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Follow Your Nose: Extended Arm Reach After Pinocchio Illusion in Virtual Reality

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In this study, we recreate the Pinocchio Illusion—a bodily illusion whereby the perceived length of one's nose is extended—in Virtual Reality. Participants (n = 38) self-administered tapping on the tip of the nose of a virtual avatar seen from the first-person perspective (using a hand-held controller) while the nose of the avatar slowly grew with each tap. The stimulating virtual arm and the virtual nose were linked such that while the nose grew the arm extended, and then also grew up to 50%. This produced an extension of the perceived reach of the stimulating arm, and an outward drift in the participants' real arm. A positive correlation between the extent of the outward drift of the participants' arm and the perceived reachability of distal objects was observed. These results were found both with synchronous tactile stimulation on the participants' real nose, and without, but not for control conditions in which the visuomotor synchrony or body schema were violated. These findings open new avenues for hand grasp interactions with virtual objects out of arm's-reach in immersive setups and are discussed in the context of theories of body ownership, body schema, and touch perception.

Keywords: body awareness, multisensory illusion, touch, body schema, reach, embodiment, avatars

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1 INTRODUCTION

Recent evidence in neuroscience and psychology suggests that our body schema—i.e., the perceived map, shape, and posture of our body—is not fixed, but instead an adaptable plastic representation constructed by our multisensory experience (Ehrsson et al., 2004; Lenggenhager et al., 2007; Petkova, 2011; Gentile et al., 2013). Previous work has demonstrated that tools can be incorporated into the body schema (Farnè et al., 2005a; Miller, 2018), and that the length of our limbs, our body size, peripersonal space and body shape can be drastically altered given the right combination of tactile, motor, proprioceptive, and visual cues (Calzolari et al., 2017; Guterstam et al., 2018; Miller, 2018). One fascinating and rarely examined example of the plasticity of the body schema is the Pinocchio Illusion.

The Pinocchio Illusion is a bodily illusion in which a blindfolded participant experiences an illusory elongation of their nose and/or finger (Lackner, 1988; Medina and Coslett, 2010; Ramachandran and Hirstein, 1998; Kilteni et al., 2015). The illusion is traditionally induced in two possible ways. The simplest version situates the participant with their eyes closed behind a mannequin (**Figure 1A**), sometimes also referred to as the phantom nose (Ramachandran and

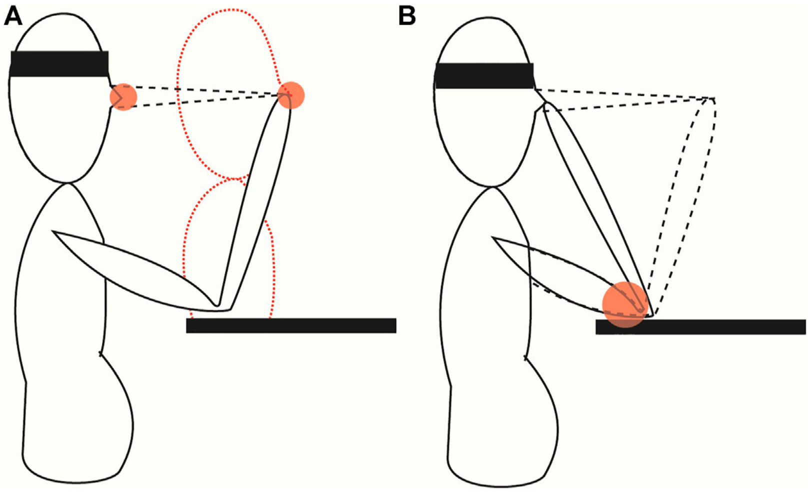

FIGURE 1 | Variants of the Pinocchio Illusion. **(A)** Shows the version in which the participants passive touch the nose of a mannequin with their eyes closed. The experimenter operates the hand of the participant and provides synchronous taping both on the nose of the participant and the mannequin. **(B)** Depicts the Pinocchio Illusion enabled by tendon vibrations at the elbow. The participant also maintains the eyes closed.

Hirstein, 1998; Kilteni et al., 2015). The participant extends their arm to reach the nose of the mannequin. The experimenter holds the index finger of the participant to tap on the mannequin's nose while synchronously tapping with their own finger on the participant's nose. In this setup, the participant might experience an illusory long nose (about the size of their arm length), which is thought to stem from an integration of the (passive) touching action from their own hand on the manikin's nose in front of them with the felt touch on their real nose.

In another version of the Pinocchio Illusion (**Figure 1B**), the illusion is induced by vibrotactile stimulation on the ipsilateral (brachii) biceps tendon (Medina and Coslett, 2010). In this version, a blindfolded participant holds their nose while undergoing tendon vibration which creates the illusion that the arm extends and thus, as a consequence, the nose grows (**Figure 1B**). However, illusion induction using tendon vibration is more difficult as it requires that the participants first experience the illusory arm extension in order to create the illusory experience of nose elongation (Burrack and Brugger, 2005), while on the other version the arm is already extended. Generally, there are strong individual differences and Lackner also describes that some participants experienced the index finger instead of the nose growing (Lackner, 1988). In a study on the interference of self-touch and proprioception on mental imagery, they found a stronger modulation of the body schema in the self-touch condition when there is mental imagery (Conson et al., 2011), which could indicate that this type of Pinocchio illusion using tendon vibration could be stronger than the mannequin one. Nevertheless, given the various multisensory manipulations that might induce a growing nose or limb, the precise features and or stimulus combinations that give rise to these alterations in the perceived body schema remain unclear.

Interestingly, both vision and action, two components that have been suggested to play a key role in the induction of illusory body ownership in other bodily illusions [e.g., the long arm illusion, the rubber hand illusion or the giant body illusion (Normand et al., 2011; van der Hoort et al., 2011; Kalckert and Ehrsson, 2012; Kilteni et al., 2012; Kalckert and Ehrsson, 2014; Abtahi et al., 2019)] are not modulated in the classical version of the Pinocchio illusion. But vision and action might actually play a bigger role than originally anticipated in this illusion, will in that scenario touch still be so important? Previous work has found that the relationship between the body part that does the touching (touchant) and the body part that is touched (touché) has a significant impact on both the touching and touched body part. In an active Pinocchio illusion, we can further explore the interaction between these two models of touching and touched. In particular, Schutz-Bosbach, et al. (2009) designed an experiment where participants used the fingers of one hand (the "active" hand) to touch the fingers of the other (the "passive" hand), and demonstrated a touchant-touché effect for unseen touch, whereby self-touch can modify the body schema representation for both the active (i.e., the touchant) and passive (i.e., touché) body parts (Schütz-Bosbach et al., 2009). We expected similar effects in the Pinocchio illusion, where the nose is the touché and the hand is the touchant, and built the setting accordingly in virtual reality (VR).

Using visuo-tactile stimulation inside VR, researchers have been able to change the mental representation of participants' body parts, and have enlarged participants' arms (Kilteni et al., 2012) or bellies (Normand et al., 2011). VR is a powerful tool for the investigation and manipulation of the body schema, and might thus provide the potential to overcome some limitations of classic versions of the Pinocchio illusion, such as blindfolding participants. This line of work often uses mismatching visuo-tactile information caused by active movement of the participants, e.g., they actively touch their belly but see the tactile stimulation on the larger belly (Normand et al., 2011). Which corroborates literature suggesting that both, active movements and self-touch, enhance the illusion of body ownership and the feelings of immersion in VR (Gonzalez-Franco, 2010). Furthermore, the self-avatar follower effect suggests that participants implicitly match the position and motions of the seen and embodied avatars, suggesting a mutual interaction of motor action and embodiment (Cohn et al., 2020).

Here, we adapted the Pinocchio Illusion to explore whether the dynamic enlargement of an avatar's virtual nose and arm can trigger a self-avatar follower effect (Gonzalez-Franco et al., 2020), and thereby affect the participants' perception of reach. This goes beyond previous long arm experiments (Kilteni et al., 2012) and it aims for an implicit drift that shall expand the peri-personal space of the participant. Previous studies on tool interactions as well as on patients with disorders of embodiment have found that peri-personal hand space can be dynamically altered affecting this reach perception (Farnè et al., 2005a; Bonifazi et al., 2007; di Pellegrino et al., 1997; Folegatti et al., 2009). The plasticity of the peri-personal or reachable space has been studied also in different multisensory contexts, including visual-tactile extinction in homologous and nonhomologous body parts (Serino et al., 2015), synchronous pairing of tactile and auditory inputs (Farnè et al., 2005b), and the prospective characteristics of body-object interactions (Coello et al., 2012). In our experiment we measured the physical drift of the participant's real arm and the subsequent change on perceived arm reach as an indication for the strength of the illusion.

Under normal circumstances, the reach of our arms defines the extent of the working space we have to interact with and experience the world around us (the peri-personal space). However, one common method of extending one's reach, and research on the extension of body schema in humans and non-human primates suggests that the extended motor capability from tool use is interpreted by the brain as an elongation of our own effector (e.g., the hand), as if it were transferred to the tip of the tool (Berti and Frassinetti, 2000; Maravita et al., 2003; Maravita and Iriki, 2004). After tools use, visual receptive fields normally only sensitive to objects near one's hand adapt to respond to objects near the tool, suggesting an extension of peripersonal space and plasticity of the body schema (Maravita and Iriki, 2004; Miller, 2018). Passive holding of the tool does not elicit this adaptive change in the body schema, suggesting that this adaptation requires active intentional use, and not merely the grasping of tool (Berti and Frassinetti, 2000; Maravita and Iriki, 2004; Guterstam et al., 2018; Miller, 2018). However, studies on tool versus hand operation show that despite the fact that humans can use tools to extend their physical capabilities and explore surrounding objects, the interactions are very different than when using the hands directly (Vaesen, 2012). In particular, tools require familiarity and they introduce difficulties that depend of the characteristics of the tool and its relationship to the body and other objects (Farnè et al., 2005a).

An alternative means of expanding the felt reach entails using bodily illusions that create ownership over an enlarged or extended external body or body part (Botvinick and Cohen, 1998; Petkova, 2011). Body ownership can be achieved using multisensory integration and synchronous visuo-tactile or visuo-motor stimulation (Lenggenhager et al., 2007; Slater et al., 2009; Maselli and Slater, 2013; Kokkinara and Slater, 2014). Body ownership illusions can be established towards a mannequin or a Virtual Reality avatar (Spanlang, 2014), shown in different perspective or appearance (Lenggenhager et al., 2007; Peck et al., 2013). Body resizing can also be enabled through full body ownership illusions, in which participants generally overestimate distances when embodied in smaller avatars and underestimate distances when embodied in bigger bodies (van der Hoort et al., 2011; Banakou et al., 2013). However in the case of resized body ownership illusions, objects around the participants are also perceived to be greater or smaller depending on whether they had been embodied in smaller or bigger bodies (van der Hoort et al., 2011; Banakou et al., 2013). Thus, in scenarios in which the scale of objects is to remain true-to-life, a complete altered body resizing would not be appropriate, as it may introduce other undesirable effects such as the change on the perceived surrounding objects or the environment.

2 MATERIALS AND METHODS

We implemented a Pinocchio Illusion based on synchronous nose touching, i.e., without tendon vibration (see **Figure 1A**). In our setup the hand of the avatar is attached to the tip of the virtual nose, and every time the participant taps on the hand-held controller with his or her real index finger (i.e., seemingly on the nose of the avatar). The avatar nose grows with every tap until the nose reaches a maximum of 70 cm in length (see **Figure 2**). The virtual arm extends with each tapping to follow the virtual noise. Once the arm is fully extended to its physical limit, the virtual arm will continue growing (to be 50% longer than the real one).

Using this setup we aimed to test whether i) the illusion induces a self-avatar follower effect on the hand of the participant (i.e., a motor adaptation of the arm position) ii) examine the effects of visual-tactile stimulation in the Pinocchio Illusion in participants who are not blindfolded, iii) enable visuo-motor stimulation in which the touchant body part is controlled by the active motions of the participants, rather than passively delivered by the experimenter.

In our first experiment, we examined to what extend illusory ownership, subjective reaching space and actual hand position were altered in two different versions of the virtual Pinocchio illusion: either using visuomotor synchrony, i.e., with tactile feedback on the nose of the participant, or without tactile feedback. Importantly, the tactile feedback was not given by the experimenter as in the original version of the Pinocchio illusion but by the participant themself with the left hand (bimanual condition, see **Figure 3B**). In the condition without tactile feedback, the participant did not tap their real nose, and instead placed their left hand out of view (unimanual condition, see **Figure 3A**).

In a follow-up control experiment, only with unimanual setups, we examined three variations: to understand whether the perceived extension of reach would also affect to the non-stimulating hand (Other Hand Reach Condition), whether the extension of touch would persist if the body schema was violated

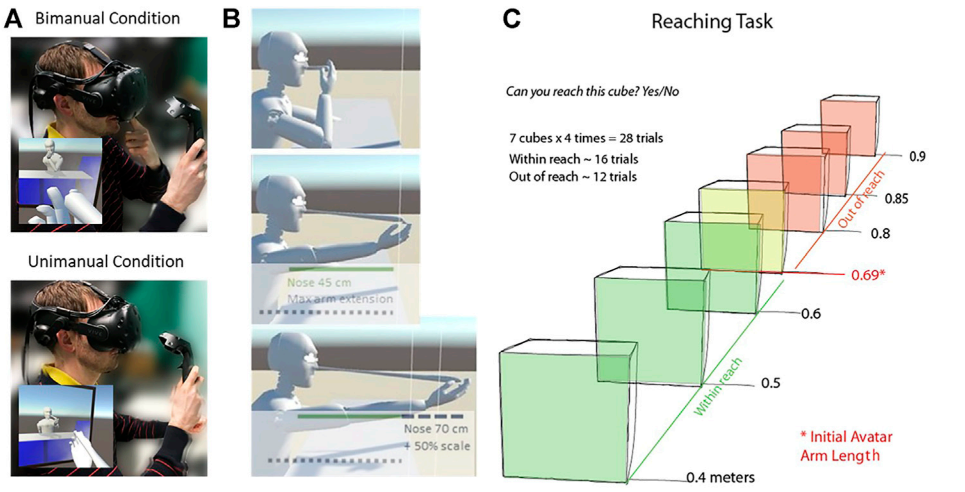

FIGURE 2 | Experimental Overview. **(A)** Participant performing the Pinocchio-Illusion stimulation in the Bimanual (top) and Unimanual (bottom) stimulation conditions, with first person view from the HMD and reflection in the mirror. **(B)** Elongation of the nose as the participant taps on the ventral pad of the controller. The nose elongates every time it is tapped with the finger. At the maximal arm extension the nose is of 45 cm, but the nose continues to grow up to 70 cm; and the arm of the avatar grows to be 50% longer. **(C)** Schematic overview the reach estimation task: seven cubes were presented at different distances (4 times each). Three cubes were within arm reach, one at the threshold, and three out of reach. The cubes were presented in random order.

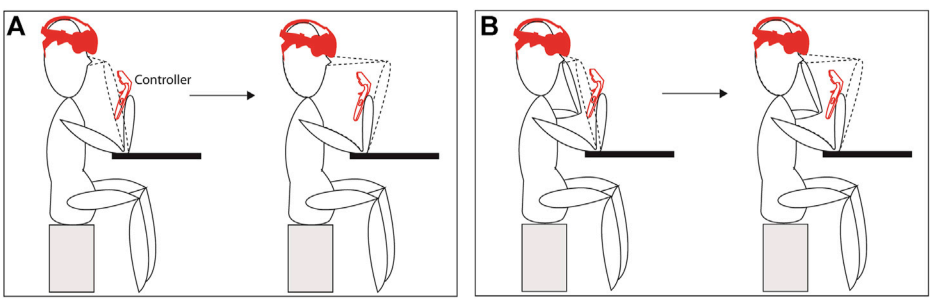

FIGURE 3 | Pinocchio Illusion in Virtual Reality. **(A)** Unimanual stimulation, only touchant enabled. The participant taps on the controller and this translates into a virtual hand taping the virtual nose. The nose grows with every tap. **(B)** Bimanual stimulation. The participant taps both on the controller (touchant) and on his own nose (touché) with the finger on of their other hand synchronously. Each tap translates into a virtual hand taping the virtual nose and the nose grows.

by having the opposite virtual hand performing the synchronous tapping (Other Hand Touch Condition), or whether the temporal congruence between the participants' hand and the seen tapping of the virtual hand was violated (Visuo-Motor Incongruent Condition). In all the control conditions the participants never feel the actual touch on the nose, and instead we focus only on the visual only touché (See **Supplementary movie S1**).

2.1 Participants

A total of 18 participants (33.78 ± 8 years old, 6 female) were recruited for the main experiment, and an additional 20 participants (from 27 to 51 years old, 4 female) were recruited for the control experiment.

All participants in the main experiment underwent both the unimanual and bimanual conditions in counterbalanced order, this allowed for within subject comparisons. All participants in the control experiment experienced all three control conditions (in counterbalanced order). They were all right -handed, healthy, reported no history of psychiatric illness or neurological disorder, and reported no impairments of touch or vision (or had corrected-to-normal vision). The experimental protocol for each experiment lasted for 15 min, was approved by Microsoft Research's Institutional Review Board under the name "Manipulating the Body-Schema in Virtual Reality," and followed the ethical guidelines of the Declaration of Helsinki. Participants gave written informed consent and received monetary compensation in exchange for their participation. Informed consent was also obtained to publish the information/image(s) in an online open-access publication.

2.2 Apparatus

All visual stimuli were presented *via* an HTC Vive head mounted display (HMD) equipped with the integrated positional tracking system. The tracking system is enabled by stationary reference units that use lidar technology and inertial sensors to track the user's head and handheld controllers. The HTC Vive uses an OLED display with a combined resolution of 2160 × 1200 (1080 × 1200 per eye) and a refresh rate of 90 Hz. The effective field of view (FOV) for the participants is of 110 degrees.

Participants provided the tapping using the ventral pad and the right index finger of the VR controller (**Figure 2A**). The VR scenario was implemented in Unity 3D Software (version 2017.1.0f3).

2.3 Measurements

Before and after the stimulation participants performed an arm reach estimation task inside VR. This task consisted of participants responding verbally (yes/no) whether they thought they could reach up to a virtual cube at different distances (7 distances, 4 times each, 28 estimations total; see **Figure 2C**) in a two-alternative forced choice task (2AFC). During the arm-reach estimation procedure, participants rested their arms on the table and the avatar disappeared for the duration of the 28 estimations. By default, some cubes were out of reach, and some were in reach, covering a distance between 0.4 till 1 m from the participants position.

To examine whether the perception of arm reach was extended following the Pinocchio illusion, we fit a logistic regression to each participants' reachability data from the 2AFC task pre- and post-Pinocchio Illusion stimulation using a glm () function with a "binomial" family argument in R (R Core Team, 2017) using the base R package STATS. From these fits, the point of subjective equality (PSE)—i.e., the point at which the participant can no longer distinguish between whether the object is reachable or not—was calculated using an inverse logit function extracting the distance at which the probability of a "reachable" response was 0.5. These individually-extracted PSE values were then compared at the group level using a paired-samples t-tests for a-priori planned comparisons.

The data from two participants of the main experiment were removed due to poor model fit for one or more of the conditions (i.e., two participants perceived all objects to be reachable pre- and post-illusion in one or more of the conditions). At the conclusion of each condition's block of estimations, participants completed a questionnaire about their virtual experience, in which they answered the following questions:

1. I felt as if the virtual body were my body.
2. It felt as if the virtual body I saw belonged to someone else.
3. I felt as if my body was located where I saw the virtual body.
4. It felt like I could control the virtual body as if it was my own body.
5. I felt out of my body
6. The virtual body began to resemble my body
7. I felt as if I had two bodies.
8. As the nose elongated, I felt the instinct to move my hand.

Responses to these statements were on a −3 to 3 Likert scale, where −3 was anchored to strong disagreement and 3 to strong agreement. Questions 1 to 7 were related to the sense of ownership of the body, with questions 1, 3, 4 expected to record high scores while questions 2, 5, 7 expected to record low scores. Questions 8 was to examine whether participants had any subjective urge to move their arm. These expected scores are typical for participants that have high embodiment, as it is shown in previous experiments (Gonzalez-Franco and Peck, 2018; Peck and Gonzalez-Franco, 2020).

The above measurements allowed us to examine to what extent tactile stimuli on the nose (i.e., touché) affected the illusion and the perception of reach of the touchant (i.e., how far away does the participant perceive his or her virtual arm to be able to reach).

2.4 Experimental Procedures and Design

In all conditions of Experiment one and the Control Experiment, we first embodied the participants in an avatar during a period of 1 min. During this embodiment-induction period, the participants moved their upper body, and the upper body of the avatar was spatially and temporally linked to the participants using inverse kinematics derived from the controller and HMDs. The participants could also see their virtual avatar in a virtual mirror. This active visuo-motor control has been shown to enhance the experience of body ownership over a virtual avatar (Gonzalez-Franco, 2010; Kokkinara and Slater, 2014).

They then completed the pre-stimulus 2AFC reaching task.

Next, using a hand-held controller, the participants bring their hand to the tip of the virtual nose and start tapping (**Figure 2A**). In some experimental conditions (e.g., bimanual), the participants also tap their real noses with the index finger of their other hand (not holding the controller). After the virtual hand establishes contact with the nose, both body parts "snap" together. From there on, every tap translates on an increment in the size of the nose. As informed, the participants are not required to move their arm during the stimulation in order to produce the tapping. For simplicity, the virtual fingertip remains snapped to the nose tip no matter what. This caused an effect whereby, independently of the actual position of the hand of the participant, both the virtual arm and the virtual nose are extended and growing progressively with each tap. This meant that eventually the virtual arm was fully extended, even if the participant's real arm was not. This discrepancy was the basis for an arm drift measure. Consistent with the self-avatar follower effect, some participants should feel the urge to maintain a visual-proprioceptive congruency between their virtual arm and real arm, and will therefore move their hand as they tap. Others will not. This form of hand snapping allows for the experiment to start a non-natural elongation of the arm: after reaching the maximum natural extension, in our experiment the arm will enlarge up to 50% longer. Arms up to two times longer have been shown to be acceptable body scales that do not necessarily break the illusion of ownership (Kilteni et al., 2012; Tajadura-Jiménez et al., 2015).

In total, we conducted two experiments with five conditions to investigate the extent to which touché input on the nose provided meaningful input to the users.

2.4.1 Main Experiment

In the first experiment, the participants repeatedly experienced one of two conditions in a counterbalanced within-group design:

the Bimanual Condition in which the participant tapped both on the controller and on their own nose synchronously, each tap translated into a virtual hand tap on the virtual nose and resulted in the nose growing one increment (see **Figures 2A,B**), and the Unimanual Condition in which the participant tapped on the controller and this was translated into a virtual hand tap on the virtual nose and resulted in the nose growing one increment with each tap. In the first experiment, there was 1 block of Unimanual estimations and 1 block of Bimanual estimations (28 estimations per block, 56 total estimations). Each block consisted of four parts (see **Supplementary movie S1** for an overview of the whole experiment):

1. Avatar Embodiment: the participant looked at the virtual body in the virtual mirror and familiarized themselves with the real-time movement of the virtual body (1 min).
2. Arm Reach Pre-test—Psychometric Reaching Task: the participant responded verbally (yes/no) in a 2AFC task whether they thought they could reach a cube placed at different distances (7 distances, 4 times each, see **Figure 2C**).
3. Pinocchio Illusion Stimulation: the participant engaged in either Bimanual or Unimanual condition taps in front of a virtual mirror to experience Pinocchio illusion.
4. Arm Reach Post-test - Psychometric Reaching Task: the participant responded verbally (yes/no) in the 2AFC task whether they thought they could reach a cube placed at different distances (7 distances, 4 times each, see **Figure 2C**).

At the conclusion of each condition's block of estimations, the participants completed a questionnaire about their virtual experience. And at the end of the whole experiment before debriefing participants we asked them if they noticed anything a change of size on the virtual arm and/or nose during the experiments.

2.4.2 Control Experiments

In order to examine whether the extension of perceived reach was affected by violations of visuomotor synchrony and the body schema, as well as whether the extended perception of reach was limited to the stimulating (i.e., touchant) arm, we conducted a control experiment with the following conditions, all of them on an unimanual setup:

(i) Other Hand Reach Condition: in this control, participants were asked only whether they could reach the cubes with the non-touchant hand. i.e., by asking participants about their non-stimulated hand reachability we can assess if the whole peri-personal space has been enlarged or only that of the stimulated hand. Our expectation was to find no changes on the second hand.

(ii) Other Hand Touch Condition: in this control, participants used one hand as touchant but saw the virtual avatar perform the task with the opposite hand. This control is mostly to show that the illusion did not happen if there was a large proprioceptive mismatch.

(iii) Visuo-Motor Incongruent Condition: in this control, participants did not see the virtual taping being applied to their virtual nose. The expectation here was that the illusion would cease even with a small incongruent stimulation effect, by which participants would not see their hand tap, while they see their arm being extended with a static finger attached to the tip of the nose.

The conditions in these control experiments allow us to examine the limitation of the extension of touch in the Pinocchio Illusion, but also allow us to rule out alternative explanations based on demand characteristics. In all the control conditions the participants never feel the actual touch on the nose, and instead we focus only on the visual only touché. Which also allowed us to further examine the role of the self-avatar follower effect.

3 RESULTS

In our first experiment, we explored whether the tapping finger (touché) of the participant could elicit the Pinocchio illusion and the perceived extension of one's arm, by introducing two conditions: Unimanual stimulation condition, and Bimanual stimulation condition (**Figure 2A**). During both conditions, the virtual nose as well as the virtual arm grow beyond their natural size. We measure the physical drift of the participant's real arm and the subsequent change on perceived arm reach.

3.1 Reach Psychophysics Results

The planned comparisons revealed that the Pinocchio illusion led to a significant shift in the perceived reachability of more distant objects post-illusion in the unimanual [t (15) = 3.00, p = 0.008], and the bimanual conditions [t (15) = 3.11, p = 0.007] compared to pre-illusion reachability (see **Figure 4** and **Supplementary Table S2**). No significant difference between the post-illusion PSEs for Unimanual and Bimanual conditions were observed [t (15) = 1.08, p = 0.29] Additionally, no significant difference between pre-illusion PSEs were observed for Unimanual and Bimanual conditions [t (15) = 1.11, p = 0.281].

The same procedure was also used to conduct the psychophysical analysis for the reachability data in the control conditions. A planned comparisons revealed that there was no significant increase in the perceived reachability of distal objects post-stimulation vs. pre-stimulation when the participants performed the unimodal stimulation version of the Pinocchio Illusion induction with incongruent visuomotor stimuli [t (19) = 0.31, p = 0.760], and when the body schema was violated by having the opposite seen hand of the virtual avatar perform the tapping [t (19) = 0.60, p = 0.560] in the Visuomotor Incongruent and Other Hand Touch conditions, respectively. Interestingly, when the participants performed the reachability estimations for their non-stimulating hand in the Other Hand Reach Condition, the reported a significant decrease in the perceived reachability of that hand post-illusion compared to pre-illusion [t (15) = −2.49, p = 0.024] (see **Figure 5** and **Supplementary Table S2**).

We also examined whether there were changes in the sensitivity of participants' ability to discriminate between a reachable or non-reachable cube by calculating the just noticeable difference (JND) from each participants' logistic

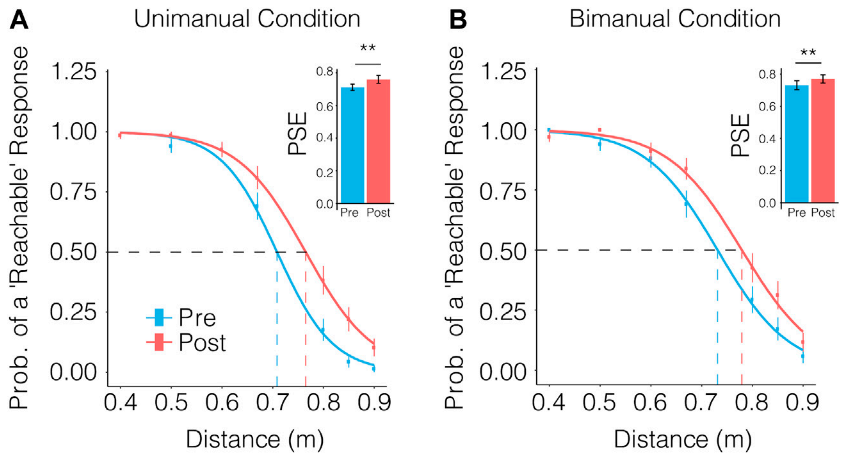

FIGURE 4 | Psychometric curves for reach estimation. Logistic regression fits for the perceived reachability for all cube distances pre- and post-Pinocchio Illusion stimulation in both the unimanual **(A)** and bimanual **(B)** conditions. Dotted lines indicate point of subjective equality for each curve. Bar plots represent mean points of subjective equality (PSEs) for pre- and post-Illusion reachability data extracted from psychometric curves fit to each participant's data. Error bars represent ± SEM. Asterisks between bars indicate significant post- vs. pre-Illusion PSE comparison (** $p < 0.01$). Plotted with R.

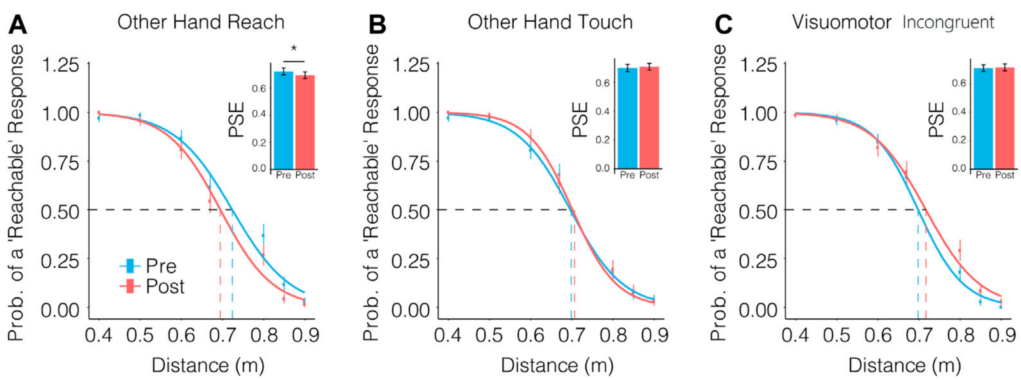

FIGURE 5 | Psychometric curves for reach estimation in control conditions. Logistic regression fits for the perceived reachability of all cube distances pre- and post-Pinocchio Illusion stimulation in the Other Hand Reach **(A)** Other Hand Touch **(B)** and Visuomotor Incongruent **(C)** conditions. Dotted lines indicate point of subjective equality for each curve. Bar plots represent mean points of subjective equality (PSEs) for pre- and post-Illusion reachability data extracted from psychometric curves fit to each participant's data in each condition. Error bars represent ± SEM. Asterisk between bars indicates a significant decrease in perceived reachability in the post- vs. post-Illusion (* $p < 0.05$) in the Other Hand Reach condition. Plotted with R.

regression fits. The JND was calculated as the distance between the PSE (i.e., 0.5 probability of a "reachable" response), and 0.75 probability of a "reachable" response. However, no significant differences in the JND were observed when comparing pre- and post-Illusion JNDs in any of the conditions of the first and control experiments, suggesting that although the reachability increased for both conditions in the first experiment, the sensitivity to detect the distances of objects remained unaltered (see Supplemental Analyses in **Supplementary Material** for additional analyses).

3.2 Real Arm Drift

We found that during the stimulation phase, when the nose and arm grew, participants showed a drift i.e., they moved their real hand as their virtual hand was more distant due to an elongated virtual arm (**Figure 6**). This automatic behavioral response is in accordance with the type of responses triggered by the self-avatar follower effect (Gonzalez-Franco et al., 2020). Notably, when asked at the end of each condition, none of the participants noticed the hand drift (despite the fact that many participants rated the intention to move rather highly in a post-experiment questionnaire—see details below). This was true in both the Bimanual and in the Unimanual condition (**Figure 6**). Wilcoxon Signed Rank Paired Test (pre-post z-position) Bimanual [V = 171, $p < 0.001$, CI 95% (0.06, 0.15)]; Unimanual [V = 171, $p < 0.001$, CI 95% (0.08, 0.24)]. Although arm drift is significant in both conditions, we find that the actual hand drift is more pronounced in the Unimanual

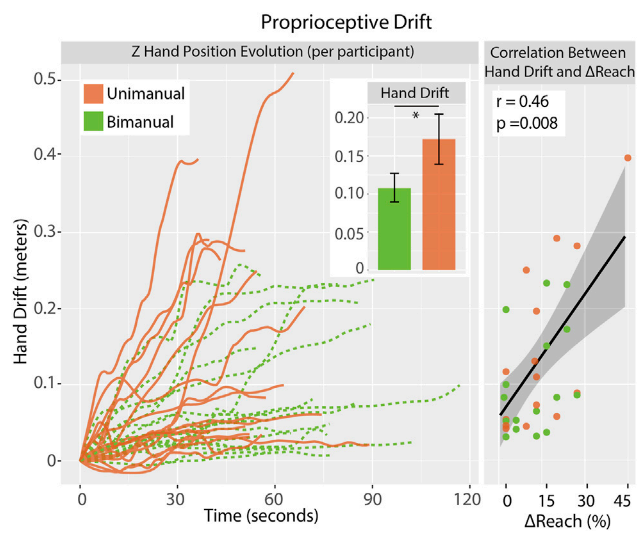

FIGURE 6 | Arm Drift in Unimanual and Bimanual Conditions. The graph shows the Z hand position evolution over the stimulation time (left panel). An overall drift was found for both the Bimanual and the Unimanual conditions. Pearson correlation (and 95% confidence bands) between the proprioceptive drift and incremented reach (right panel). The more the participants' hand drifted during the stimulation the greater the incremented reach they underwent. Plotted with R.

condition (0.17 ± 0.14 m) than in the Bimanual (0.11 ± 0.08 m) [V = 143, p = 0.01, CI 95% (0.01, 0.11)]. No order effects were found after the question on hand drift noticeability, so we believe that the question in itself wasn't a sufficient priming for participants. All conditions were counterbalanced.

Further data analysis shows that the drift significantly correlates with the arm reach increment over both conditions (Spearman r = 0.46, S = 2636.8, p = 0.0078). Outliers were removed from the correlation analysis, this included 1 sample whose hand drift was greater than 2*SD, and 4 samples that did not increment their reach (which correspond to the two participants who were removed before because they responded all objects to be reachable).

In our questioning at the end of the experiment we found that only two participants had noticed the arm elongating. Whereas for the rest that alteration went unnoticed. All the participants had noticed the nose elongating.

3.3 Questionnaire Results

To examine whether participants differed on their experience of embodiment in the virtual avatar during the experiments, we asked participants to complete an embodiment questionnaire at the conclusion of the experiment (**Figure 7**). This questionnaire was comprised of 3 questions, each probing a different aspect of embodiment of the virtual avatar (e.g., ownership, agency, or self-location), and four control questions (31, 32). We calculated an embodiment score for each condition by reverse scoring the control questions (i.e., questions 2, 5, 6, and 7) then calculating the mean response of all 7 questions. This is the standard procedure to account for these questions into an embodiment score (Gonzalez-Franco and Peck, 2018; Peck and Gonzalez-Franco, 2020).

A Wilcoxon signed rank test showed there was no significant difference between the sense of embodiment in the virtual avatar between the unimanual (Mdn = 0.93, IQR = 0.96) and bimanual (Mdn = 0.71, IQR = 0.89) conditions (V = 70.5, p = 0.09). Additional analyses revealed that there were significant differences between participants' responses to the embodiment and the non-transformed control questions in both the unimanual (V = 171, p < 0.001) and bimanual (V = 170, p < 0.001) conditions (see **Figure 7A**), suggesting that all participants experienced a genuine embodiment in the virtual avatar during the experiment, and that the affirmative responses on the questionnaire are not merely due to suggestibility. Together, these results suggest that participants felt genuinely embodied in the virtual avatar during both unimanual and bimanual conditions and did not significantly differ in their experience of the illusion.

Additionally, we also included one question on the questionnaire (Q8) probing the participants' urge to move the hand tapping the controller during the experiment. A Wilcoxon signed rank test between unimanual and bimanual conditions revealed there was a significant difference between unimanual (Mdn = 1, IQR = 3.75), and bimanual conditions (Mdn = 1, IQR = 3.5) (V = 33.5, p = 0.033). Note, this difference is rather small, as the medians for these conditions were the same, and an omnibus Kruskal-Wallace rank sum test failed to detect differences in the responses of participants on this question when examining all conditions from both the first and control experiments (see details below).

We also calculated an embodiment score for participants in the control study to examine whether there were significant differences in the embodiment between the Incongruent (Mdn = 1, IQR = 0.71), Other Hand Touch (Mdn = 0.86, IQR = 1.07), or Other Hand Reach (Mdn = 0.71, IQR = 0.79) conditions using a Kruskal-Wallace test. No significant differences were observed ($\chi 2$ = 0.25, p = 0.885). Comparisons between the embodiment and control questions using Wilcoxon signed rank tests revealed that the participants' responses were significantly higher for the embodiment questions compared to the non-transformed control questions in the Incongruent (V = 143, p < 0.001), Other Hand Touch (V = 170, p = 0.003), and Other Hand Reach (V = 170, p < 0.001) conditions (see **Figure 7B**).

Additionally, an omnibus Kruskal-Wallace rank sum test was conducted to determine whether there were significant differences between the embodiment scores from all conditions in both experiments (i.e., Unimanual, Bimanual, Incongruent, Other Hand Reach, and Other Hand Touch conditions) and revealed that there was no significant difference between conditions ($\chi 2$ = 1.71, p = 0.789). Similarly, an omnibus Kruskal-Wallis rank sum test showed that there were no significant differences in the urge to move one's hand (i.e., Q8) between all conditions in both experiments ($\chi 2$ = 3.81, p = 0.433). Overall, all participants experienced high embodiment over their avatar in all conditions of both experiments.

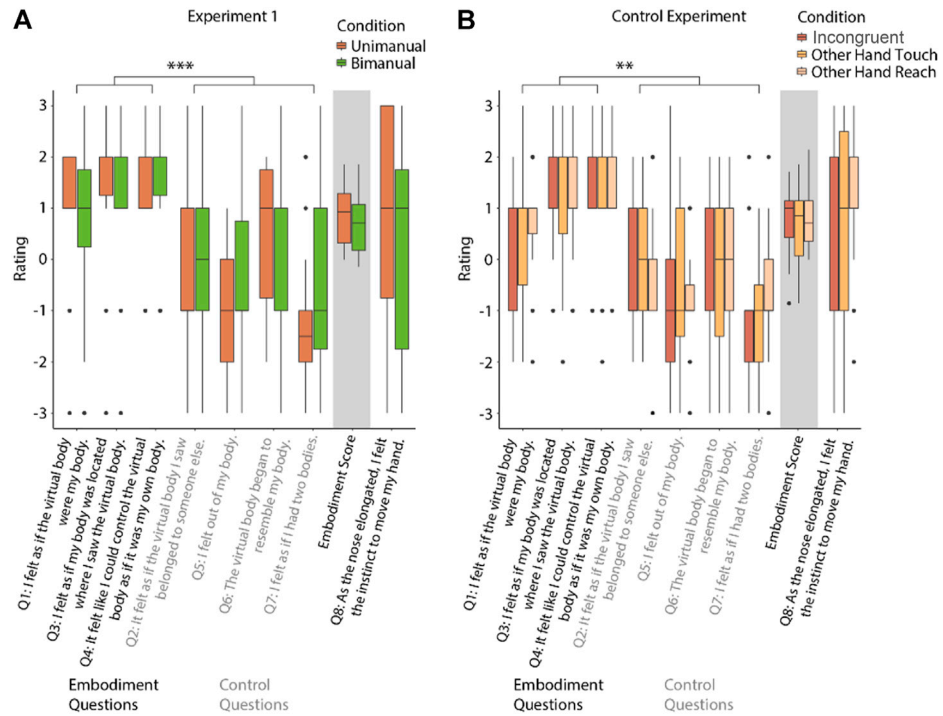

FIGURE 7 | Questionnaire Results. Box and whisker plots of the questionnaire results for Experiment one **(A)** and the Control Experiment **(B)** showing the median responses (horizontal bars within colored boxes), interquartile ranges (upper and lower bounds of the boxes) and ± 1.5 times the upper and lower quartiles (upper and lower whiskers), with outliers beyond this shown as single points. Stars between groups of bars indicate significant differences between average responses on embodiment vs. control questions (***ps < 0.001, **ps < 0.01). The embodiment score was calculated by taking the average of embodiment and reverse scored control questions. No significant differences were found for embodiment between conditions in either experiment. Responses to Q8 regarding participants' urge to move their hand are also displayed.

4 DISCUSSION

The results from this study showcase an extension of the perceived reachability of our limbs in an eyes-open touché-touchant variant of the Pinocchio Illusion. We demonstrate that participants in an immersive VR environment experiencing a novel variant of the Pinocchio Illusion experienced an extension of perceived reachability for the touchant hand, both when they received self-administered tactile stimulation on their nose together with visuomotor synchrony of their other real and virtual arm performing a tapping action on their nose in the Bimanual Condition, and when the self-administered tactile stimulation was not delivered to the nose in the Unimanual Condition. This extension of perceived reach did not occur for control conditions in which the body schema was violated by having the opposite virtual hand perform the tapping action in the Other Hand Touch control condition, or when the temporal relationship between the real and seen motor actions were violated in the Visuomotor Incongruent condition.

Both the bimanual and unimanual conditions provide the effect of Pinocchio illusion, as measured by the increased reachability and drift during the experience. This suggests that under embodiment, the visual feedback of the virtual avatar combined with motor feedback of one's touching is sufficient to elicit the illusion, which is expected under our hypothesis.

Moreover, the results show that there was a significant reduction in the perceived reachability of the opposite hand following unimanual stimulation. This reduction in reachability could be an example of the body-based scaling hypothesis (Proffitt and Linkenauger, 2013; Linkenauger et al., 2015), that the action relevant aspect of the body is used as a perceptual ruler to measure and scale the surrounding environment. As a result of this scaling, the perceived spatial layout of the world is seen as a function of the perceiver's ability to interact within it. Reversely, the perceiver's ability to interact within it can also be seen as a function of the perceived spatial layout of the world—as in our case, the object is innately perceived farther away, but the body schema for the Other Hand Reach arm doesn't adapt to elongate with its mirroring counterpart, thus yielding a relative effect of the arm perceived as shorter.

In this study, we also show that the extension of perceived reach depends on the participants undergoing the self-avatar follower effect on their arms. We measured an unintentional hand drift during the stimulation in the Unimanual and Bimanual conditions in addition to the post-Illusion increase in perceived reach these conditions. In agreement with the follower effect, the perceived increase in reach and the drift in participants' hand were found to be significantly positively correlated suggesting a strong relationship between the extent to which the participants moved their arm outward and the perceived reachability of out of reach objects. Which we argue could be a good proxy for the strength of the Pinocchio illusion. It is a seeming paradox that the participants who extended their arm out further, and were therefore more familiar with their reachable space, nevertheless overestimated their reachable space.

Importantly, however, although the participants mean rating on the questionnaire (question 8) indicated that the participants overall experienced a strong urge to move their arm during the experiment, none of the participants reported awareness of their actual arm movement when questioned about it at the conclusion of the experiment. We therefore speculate that the unintentional nature of this drift, and the lack of conscious awareness of having moved their arm, is the driver of this effect. This interpretation of this finding is also supported by research which has found that participants are more accurate at locating their surreptitiously displaced hand when it was displaced by passive compared to active movements, suggesting different central processes for integrating active and passive movements with other sensory stimuli (Abdulkarim and Ehrsson, 2018).

One caveat to our interpretation is that we do not directly measure the Pinocchio illusion, as we only assess it by the involuntary hand drift. While this might be a good proxy during the bimanual stimulation, the same might not be true for the other conditions. We believe that precisely the two participants who did not have any drift, where probably also not experiencing the illusion. Nevertheless, we believe that the proprioceptive drift is induced because of the nose elongation illusion during the active stimulation. While the use of active interactions has previously been found to widen the integration window for multisensory stimuli (Maselli et al., 2016), and can even reduce the experience of the "uncanny valley of haptics" in VR (Berger et al., 2018), our results show an enlargement in the perceived reachable space in both unimanual and bimanual variants of this illusion. This similarity of the results between unimanual and bimanual conditions, demonstrates that the perceived tactile feedback in the nose (touché) is unnecessary for the experience of the illusion in the presence of visual stimuli and active touch. Notably, however, this was only true if the hand delivering the active visuomotor stimuli is visually and temporally aligned with the participant's movements.

5 CONCLUSION

Here, we have demonstrated that the perception of reach can be extended in participants without the explicit knowledge of a change in the appearance or size of that limb. This finding is important for our understanding of the relationship between what the brain considers proximal vs. distal space and its relationship to the body schema.

Our findings shed new light on both the experience of the Pinocchio Illusion and the experience of the body schema with respect to the stimulating and stimulated body part within a touché-touchant framework. Despite the limited sample size, we hope that this work also paves the way for possible new touche-touchant interfaces that extend previous studies in exploring complex body-object interactions (Schütz-Bosbach et al., 2009), real-world visual inputs (Lin, 2020), and modular representations of different body parts (Farnè et al., 2005b), to eventually manipulate peri-personal or reachable space.

Together, our findings have important implications for our understanding of the body schema, body ownership, and how we perceive the space around us.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Microsoft Research IRB. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CB, MG-F, BaL, BiL, and JL conceived of and designed the experiment. MG-F and BaL wrote the scripts and implemented the virtual reality set-up, and conducted the experiments. CB and MG-F conducted the data analysis, made the figures, and wrote the paper. BaL, BiL, and JL provided critical revisions.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2022.712375/full#supplementary-material

REFERENCES

Abdulkarim, Z., and Ehrsson, H. H. (2018). Recalibration of Hand Position Sense during Unconscious Active and Passive Movement. *Exp. Brain Res.* 236, 551–561. doi:10.1007/s00221-017-5137-7

Abtahi, P., Franco, M. G., Ofek, E., and Steed, A. (2019). I'm a Giant: Walking in Large Virtual Environments at High Speed Gains, in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19). Association for Computing Machinery, New York, NY, USA, Paper 522, 1'13*. doi:10.1145/3290605.3300752

Banakou, D., Groten, R., and Slater, M. (2013). Illusory Ownership of a Virtual Child Body Causes Overestimation of Object Sizes and Implicit Attitude Changes. *Proc. Natl. Acad. Sci.* 110, 12846–12851. doi:10.1073/pnas.1306779110

Berger, C. C., Gonzalez-Franco, M., Ofek, E., and Hinckley, K. (2018). The Uncanny Valley of Haptics. *Sci. Robot.* 3, 7010. doi:10.1126/scirobotics.aar7010

Berti, A., and Frassinetti, F. (2000). When Far Becomes Near: Remapping of Space by Tool Use. *J. Cogn. Neurosci.* 12, 415–420. doi:10.1162/089892900562237

Bonifazi, S., Farnè, A., Rinaldesi, L., and Làdavas, E. (2007). Dynamic Size-Change of Peri-Hand Space through Tool-Use: Spatial Extension or Shift of the Multi-Sensory Area. *J. Neuropsychol.* 1, 101–114. doi:10.1348/174866407x180846

Botvinick, M., and Cohen, J. (1998). Rubber Hands "Feel" Touch that Eyes See. *Nature* 391, 756. doi:10.1038/35784

Burrack, A., and Brugger, P. (2005). Individual Differences in Susceptibility to Experimentally Induced Phantom Sensations. *Body Image* 2, 307–313. doi:10.1016/j.bodyim.2005.04.002

Calzolari, E., Azañón, E., Danvers, M., Vallar, G., and Longo, M. R. (2017). Adaptation Aftereffects Reveal that Tactile Distance Is a Basic Somatosensory Feature. *Proc. Natl. Acad. Sci.* 114, 4555–4560. doi:10.1073/pnas.1614979114

Coello, Y., Bourgeois, J., and Iachini, T. (2012). Embodied Perception of Reachable Space: How Do We Manage Threatening Objects? *Cogn. Process.* 13, 131–135. doi:10.1007/s10339-012-0470-z

Cohn, B. A., Maselli, A., Ofek, E., and Gonzalez-Franco, M. (2020). Snapmove: Movement projection mapping in virtual reality, in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR), pp. 74-81. IEEE, 2020*. Utrecht, Netherlands: AIVR, 74–81. doi:10.1109/AIVR50618.2020.00024

Conson, M., Mazzarella, E., and Trojano, L. (2011). Self-touch Affects Motor Imagery: a Study on Posture Interference Effect. *Exp. Brain Res.* 215, 115. doi:10.1007/s00221-011-2877-7

di Pellegrino, G., Làdavas, E., and Farné, A. (1997). Seeing where Your Hands Are. *Nature* 388, 730. doi:10.1038/41921

Ehrsson, H. H., Spence, C., and Passingham, R. E. (2004). That's My Hand! Activity in Premotor Cortex Reflects Feeling of Ownership of a Limb. *Science* 305, 875–877. doi:10.1126/science.1097011

Farnè, A., Bonifazi, S., and Làdavas, E. (2005). The Role Played by Tool-Use and Tool-Length on the Plastic Elongation of Peri-Hand Space: a Single Case Study. *Cogn. Neuropsychol.* 22, 408–418. doi:10.1080/02643290442000112

Farnè, A., Demattè, M. L., and Làdavas, E. (2005). Neuropsychological Evidence of Modular Organization of the Near Peripersonal Space. *Neurology* 65, 1754–1758. doi:10.1212/01.wnl.0000187121.30480.09

Folegatti, A., de Vignemont, F., Pavani, F., Rossetti, Y., and Farnè, A. (2009). Losing One's Hand: Visual-Proprioceptive Conflict Affects Touch Perception. *PLoS One* 4, e6920. doi:10.1371/journal.pone.0006920

Gentile, G., Guterstam, A., Brozzoli, C., and Ehrsson, H. H. (2013). Disintegration of Multisensory Signals from the Real Hand Reduces Default Limb Self-Attribution: an FMRI Study. *J. Neurosci.* 33, 13350–13366. doi:10.1523/jneurosci.1363-13.2013

Gonzalez-Franco, M., Perez-Marcos, D., Spanlang, B., and Slater, M. (2010). The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. *IEEE Virtual Reality Conference (VR)*. IEEE, 111–114. doi:10.1109/VR.2010.5444805

Gonzalez-Franco, M., Cohn, B., Ofek, E., Burin, D., and Maselli, A. (2020). The Self-Avatar Follower Effect in Virtual Reality. *Proc. 2020 IEEE Conf. Virtual Real. 3D User Interfaces VR* 2020, 18–25. doi:10.1109/vr46266.2020.00019

Gonzalez-Franco, M., and Peck, T. C. (2018). Avatar Embodiment. Towards a Standardized Questionnaire. *Front. Robot. Ai.* 5, 74. doi:10.3389/frobt.2018.00074

Guterstam, A., Szczotka, J., Zeberg, H., and Ehrsson, H. H. (2018). Tool Use Changes the Spatial Extension of the Magnetic Touch Illusion. *J. Exp. Psychol. Gen.* 147, 298. doi:10.1037/xge0000390

Kalckert, A., and Ehrsson, H. H. (2012). Moving a Rubber Hand that Feels like Your Own: A Dissociation of Ownership and Agency. *Front. Hum. Neurosci.* 6, 40. doi:10.3389/fnhum.2012.00040

Kalckert, A., and Ehrsson, H. H. (2014). The Moving Rubber Hand Illusion Revisited: Comparing Movements and Visuotactile Stimulation to Induce Illusory Ownership. *Conscious. Cogn.* 26, 117–132. doi:10.1016/j.concog.2014.02.003

Kilteni, K., Maselli, A., Kording, K. P., and Slater, M. (2015). Over My Fake Body: Body Ownership Illusions for Studying the Multisensory Basis of Own-Body Perception. *Front. Hum. Neurosci.* 9, 141. doi:10.3389/fnhum.2015.00141

Kilteni, K., Normand, J. M., V Sanchez-Vives, M., and Slater, M. (2012). Extending Body Space in Immersive Virtual Reality: a Very Long Arm Illusion. *PLoS One* 7, e40867. doi:10.1371/journal.pone.0040867

Kokkinara, E., and Slater, M. (2014). Measuring the Effects through Time of the Influence of Visuomotor and Visuotactile Synchronous Stimulation on a Virtual Body Ownership Illusion. *Perception* 43, 43–58. doi:10.1068/p7545

Lackner, J. R. (1988). Some Proprioceptive Influences on the Perceptual Representation of Body Shape and Orientation. *Brain* 111, 281–297. doi:10.1093/brain/111.2.281

Lenggenhager, B., Tadi, T., Metzinger, T., and Blanke, O. (2007). Video Ergo Sum: Manipulating Bodily Self-Consciousness. *Science* 317, 1096–1099. doi:10.1126/science.1143439

Lin, B. (2020). "Keep it Real: a Window to Real Reality in Virtual Reality," in Proceedings of the Twenty-Ninth International Joint Conference on Artificial Intelligence, 10313. *arXiv Prepr. arXiv2004*. doi:10.24963/ijcai.2020/766

Linkenauger, S. A., Bülthoff, H. H., and Mohler, B. J. (2015). Virtual Arm′ S Reach Influences Perceived Distances but Only after Experience Reaching. *Neuropsychologia* 70, 393–401. doi:10.1016/j.neuropsychologia.2014.10.034

Maravita, A., and Iriki, A. (2004). Tools for the Body (Schema). *Trends Cogn. Sci.* 8, 79–86. doi:10.1016/j.tics.2003.12.008

Maravita, A., Spence, C., and Driver, J. (2003). Multisensory Integration and the Body Schema: Close to Hand and within Reach. *Curr. Biol.* 13, R531–R539. doi:10.1016/s0960-9822(03)00449-4

Maselli, A., Kilteni, K., López-Moliner, J., and Slater, M. (2016). The Sense of Body Ownership Relaxes Temporal Constraints for Multisensory Integration. *Sci. Rep.* 6, 30628. doi:10.1038/srep30628

Maselli, A., and Slater, M. (2013). The Building Blocks of the Full Body Ownership Illusion. *Front. Hum. Neurosci.* 7, 83. doi:10.3389/fnhum.2013.00083

Medina, J., and Coslett, H. B. (2010). From Maps to Form to Space: Touch and the Body Schema. *Neuropsychologia* 48, 645–654. doi:10.1016/j.neuropsychologia.2009.08.017

Miller, L. E. (2018). Sensing with Tools Extends Somatosensory Processing beyond the Body. *Nature* 561, 239–242. doi:10.1038/s41586-018-0460-0

Normand, J.-M., Giannopoulos, E., Spanlang, B., and Slater, M. (2011). Multisensory Stimulation Can Induce an Illusion of Larger Belly Size in Immersive Virtual Reality. *PLoS One* 6, e16128. doi:10.1371/journal.pone.0016128

Peck, T. C., and Gonzalez-Franco, M. (2020). Avatar Embodiment. A Standardized Questionnaire. *Front. Virtual Real.* 1, 44. doi:10.3389/frvir.2020.575943

Peck, T. C., Seinfeld, S., Aglioti, S. M., and Slater, M. (2013). Putting Yourself in the Skin of a Black Avatar Reduces Implicit Racial Bias. *Conscious. Cogn.* 22, 779–787. doi:10.1016/j.concog.2013.04.016

Petkova, V. I. (2011). From Part- to Whole-Body Ownership in the Multisensory Brain. *Curr. Biol.* 21, 1118–1122. doi:10.1016/j.cub.2011.05.022

Proffitt, D. R., and Linkenauger, S. A. (2013). Perception Viewed as a Phenotypic Expression. *Action Sci. Found. Emerg. Discip.* 171. doi:10.7551/mitpress/9780262018555.003.0007

R Core Team (2017). *A Language and Environment for Statistical Computing. R Found. Stat. Comput*. ViennaAustria. {ISBN}3-900051-07-0. Available at: http://www.R-project.org/.

Ramachandran, V. S., and Hirstein, W. (1998). The Perception of Phantom Limbs. *D. O. Hebb Lect. Brain.* 121, 1603–1630. doi:10.1093/brain/121.9.1603

Schütz-Bosbach, S., Musil, J. J., and Haggard, P. (2009). Touchant-touché: The Role of Self-Touch in the Representation of Body Structure. *Conscious. Cogn.* 1818, 22–1111. doi:10.1016/j.concog.2008.08.003

Serino, A., Canzoneri, E., Marzolla, M., Di Pellegrino, G., and Magosso, E. (2015). Extending Peripersonal Space Representation without Tool-Use: Evidence from a Combined Behavioral-Computational Approach. *Front. Behav. Neurosci.* 9, 4. doi:10.3389/fnbeh.2015.00004

Slater, M., Perez-Marcos, D., Ehrsson, H. H., and V Sanchez-Vives, M. (2009). Inducing Illusory Ownership of a Virtual Body. *Front. Neurosci.* 3, 214–220. doi:10.3389/neuro.01.029.2009

Spanlang, B. (2014). How to Build an Embodiment Lab: Achieving Body Representation Illusions in Virtual Reality. *Front. Robot. Ai.* 1, 1–22. doi:10.3389/frobt.2014.00009

Tajadura-Jiménez, A., Tsakiris, M., Marquardt, T., and Bianchi-Berthouze, N. (2015). Action Sounds Update the Mental Representation of Arm Dimension: Contributions of Kinaesthesia and Agency. *Front. Psychol.* 6, 689. doi:10.3389/fpsyg.2015.00689

Vaesen, K. (2012). The Cognitive Bases of Human Tool Use. *Behav. Brain Sci.* 35, 203–218. doi:10.1017/s0140525x11001452

van der Hoort, B., Guterstam, A., and Ehrsson, H. H. (2011). Being Barbie: the Size of One's Own Body Determines the Perceived Size of the World. *PLoS One* 6, e20195. doi:10.1371/journal.pone.0020195

Conflict of Interest: BaL and BiL authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. MG-F, CB and JL were with Microsoft Research at the time of the study. Microsoft, is an entity with a financial interest in the subject matter or materials discussed in this manuscript. Nonetheless, the authors declare that the current manuscript presents balanced and unbiased results, the studies were conducted following scientific research standards. Approved by the Microsoft Research review board and collected with the approval and written consent of each participant in accordance with the Declaration of Helsinki.