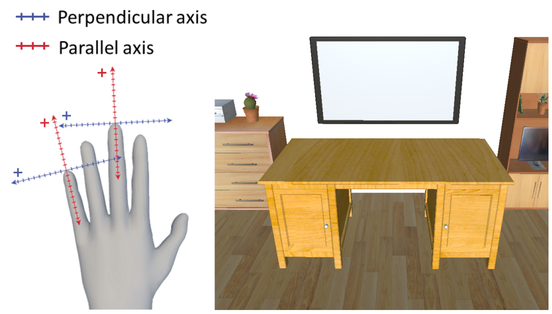

Figure 2: Parallel and perpendicular axis on the middle and pinky finger, used for calculating the pointing task results (left) and virtual environment setup (right).

The *stimulation* variable tested the effect of two different visuotactile stimulation techniques: ET and ST. Each condition was presented during a phase in which participants' left hand was stroked by a brush, whose effector was either the experimenter (ET condition) or participants themselves (ST condition). The virtual brush position was modified in order to ensure coherence in the visual and tactile contact between the brush and the real hand according to a retargeting algorithm presented in Section 3.5.1.

3.2 Participants and Apparatus

24 right-handed participants (10 females, 13 males, and 1 non-binary) aged between 22 and 33 years old (M=25.8, SD=3.55) were recruited; 50% declared having no experience in VR, 29.2% declared using it less than once a month, and 20.8% more than once a month.

Participants were immersed in the VE using an Oculus Quest Head-Mounted Display (HMD), plugged into a computer running the experiment application. A LeapMotion tracker was attached to the HMD, in order to track participants' hand movement and position (note that we did not use the hand tracking system integrated with the HMD, since it did not allow to track hands and controllers at the same time, and to control the switch of tracking focus between them). During the experiment, participants were seated in front of a table that was covered by an infrared-absorbing material, in order to avoid the table light reflection to impact the tracking quality. On the table, a brush attached to an Oculus controller (hereafter referred to as brush-controller, see Figure 1) was placed. The VE consisted of an office environment, in which the table and brush-controller were replicated and a virtual nooooo placed in front of the participants, on which instructions were displayed, (see Figure 2).

It is noteworthy to mention that the use of two tracking systems, Oculus (tracking participants' head and the brush-controller) and LeapMotion (tracking participants' left hand), might generate small position or rotation offsets between tracked components. These offsets were limited by a calibration phase performed before each tactile stimulation in order to align the hand to the Oculus tracking system. They were also small enough to not be noticeable or hinder mid-air interactions, which was confirmed by pilot experiments.

As for the users' embodiment, since this study was only focused on the perception of a virtual limb, we decided to only represent the virtual hand to participants, and the rest of the body was therefore not virtually represented.

3.3 Protocol

After signing an informed consent form, participants were briefed about the different conditions of the experiment and the experiment process. Then, during a short calibration phase the experimenter

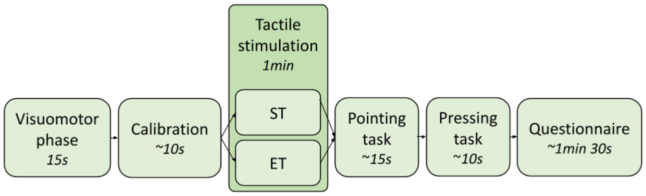

Figure 3: Overview of one section protocol.

measured each finger's length and the palm width, in order to replicate the hand's proportion inside the VE and avoid the size difference between the virtual and real hands to impact the results [29].

The experiment followed a within-subject design, and was divided into two successive blocks, one investigating the ST stimulation condition, the other investigating the ET stimulation condition, each was repeated twice, following the same order. Each block was subdivided into three sections, one for each appearance condition, for a total of 12 sections. The ordering of section's appearance conditions was similar among the four blocks in order to avoid any repetition of the same appearance condition between them. Block and section orders were randomized between participants. The experiment was preceded by one example section, presented under the anthropomorphic appearance and ST stimulation conditions, which followed a protocol identical to the experimental sections.

At the beginning of each section, the virtual left hand was displayed correspondingly to the appearance condition. Each section was presented with the following progression (see an overview in Figure 3, and the entire process in VR, in Video V2 in Supplementary Material): first, participants were presented to a visuomotor phase in order to present them under a more ecological VR application context (see Section 3.4), then they were presented to a visuotactile stimulation, either ET or ST depending on the stimulation condition (see Section 3.5). Afterward, the SoBO was tested using objective measures, in a self-pointing (see Section 3.6.1) and button-pressing (see Section 3.6.2) task, and using subjective measures via a questionnaire (see Section 3.6.3). After the experiment, participants removed the HMD and were asked to fill in a short demographic questionnaire including a field to write comments they could have about the experiment. In total the experiment lasts about 1h, with explanations included.

3.4 Visuomotor Stimulation Task

During this task, left-hand movements were tracked and reproduced in the VE. In the block condition, the hand's position and rotation followed the participants' wrist but their fingers' movement did not affect the virtual hand. A video of a virtual hand, identical to the embodied hand was displayed on the board, performing different movements during 15s (see Video V1 in Supplementary Material): circle-shaped translations, wrist rotations, and fingers-jiggling movements (except for the block condition for which fingers-jiggling was replaced by two waving movements). Participants were asked to mimic these movements, and to keep their left hand inside their field of view in order to decrease the potential negative effect of the board presence on the visual attention to their virtual hand.

3.5 Visuotactile Stimulation

Before starting this phase, participants were asked to place their left hand on the table, palm facing down. Then, a short calibration was performed (about 10*s*), intending to position the virtual hand according to the same tracking system as the brush-controller (tracked by the HMD), avoiding potential offsets between them. During the calibration, the HMD's screen turned black, while the experimenter recorded different hand-part positions, by pointing at them with an Oculus controller to which was attached a stick for more precision. After the calibration, participants were asked to keep their left hand still. In the ST condition, they were asked to grab the controller with their right hand, while in the ET condition it was held by the experimenter. The task lasted 60*s*, during which, every 7.5*s* one of the left hand's fingers (except the thumb) was randomly selected to be stroked. The selected finger was indicated by an arrow appearing above it for 2.5*s* during which no tactile stimulation was applied. When the arrow disappeared the brush-controller holder was asked to apply tactile stimulation with the brush-tip, by continuously stroking the indicated finger, from the inside to the outside. After 5*s*, the brush-controller holder had to stop stroking, as the arrow reappeared pointing at another finger. The random finger selection ensured that every finger was selected exactly twice. During this task, the virtual brush was retargeted, in order to match the visual and tactile contact position following the algorithm described in the following Section 3.5.1. Matching tactile and visual stimuli for each appearance and stimulation conditions can be seen in Video V3 in Supplementary Material.

3.5.1 Retargeting algorithm

During the visuotactile stimulation phase for the dysmorphic appearance conditions, the virtual brush-controller position was retargeted in order to match the visual and tactile contact positions between hand and brush-tip, despite the virtual and real hand's morphological differences (matching tactile positions for each condition are shown in Figure 1). For that purpose, we developed an algorithm adapted from previous research [5, 32], which calculated at every frame the appropriate virtual brush position. The execution of the algorithm can be divided into three parts: *finger* level, *hand* level and *global* level. At the *finger* level, given the set of all fingers (except thumb which does not receive any tactile stimulation) $F = \{F_1, F_2, F_3, F_4\}$, the algorithm calculates for each finger F_x a reposition vector given by $f(F_x)$, for F_x in F, that ensures coherent visuotactile contact on $f(F_x)$, and continuous visual movements. Considering that each real finger is straight and that we want the finger-stroke movement to follow a straight line on it, real fingers were defined by two points, their first knuckle P_1 and their finger-tip P_2, which we call here finger-points. Virtual equivalent of there finger-points were associated on the virtual hand, P_1' (associated to P_1) and P_2' (associated to P_2), so that for y in $\{1,2\}$, when the real brush-tip B is in contact with P_y, the virtual brush-tip B' should be in contact with P_y'. Then, $f(F_x)$ is calculated as the sum for each finger-point P_y of the distance vector between P_y and P_y', multiplied by a weight $w_f(P_y)$ depending on the distance between P_y and B, relative to the sum of each finger-point to B, given in the following equation.

$$
\begin{aligned}
w_f(P_y) &= 1 - \frac{\|\overrightarrow{P_y B}\|}{\sum_{i=1}^{i\in\{1,2\}} \|\overrightarrow{P_i B}\|} \\
f(F_x) &= \sum_{F_i \in F} w_f(P_i) \|\overrightarrow{P_i P_i'}\|
\end{aligned}
\tag{1}
$$

At the *hand* level, the algorithm calculates a reposition vector given by $h(F)$, that ensures coherent visuotactile contact on each finger and continuous visual movements. $h(F)$ is obtained by summing each finger's individual redirection $f(F_x)$, multiplied by a weight $w_h(F_x)$ depending on the lower distance between B and F_x's mesh on the anthropomorphic hand, $dist(F_x, B)$, relative to the sum of each finger's mesh distance to B, given by the following equation.

$$
\begin{aligned}
w_h(F_x) &= 1 - \frac{dist(F_x, B)}{\sum_{F_i \in F} dist(F_x, B)} \\
h(F) &= \sum_{F_i \in F} w_h(F_i) \times f(F_i)
\end{aligned}
\tag{2}
$$

At the higher abstraction level, the algorithm calculates the actual retargeting vector given by $g(F)$ which ensures coherent visuotactile contact on each finger. That retargeting is only applied when the brush is at a minimum range $\alpha = 10cm$ from the hand and continuous visual movements $g(F)$ are obtained by multiplying $h(F)$ by a weight $w_g(F)$ which depends on the minimum distance between B and fingers $d(F) = min(\overrightarrow{F_x B})$ given by the following equation.

$$w_g(F) = 1 - Clamp(0, 1, \frac{d(F)}{\alpha}) \\ g(F) = w_g(F) * h(F) \quad (3)$$

Finally, we obtain the position of the virtual brush-tip B' by adding the retargeting vector $g(F)$ to B.

$$\overrightarrow{B'} = \overrightarrow{B} + g(F) \quad (4)$$

It is worth mentioning that the mismatch induced by the algorithm depends on the matching of real and virtual points. In particular, the longer-finger condition tends to induce re-scaled movements, while the block condition tends to induce re-directed ones.

3.6 SoBO Evaluation

Considering that the outcome of subjective and objective SoBO measures can be different [41], the impact of each condition on the SoBO was evaluated by both a subjective questionnaire and two objective measures. The objective measures aimed to assess a potential proprioceptive drift and consisted in two pointing tasks: a self-pointing task and a virtual-button pressing task. In both tasks, participants had to close their eyes when pointing at their finger-tip but the HMD screen also turned black in order to avoid any accidental eye-opening.

3.6.1 Self-Pointing Task

This task inspired by previous work [36] aimed at measuring changes in the body shape perception among conditions. In particular, we expected the longer-finger condition to impact the real finger length perception, and the block condition to impact the perception of the relative difference between the pinky length and the middle finger length (as an adaptation to the alignment between visual points matching each finger-tips).

During this task, participants had to point successively with the brush tip, above (about 5cm) where they felt were localized their real index and pinky tips. When they felt confident about their answer, participants had to validate it by pressing the controller trigger. Then, they were asked to bring back their right hand to its initial position, away from the left hand, so that the pinky pointing would not be performed relatively to the previous answer. Differences between the pointed tip positions and the actual positions were calculated using the real tip position recorded during the calibration phase preceding the tactile stimulation task.

3.6.2 Button-Pressing Task

We observed participants' behavior while pressing a virtual button. We were interested in exploring whether task precision was impacted by the hand morphology [21] (e.g., by changing the hand distance to the button when pressing, as an adaption to the fingers' length) and appearance [48]. We were also interested in the difference in finger pose during the task for the block condition (e.g., pressing the button with all the fingers expanded vs. pointing with one finger).

At the beginning of the task, the participants' left hand was placed on the table. A virtual button was displayed oriented towards the participant, 30*cm* above the table, 40*cm* away from his left index tip and in front of it with an additional random angle diverging between -30° and +30°. Then, participants were asked to close their eyes and to move their left hand towards the button as if they wanted to press it. When they had the impression that they reached it, they were asked to stop their movement and to validate their position by pressing a button on the brush-controller, held in their right hand. The addition of a random diverging angle in the virtual button positioning was meant to prevent the participant to get used to the task movement and mimicking it unconsciously among sections. No more information was given considering the pressing method, in order to observe potential pressing poses among participants. At the validation, the left-hand index-tip position was recorded, as well as the enclosure of their first phalanges (the other phalanges opening were not recorded as they were not visible in the tracker field of view when the hand was closed because hidden by the hand palm).

Table 1: Questionnaire used in the experiment.

ID	Question
O1	It felt like the virtual hand was my hand.
O2	It felt like the virtual hand parts were my hand parts.
O3	The virtual hand felt like a human hand.
O4	It felt like the virtual hand belonged to me.
A1	The movements of the virtual hand felt like they were my movements.
A2	I felt like I was controlling the movements of the virtual hand.
A3	I felt like I was causing the movements of the virtual hand.
A4	The movements of the virtual hand were in sync with my own movements;
C1	I felt like the form or appearance of my hand had changed.
C2	I felt like the weight of my own hand had changed.
C3	I felt like the width of my own hand had changed.
C4	I felt like the length of my own hand had changed.
T1	It seemed as if I felt the touch of the brush in the location where I saw the virtual hand touched.
T2	It seemed as if the touch I felt was caused by the brush touching the virtual hand.
T3	It seemed as if my hand was touched by the brush.

3.6.3 Questionnaire

Participants were asked to answer a questionnaire inside the VE, investigating their subjective SoBO and additional body-related concepts that could have been impacted by the visuotactile stimulation method or the hand representation (i.e. hand change perception, sense of agency, and tactile sensation). Questions were taken from an existing questionnaire [43], which questions fit our experiment context and allowed to easily extract scores of SoBO, hand change perception, and agency). However considering the lack of questions related to the tactile sensation in this questionnaire, three additional tactile-related questions coming from another questionnaire [37] were also included. In total, the questionnaire was made of 15 questions (see Table 3.6.3) which were answered on a 7-points Likert scale (1 = strongly disagree; 7 = strongly agree). Questions order was randomized among participants.

3.7 Hypotheses

First, considering previous research reporting better scores of SoBO towards an anthropomorphic virtual hand obtained with ST stimulation compared to ET (despite using different objective measurements) [20], we hypothesized that: *for the anthropomorphic appearance condition, the ST stimulation condition will obtain better scores of SoBO than ET* (H1). Considering the same previous results on ST towards anthropomorphic hands [20] and the potential counter-balance in SoBO of mismatching sensory information during ST stimulation due to the retargeting algorithm, mentioned in Section 2.3, we hypothesized that: *for the longer-finger and block appearance conditions, the ST stimulation will obtain scores of SoBO similar to ET* (H2). Considering strong evidence of overall easier SoBO induction towards anthropomorphic body-parts [28, 40, 52], we hypothesized that: *for both ST and ET stimulation, the anthropomorphic appearance will obtain higher scores of SoBO than both the longer-finger and the block conditions* (H3). Considering theoretical evidence of overall easier SoBO induction towards dysmorphic body parts that present less structural divergence from an anthropomorphic body structure [45], we hypothesized that: *for both ST and ET stimulation, the longer-finger appearance condition will obtain higher scores of SoBO than the block condition* (H4).

4 RESULTS

Before the data analysis, duplicated data points of each participant were averaged. Then, parametric analyses were performed using two-way ANOVAs, considering the stimulation and appearance conditions as within-subject features. The normality assumption was tested using Shapiro-Wilk test and when not verified, an Aligned Rank Transformation (ART) [59] was applied to the data. Tukey's Post-hoc tests ($\alpha = .05$) were conducted to check the significance for pairwise comparisons.

4.1 Subjective data

Results of the questionnaire were split into SoBO (O1-O4), sense of agency (A1-A4), hand changes (C1-C4), and tactile sensations (T1-T3). Results can be found in Figure 4.

SoBO Questions The aggregated results of the four *SoBO* questions (see Figure 4) performed on ART data showed only a main effect on the appearance condition ($F_{2,46} = 70.54$, $p < .0001$, $\eta_p^2 = 0.75$). Post-hoc test, showed higher scores for anthropomorphic compared to longer-finger ($p < .01$), anthropomorphic compared to block ($p < .0001$) and longer-finger compared to block ($p < .0001$). The ANOVA analysis did not find any effect on stimulation or interaction effect.

Agency Questions The aggregated results of the four *agency* questions (see Figure 4) performed on ART data showed a main effect on the appearance condition ($F_{2,46} = 23.83$, $p < .0001$, $\eta_p^2 = 0.51$). Post-hocs test, showed higher scores for anthropomorphic compared to block ($p < .0001$) and longer-finger compared to block ($p < .0001$). The ANOVA analysis did not find any effect on stimulation or interaction effect.

Hand Changes Questions The aggregated results of the four *changes* questions (see Figure 4) showed a main effect on the appearance condition ($F_{2,46} = 19.48$, $p < .001$, $\eta_p^2 = 0.46$). Post-hoc tests, showed higher scores for block compared to anthropomorphic ($p < .001$), and longer-finger compared to anthropomorphic ($p < .0001$). The ANOVA analysis did not find any effect on stimulation or interaction effect.

Tactile Related Questions The aggregated results of the four *tactile* related questions (see Figure 4) on ART data showed main effects on the appearance condition ($F_{2,46} = 52.63$, $p < .0001$, $\eta_p^2 = 0.70$) and on the stimulation condition ($F_{1,23} = 6.40$, $p < .05$, $\eta_p^2 = 0.22$), with higher scores for ST. Post-hoc test, showed higher scores for anthropomorphic compared to block ($p < .0001$) and longer-finger compared to block ($p < .0001$). The ANOVA also showed a significant interaction effect ($F_{2,46}$=16.50, $p < .0001$ 0.42). Post-hoc tests showed higher differences between ST and ET in the block condition, as compared to the anthropomorphic ($p < .001$) and longer-finger ($p < .0001$) appearance conditions.

4.2 Objective Data

We also evaluated position precision (on pointing and pressing tasks) in order to investigate differences between conditions. Results regarding position precision are reported as their difference to the *baseline*, defined as the average between results of both stimulation conditions in the anthropomorphic condition (control condition).

4.2.1 Pointing Task

Participants pointing precision was calculated as the distance between the target fingertip and the brush tip positions at the position recording (when the participant pressed the controller button), projected on two separated perpendicular axis (see Figure 2), each parallel to the table plan. The first axis was defined by the targeted finger knuckle and tip (parallel axis) the second one being its perpendicular axis, from the left to the right of the hand (perpendicular axis). Results of the distances projected on the parallel axis are shown in Figure 5.

For the pointing precision of the middle finger-tip on the parallel axis, the ANOVA analysis performed on ART data showed main effects on appearance ($F_{2,46} = 21.12$, $p < .0001$, $\eta_p^2 = 0.48$) and stimulation ($F_{1,23} = 4.44$, $p < .05$, $\eta_p^2 = 0.16$), with higher values for ET. Post-hoc tests showed higher values for longer-finger compared to anthropomorphic ($p < .0001$), and longer-finger compared to block ($p < .0001$).

For the pointing precision of the pinky finger-tip on the parallel axis, the ANOVA analysis performed on ART data showed only main effect on appearance ($F_{2,46} = 10.78$, $p < .0001$, $\eta_p^2 = 0.32$). Post-hoc tests showed higher values for longer-finger compared to block ($p < .0001$).

For the pointing precision of the middle finger-tip on the perpendicular axis, the ANOVA analysis showed main effect on stimulation ($F_{1,23} = 11.75$, $p < .01$, $\eta_p^2 = 0.34$). Results aggregated by appearance conditions are the following: M=0.29*cm*, SD=1.09*cm* and M=-0.54*cm*, SD=1.16*cm*, respectively for the ST and ET conditions.

The ANOVA analysis of pointing precision of the pinky finger on the perpendicular axis did not show any significant effect.

We calculated the pointing precision difference between the pinky and middle fingers on the parallel axis. The ANOVA analysis performed on ART data showed a significant effect on appearance ($F_{2,46} = 6.19$, $p < .01$, $\eta_p^2 = 0.21$). Post-hoc tests showed a significant difference between the anthropomorphic and longer-finger ($p < .01$).

4.2.2 Pressing Task

Table 2: Pressing task precision's results for each condition (means and standard deviations).

	ST	ET
anthropomorphic	M=-0.59*cm*, SD=0.53*cm*	M=0.59*cm*, SD=0.53*cm*
longer-finger	M=-0.82*cm*, SD=1.55*cm*	M=-0.87*cm*, SD=1.40*cm*
block	M=0.78*cm*, SD=1.11*cm*	M=0.24*cm*, SD=1.11*cm*

The participant's virtual button pressing precision is calculated as the distance vector between the index-tip and the virtual button-center positions, projected on the axis defined by the initial tip-position and the button-center position (the higher the value the further the tip position). Results are gathered in Table 4.2.2.

The ANOVA analysis of the Pressing precision did not show significant effect. Analysis of the finger enclosure position during the pressing movement did not show significant effect.

5 DISCUSSION

5.1 Impact of Stimulation on subjective Anthropomorphic SoBO Induction

Our results did not indicate significant statistical differences between ST and ET stimulation conditions in the anthropomorphic condition. These results are partially in conflict with previous results which reported obtaining higher SoBO levels with the ST stimulation over ET [20] and are in contradiction with H1 hypothesis which predicted that we would obtain higher SoBO scores in the ST condition. This difference could be due to set-up differences. Indeed, while in our experiment the ST was induced by a brush directly held by participants, previous study [20] used an indirect system, where participants were manipulating a master robot which controlled a slave robot inducing the tactile feedback. Another explanation might be the addition of a visuomotor task in our experiment, which probably influenced the SoBO, consequently reducing the influence of the visuotactile stimulation on the SoBO induction. This conjecture is in line with previous results reporting an higher influence of visuomotor over visuotactile in the SoBO induction [26]. These results seem to indicate that using an ST stimulation with more direct control and the use of visuomotor stimulation may reduce the benefit of ST over ET

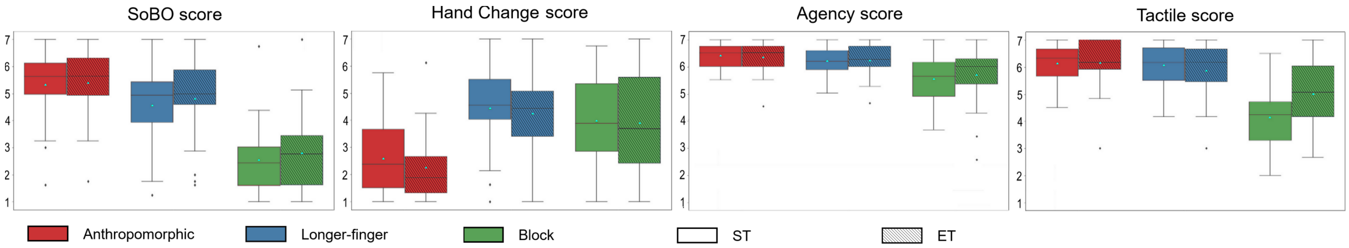

Figure 4: Questionnaire results, split into SoBO, sense of agency, hand changes, and tactile sensations. Box plots show the interquartile range (IQR), whisker plots the 1.5 IQR, cyan triangles the mean value, and black diamonds the extreme outliers.

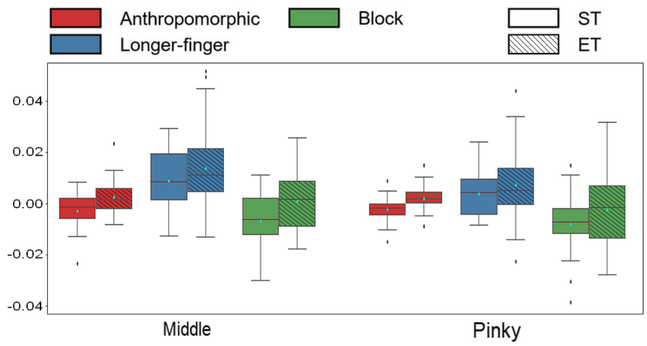

Figure 5: Pointing distance to the baseline on the parallel axis (cm), for the pointing task of middle tip (left) and pinky tip (right) for each appearance condition. Box plots show the interquartile range (IQR), whisker plots the 1.5 IQR, cyan triangles the mean value, and black diamonds the extreme outliers.

on SoBO induction, though maintaining ST efficiency at a sufficient level for its usability in replacement of ET.

5.2 Impact of visuotactile Stimulation on Objective and Subjective Dysmorphic SoBO Induction

5.2.1 Objective dysmorphic SoBO induction

Longer-Finger hand: results of the pointing task are in line with previous results [36] showing a proprioceptive drift tendency when embodied in the longer-finger condition with ET stimulation. In other words, participants tend to feel their own fingertip positions as further than in other appearance conditions. These results are often explained by the plasticity of the brain body-schema, which adapts its model to new experiences diverging from its current model. Interestingly, these effects were also observed with the ST stimulation, despite the additional perceptual information about the real finger size given by the indirect contact of the hand holding the brush-controller on the left hand. Contrary to previous research [21], we did not observe behavioral adaptation of the virtual longer-finger hand in the pressing task. These results might also be explained by the measuring method (hand tracking), which may have lacked precision, compared to measurement using a ruler.

Block hand: We had conjectured that behavioral adaptations to the block condition could be observed by a lower perceived finger length difference between the middle and pinky (pointing task) and a lower finger enclosure during simple motor tasks (pressing tasks). However, our results did not confirm this conjecture. As these objective measures of SoBO were never applied before to this type of dysmorphic representation, it is difficult to build a strong conclusion from these results.

5.2.2 Subjective dysmorphic SoBO induction

Similar to the anthropomorphic condition, we did not find any difference between ST and ET stimulation in both block and longer-finger conditions. These results confirm H2 which predicted that in both dysmorphic conditions, the subjective SoBO level induced with the ST stimulation would be equal to the ET stimulation. These results are particularly interesting as we initially predicted that dysmorphic conditions could reduce the benefit of ST over ET in terms of SoBO induction.

Overall, we did not find any evidence of the superiority of one visuotactile stimulation (ST or ET) over the other for SoBO induction. While, as mentioned earlier, we cannot exclude that differences could have been found if participants were not presented with the visuomotor task. These results are promising concerning the use of ST for SoBO induction, as it did not result in any reduction in SoBO scores in an ecological use, despite the additional sensory mismatch that it provokes.

5.3 Impact of Dysmorphism on the Subjective SoBO

Overall, in both ST and ET stimulation conditions, the anthropomorphic condition obtained a score of SoBO above the average (M=5.35, SD=1.30), significantly higher than both dysmorphic conditions, confirming hypothesis H3. However, it is interesting to note that overall, the longer-finger condition obtained a relatively high score of SoBO (M=4.69, SD=1.46) which remained above average. On the other hand, the block condition results showed a severe subjective SoBO reduction and significant SoBO score differences compared to the anthropomorphic and longer-finger conditions, as it obtained a score below average (M=2.68, SD= 1.36), confirming hypothesis H4. These results can be explained by the Bayesian causal inference model of SoBO [45], which states that it is harder to induce SoBO toward dysmorphic virtual bodies showing more divergences from anthropomorphic bodies. In addition, answers showed that participants felt overall less tactile sensation coherence in the block condition which probably impacted scores of SoBO, and that we can hypothesize to be due to the semantic mismatch between the visual shape and its tactile perception. Finally, we cannot exclude that the visuomotor stimulation played a role in the smaller SoBO score obtained by the block condition, due to the absence of finger visuomotor feedback in this condition. This is visible in the significant lower scores of agency for the block condition, as compared to other appearance conditions.

However, despite the lower scores of SoBO in the block condition, it is interesting to mention that both dysmorphic conditions showed significantly higher results to questions related to the real hand change sensation than in the anthropomorphic condition. These results show that whether the SoBO illusion occurred or not, the dysmorphic embodiment always induced a perceptual change with respect to their real hand.

5.4 Stimulation Impact Beyond SoBO

Our results showed significant proprioceptive drift differences on the perpendicular axis, at the pointing task, between ST and ET conditions. Considering that different factors could have had a global impact on the pointing task results (the use of a brush as a pointer, rather than the participant's finger-tip and the initial hand position before pointing at the right side of the target), our measure mostly has value as a comparison between techniques conditions, and are not sufficient to claim that one stimulation technique induces more proprioceptive drift than another. However, our results indicate that while producing similar subjective and objective ownership adaptations, each stimulation technique influences differently the participant body-schema perception.

Despite the absence of difference between ST and ET stimulation in the block condition, in terms of subjective and objective SoBO induction, results of the tactile sensation questions show significantly higher scores when the virtual block-hand was stimulated by the ET stimulation compared to ST. These results could find their explanation in the difference between the real and visual shape, which the additional sensory information provided by the ST technique could have intensified. In addition, observations of participants' self-touch stimulation during the experiment and post-experiment discussions revealed that they had more difficulties to accurately stroke their pinky than other fingers. Interestingly, the pinky finger is also the finger that can diverge the most to the hand-palm axis when opening. Considering that in the block condition, the virtual position associated with each finger is parallel to the hand palm, the divergence from the hand-palm axis has an effect on the re-direction scale: the more the finger opening diverges from the hand-palm axis, the more re-direction will be applied by the algorithm. These results are interesting as the difference of touch sensation realism between ST and ET is not observed in the longer-finger condition. We may thus conjecture that this difference is due to the different nature of the retargeting applied in these conditions, re-direction in the block condition, and re-scale in the longer-finger condition, and that re-scale algorithms might be easier to adapt to, even if further investigations with different re-targeting scales are required.

6 Limitations and Future Work

6.1 Visuotactile limitation for SoBO induction

Our results showed similar level of objective and subjective SoBO inductions between ST and ET for each appearance condition. These results suggest that ST is not only a viable but also a more practical alternative to ET stimulation for dysmorphic SoBO induction in VR. Regrettably, both ST and ET still encounter limitations in inducing substantial SoBO towards dysmorphic appearances, reinvigorating the need to futher investigate alternative methods to induce SoBO towards dysmorphic appearances.

6.2 Influence of the Type of Body Dysmorphism

There is virtually an infinite number of different dysmorphic bodies with unique specificity. While this study is a first exploration of the potential of ST in the induction of SoBO towards dysmorphic bodies, it was impossible to cover dysmorphic bodies as a whole, and further research is required to investigate potential effects of different dysmorphic body shapes on the SoBO induction, and the feasibility to propose retargeting algorithm introducing reduced perceptual mismatches. In particular, the type of body dysmorphism has a strong influence on the nature of the retargeting method. For the longer-finger condition, the movement was only re-scaled as it followed the same finger direction, when it the block condition the movement was also redirected to match the different shape. We observed and have been reported difficulties to accurately stroke the indicated path in the ST condition when embodied with the block-shaped hand, which is consistent with the questionnaire results concerning tactile sensation realism, showing significant decline in the ST condition. As we did not find similar results in the longer-finger condition, we hypothesize that this difficulty when performing the stroking task might be due to the nature of the retargeting induced. Furthermore, another potential limitation of our experiment is that only the hand of participants was represented in the VE, which is non coherent with a normal body representation and could have influenced the SoBO scores.

6.3 Missing Pieces for free ST Stimulation

While our results showed that ST seems to be a promising alternative to ET, as a more practical way to induce SoBO towards dysmorphic bodies, technical challenges and theoretical questions remain to provide a totally free ST with a dysmorphic embodiment. Firstly, our experiment restricted the haptic stimulation to a continuous single contact point. In order to provide a completely free self-tactile feedback, more research is required to find solutions to more complex tactile interaction, such as multi-contact point interaction (similar to [32]) or self-tactile stimulation with the hand directly. Secondly, in this experiment the tactile stimulation was restricted to a simple linear movement, this was made to control that the tactile stimulation would be identical among trials, participants and conditions. However, a free tactile exploration might let users explore the critical area where the retargeting algorithm produces more perceptual mismatches, which could reduce the SoBO induction. This concern seems mostly relevant for dysmorphic hands showing a large shape divergence with humans' hand. For example, we can expect that when embodied with a block-shaped hand, ST would probably provoke a higher perceptual mismatch if users try to touch the hollow between hands, as this tactile information can not be mapped with any visual information without creating perceptual mismatches. Thus, research are required to uncover mismatches induced by free explorations, to which extent they will affect the SoBO, and the potential solutions to mitigate them. Finally, while visuomotor stimulation was present in our study, its interrelation with ST in the induction of SoBO was not explored. More generally, it would be interesting to explore the use of ST stimulation in combination with other types of feedback stimuli. For instance, some works found that contingent sounds could change the mental representation of one's finger length [51]. We believe it would be of great value to explore the combination of ST stimulation with auditory feedback in the elicitation of SoBO towards dysmorphic bodies.

7 Conclusion

In this paper, we presented an experiment investigating the potential of self-touch stimulation using retargeting techniques to provide a sense of body ownership towards dysmorphic virtual hands, and its usability as a more practical alternative than the classical external-touch stimulation. Promisingly, we found that with the use of retargeting, ST stimulation reaches similar objective and subjective levels of SoBO towards two different dysmorphic bodies compared to ET stimulation. We also discuss the potential limitations of this methodology in terms of application and type of dysmorphic body. We raise in particular the question of its use for interaction, which may depend on the type of dysmorphic body and the nature or scale of the retargeting that might require. Taken together, our results pave the way for further research exploring solutions for the current technical and cognitive challenges limiting the use of a totally free ST stimulation in a dysmorphic embodiment context.

Acknowledgments

This work was partially supported by JST Moonshot Research & Development Program (JPMJMS2013) and Grant-in-Aid for Challenging Research (Exploratory) (20K21801).

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