Modulating the fidelity and spatial extent of electrotactile stimulation to elicit the embodiment of a virtual hand

Martin A. Garenfeld, Alba Jiménez-Díaz, Victor Navarro-Moreno, Mario Tormo, Matija Štrbac, Erik Hernández, Rosa M. Baños, Rocío Herrero, Strahinja Došen

***Abstract*— Restoring tactile feedback in virtual reality can improve user experience and facilitate the feeling of embodiment. Electrotactile stimulation can be an attractive technology in this context as it is compact and allows for high-resolution spatially distributed stimulation. In the present study, a 32-channel tactile glove worn on the fingertips was used to provide tactile sensations during a virtual version of a rubber hand illusion experiment. To assess the benefits of multichannel stimulation, we modulated the spatial extent of feedback and its fidelity. Thirty-six participants performed the experiment in two conditions, in which stimulation was delivered to a single finger or all fingers, and three tactile stimulation types within each condition: no tactile feedback, simple single-point stimulation, and complex sliding stimulation mimicking the movements of the brush. Following each trial, the participants answered a multi-item embodiment questionnaire and reported the proprioceptive drift. The results confirmed that modulating the spatial extent of stimulation, from a single finger to all fingers, was indeed a successful strategy. When stimulating all fingers, tactile stimulation significantly improved all subjective measures compared to receiving no tactile stimulation. However, unexpectedly, the second strategy, that of modulating the fidelity of feedback, was not successful in promoting a difference between the simple and complex tactile feedback in any of the measures. The results, therefore, imply that the effects of tactile feedback are better expressed in a more dynamic scenario (i.e., making/breaking contact and delivering stimulation to different body locations), while it still needs to be investigated if further improvements of the complex feedback can make it more effective compared to the simple approach.**

***Index Terms*— Electrotactile stimulation, embodiment, immersion, matrix electrodes, presence, rubber hand illusion, virtual reality.**

I. INTRODUCTION

VIRTUAL Reality (VR) is a technology that visually simulates a three-dimensional environment and places the user in a first-person perspective. If designed carefully, the virtual environment mimics the natural equivalent so convincingly that it can create an illusion of being physically present in the artificial setting. The users not only see a virtual body in place of their own, but they can also experience the virtual body parts as being connected to their own body. Such experience of embodiment has been described as the sense through which an individual locates themselves within the physical boundaries of their own body [1]. The sense of body location is complemented by self-awareness and body ownership. They are formed through the integration of several bodily sensory signals (sight, touch, proprioception, etc.), along with the sense of body agency, which is the subjective awareness that we perform and control our body actions [2]. The corporeal experience involves a complex integration of bottom-up processes with higher-order top-down processes related to the establishment of the body schema and the perceptual representations of the body image, respectively [3], [4], [5]. De Vignemont [6] provides a digestible definition of this multi-faceted construct, where something is embodied only if some of its properties are processed in the same way as the properties of one's body [6].

Botvinick and Cohen [7] first reported the induction of the illusion in which an inanimate object can be felt as part of a subject's own body through multisensory correlations induced, for instance, by simultaneous visuo-tactile stimulation. In the original experiment, participants were placed in front of a rubber hand aligned with their physical hand which was hidden from view. The experimenters then applied synchronous tactile stimulation with two paintbrushes to both hands. The multisensory stimulation provided by the rubber hand illusion (RHI) experiment generated biases in the perception of body ownership. Through this bias, participants experienced the illusion that the rubber hand was to some degree their natural hand, thereby demonstrating that one can deceive or blur the perceptual boundaries between self and others. During the experiment, the brain makes the "mistake" of taking ownership

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of a rubber hand that does not belong to it. However, this illusion is disrupted if the strokes toward the hands (physical and rubber) are performed with a time delay, a condition called asynchronous stimulation [8].

It has been shown that such an illusion can be induced also in VR by following a similar protocol based on synchronous visuotactile stimulation [9], [10]. In these cases, the subject received modality-matched somatosensory feedback in the virtual scene and in reality, e.g., a ball press [9] and brush stroke [10], simulated visually in VR using a virtual hand and delivered manually by the experimenter to the subject's real hand. Eliciting the illusion of ownership in VR could be an important instrument to increase the feeling of immersion. However, delivering modality-matched stimulation usually requires a complex and bulky mechanical system [11], [12].

Therefore, other approaches to deliver tactile sensations using compact but not necessarily modality-matched interfaces were tested with promising results. Simple tactile sensation elicited using a single vibrotactor has been shown to evoke the RHI if the visuotactile stimulation is synchronized [13] and, more generally, to also increase the feeling of presence in VR [14], [15]. However, to better replicate the fidelity of natural tactile feedback, which includes moving and spatially distributed sensations, a multichannel interface that can deliver stimulation through many points is required. Electrotactile stimulation is a particularly attractive technology for this application as a network of stimulation pads can be printed on a thin film creating a high-resolution, compact, and wearable solution. Indeed, multichannel electrotactile stimulation delivered to the hand was tested in VR to create different tactile effects [16]. However, only two studies have been conducted with immersive VR using electrotactile stimulation to investigate task performance [17], [18] and embodiment [19], [20], respectively. The embodiment study included only a few participants while the stimulation was delivered using a single channel (hence, without exploiting the real advantage of the technology). Therefore, no systematic investigation has yet been performed regarding the use of multichannel electrotactile stimulation to elicit the feeling of embodiment in immersive VR.

In the present study, therefore, we assessed the embodiment of a virtual hand when providing tactile stimulation through a matrix electrode to imitate the sensation of a virtual brush stroke applied to the volar side of the finger(s). The stimulation was delivered using a specially designed glove that integrated a matrix of stimulation pads. We also modulated the extent of delivered feedback by stimulating single or multiple fingers and changed the fidelity of feedback by activating the pads all at once (simple feedback) or sequentially (complex feedback). The sequential stimulation was designed to create feedback that better mimics the brush movements. The main hypothesis was that the complex (sequential) feedback would elicit a stronger feeling of embodiment compared to the single-point stimulation because sequential feedback presumably better approximates the dynamic tactile stimulation of a real brush stroke. Secondarily, we hypothesized that stimulating multiple fingers would increase embodiment compared to stimulating a single finger as the former is a more engaging scenario that activates a larger area of the body (hand).

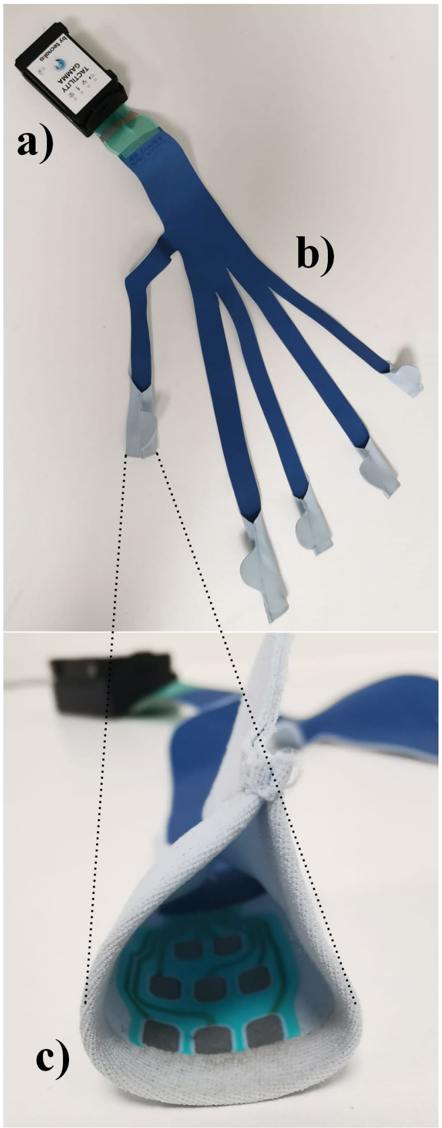

Fig. 1. The stimulation interface comprising (a) compact stimulator, (b) textile glove, and (c) embedded electrodes (zoom-in on thumb electrode pads for representative example). The arrangement of pads for other fingers is shown in Fig. 3a.

II. METHODS

A. Equipment

The HTC Vive Pro Eye (Vive, Taoyuan City, Taiwan) was used to show the virtual scene to the participant. A head-mounted display tracked the participant's point of view and two base stations mapped the room with infrared light. The experiment did not involve motor tasks and hence hand tracker was not used. The electrotactile stimulation was delivered by a compact 6.5×4.5×3.5 cm 32-channel stimulator developed by Tecnalia Research and Innovation, San Sebastián, Spain, see *Fig. 1a*. The stimulator generated symmetric bi-phasic rectangular pulses asynchronously separated by a fixed 500 µs inter-pulse interval. Cathodic-first stimulation waveforms are generated as they induce a more selective sensation in the active electrode [21]. Pulse frequency was a global parameter common to all pads while pulse amplitude and width could be

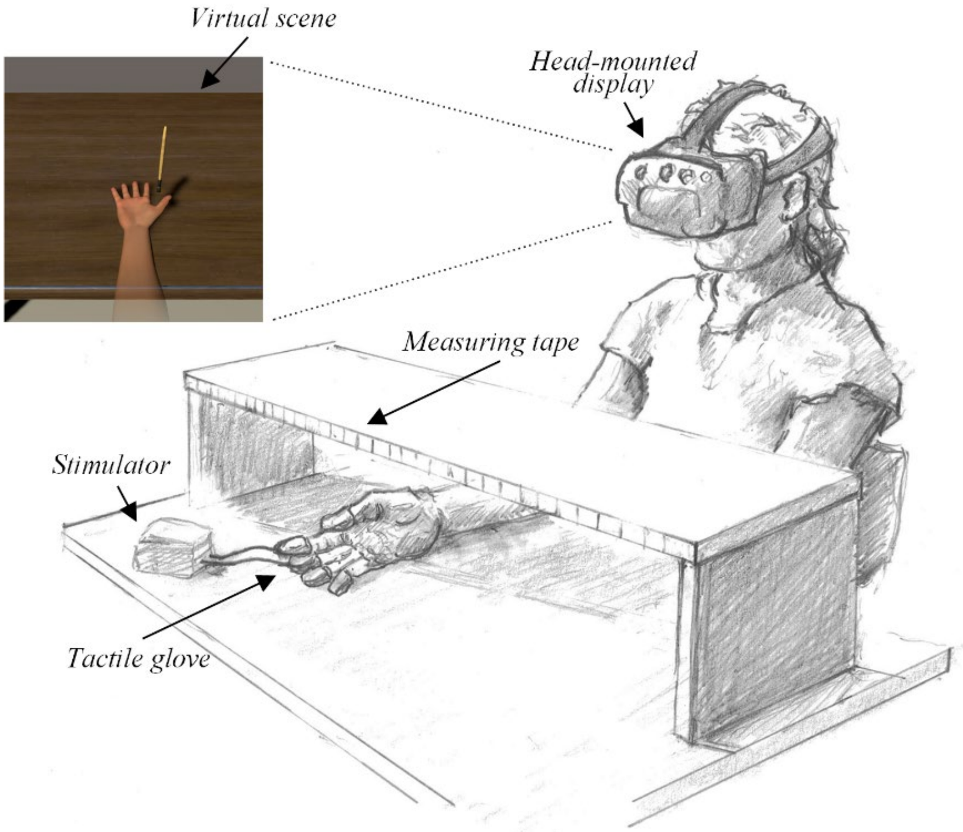

Fig. 2. The illustration of the experimental setup (head-mounted display, measuring tape to indicate proprioceptive drift, stimulator and tactile glove), and visual feedback in VR scene. The participants looked at the virtual hand while a brush was sliding across a single finger or all fingers, depending on the condition. While the brush contacted the fingers, the participants also received electrotactile stimulation according to the type of stimulation provided.

modulated individually for each pad in the range of 1-200 Hz, 0.1-9 mA, and 50-500 µs with 1 Hz, 0.1 mA, and 10 µs increments, respectively. When delivering stimulation, some pads are activated to generate sensation while at least one pad needs to act as a reference to close the electrical circuit. To avoid producing sensation below the reference pad, the total area of the reference pad(s) should be larger than the active pad to lower the current density and thus avoid the depolarization of afferent nerves. A finger cap electrode (tactile glove) was used to deliver the stimulation in the present study, see *Fig. 1b*. The tactile glove (see *Fig. 1c*) was manufactured by integrating printed electrodes on a flexible and soft PET film laminate, produced by Policrom Screens S.p.A, Carvico, Italy (developed by Tecnalia Serbia Ltd., Belgrade, Serbia) with a of 250 gr/sqm glove made of GGT5 fabric (developed by Smartex S. R. L., Prato, Italy) making it slightly flexible and comfortable to wear. It contained 32 stimulation pads distributed over all fingertips and the middle phalange of the index finger. The pads were of equal size (4×3 mm) and could be configured to act as either active or reference pads. The firmware of the stimulator automatically configured all the pads that were not active to act as the reference to maximize the total area of the reference. This approach has been tested in pilot tests, demonstrating that localized sensations were generated only below the active pads.

B. Virtual scenario

An experiment was designed to induce the RHI of a virtual hand. The subjects wore the VR headset and the tactile glove, and they sat comfortably in a chair with the forearm relaxed on a table in front of them with the volar side facing upwards, see *Fig. 2*. The VR headset displayed a virtual scene showing a realistic avatar hand placed on a table slightly to the right of the subject's center of view, see screenshot to the left in *Fig. 2.* The brush moved in two different patterns to test the impact of the extent of feedback: it either stroked the fingertips of all fingers (see green arrow in *Fig. 3a*), or it moved over a segment of a single finger, namely, the index finger (see green arrow in *Fig. 3b*). When stimulating all fingers, the brush moved across the fingers in sequence, from thumb to little finger and back, stroking the fingertips of each finger. The movement lasted approximately 8 s and after a brief pause of 1s, the pattern was repeated. For the single-finger condition, the brush stroked the index finger from the fingertip across the middle phalange and back. The stroke lasted approximately 4 s and, similarly, as in the all-fingers condition, the movement was repeated after a brief pause of 1s. The movement velocity of the brush was equal in the two blocks. The distance covered by the brush when stimulating all fingers was longer compared to stimulating only a single finger. To make the brush velocity equal in these two cases, the overall stroke duration varied across conditions. Eight and fifteen brushstroke loops were performed per trial

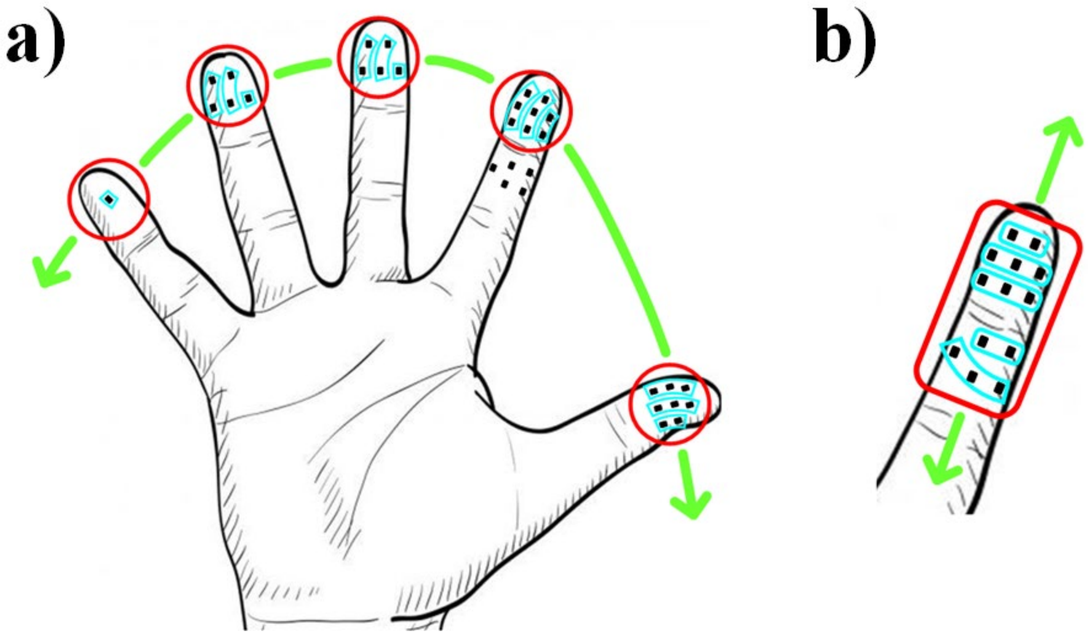

Fig. 3. Illustration of the visual and tactile feedback in (a) all-fingers, and (b) single finger condition. The green arrows show the trajectory of the brush movement (visual feedback), where the arrowheads are the end positions in each direction. The black markings are the individual electrode pads, and the red and blue lines show the tactile stimulation patterns in the simple (single point) and complex (sliding motion) stimulation. In the simple approach, all pads on a finger were activated at once when the brush touched that finger. In the complex scheme, the pads were organized in columns (all-fingers condition) and rows (single-finger condition), and the columns/rows were activated sequentially following the movement of the brush across the skin.

when stimulating all fingers and a single finger, respectively, so that the stimulation lasted ~60 s in total, to reliably induce the RHI [22]. The virtual scenario was implemented using Unity software (Unity Technologies, California, USA).

C. Stimulation types

Three stimulation types were designed to simulate the tactile sensation of a brush stroking the skin at various levels of realism (mimicking natural feedback): no tactile stimulation (baseline), and stimulation using simple (single point) and complex feedback patterns (sliding motion). *Fig. 3a* and *b* depict the tactile stimulation provided in each of the two conditions. The visual and tactile feedback were synchronized [23], and thus, visual, and tactile stroking were always congruent. The visual feedback was identical in all stimulation types, as explained in the previous section. When no tactile stimulation was provided, the electrotactile stimulation was off, and therefore only visual feedback (virtual hand and brush movement) was provided. For the simple tactile stimulation, when the brush touched the finger, all pads placed on that finger were activated simultaneously, creating thereby a non-specific distributed sensation spreading over the whole area (see the pads encapsulated by the red shapes in *Fig. 3*). This tactile stimulation type, therefore, represented low-resolution feedback that could be created by using a single or few tactors located on each finger, as demonstrated before [13], [24], [25], In the complex tactile stimulation, the electrode pads were activated sequentially thereby creating a sliding sensation that matched the movement of the brush stroking the skin (see the pads encapsulated by the blue shapes in *Fig. 3*). In the all-fingers condition, the pads on each finger were divided into three segments (the columns of pads) that were activated in sequence to follow the constant velocity of the brush. The only exception to this was the little finger as it contained only one pad. In the single-finger condition, the pads were divided into five segments (the rows of pads), which were activated sequentially to follow the brush movement along the finger.

D. Experimental procedure

A total of 36 participants (age (mean ± standard deviation): 24.7 ± 6.6; range: 18−53 years old; gender: 26 females, 10 males, handedness: all right-handed) were recruited and completed the experiment after reading the information leaflet and signing a consent form. The experimental protocol was approved by the ethics committee of the University of Valencia (approval number 1317893).

First, the subject was seated in front of the experimental setup, as explained in Methods, section *Virtual scenario*. The tactile glove was then placed on the right hand. The electrode was "dry", so no skin preparation was applied before fitting the tactile glove. However, the subject was inspected for potential skin damage at expected pad positions, to prevent painful sensations [26]. It was important to ensure stable and tight contact between the skin and the electrode without occluding blood circulation because the latter could create the sensation of blood pulsing and/or lead to numbness after prolonged pressure. As mentioned before, the tactile glove was fabricated using a textile with limited stretchability. Therefore, we recruited participants with fingers that were not too large, while for those with smaller fingers, paper clips were used to tighten the fit.

The stimulation intensity was then calibrated for each pad to the localization threshold (the sensation that is clear and localizable) [27] using the ascending method of limits. The experimenter increased the pulse amplitude in steps of 0.1 mA every 1 s until the subjects reported that they felt a clear sensation localized below the activated pad. The pulse width and frequency were held constant and set at 100 µs and 50 Hz, respectively. To shorten the calibration duration, the central pads of each finger were calibrated first, starting from 0.5 mA and the obtained value was then used as an initial amplitude for the remaining pads on the same finger [28]. After each pad was calibrated, all 32 pads were activated sequentially, and the stimulation intensity was individually finetuned to elicit clear and localized sensations that were similar across pads. Such sequential adjustment was repeated twice to ensure a good quality of the tactile feedback. Additionally, the subjects were instructed to report if the perceived sensation changed (for any reason) during experimental trials, and in this case, the stimulation was re-calibrated to ensure haptic effects that were as consistent as possible. Considering the large number of pads, the calibration would last excessively long if more reliable methods, e.g., staircase procedure, were used. In addition, the simple but quick approach employed in this and other studies [29], [30], [31] is convenient for the future practical applications of the electrotactile glove (where complex and long calibration would not be tolerated by the user).

In the simple tactile stimulation, many pads were simultaneously activated, which is known to increase the overall intensity of the elicited sensation. Therefore, to compensate for this effect and ensure that the intensity was similar to that in the complex stimulation (where only a single or a few pads were activated at once), the amplitudes of all active pads were decreased by multiplying the calibrated value by 0.8. The downscaling factor was determined in pilot tests in which we tested a set of values (0.95, 0.9, 0.85, 0.8, 0.75, and 0.7) and discovered that a factor of 0.8 leads to most similar intensity.

Afterward, the head-mounted display was placed on the participant's head and adjusted to ensure a comfortable fit. The display and base stations were pre-calibrated such that the participant's view was in the center of the virtual scene. The position of the physical hand was then calibrated so that the proprioceptive drift could be measured following each experimental trial [32]. The participants were asked to use their left hand to mark on the top board (see *Fig. 2*) where they thought the virtual index fingertip was located. The physical hand was moved 17.5 cm to the right from that position (using measuring tape as seen in *Fig. 2*) to comply with the distance between the physical and artificial hand used in [32]. The subject was then asked to close the eyes and mark on the top board the perceived position of the physical hand. This position was noted to account for the proprioception bias when calculating the proprioceptive drift. Throughout the experiment, the participants could only view the virtual hand through the head-mounted display, while the physical hand remained stationary and hidden from view.

The experiment consisted of six experimental trials (2 conditions × 3 stimulation types). All stimulation types within the first condition were finished before continuing with the second condition. After a condition was completed, the subject was asked to rank the stimulation types based on how realistic the experience was, and after each type of stimulation, the outcome measures were assessed, as explained in the next section. The stimulation types were ranked from 1-3, where 1 was the least realistic stimulation type. If the subject stated that they could not decide whether the simple or complex condition

Table 1. Embodiment questionnaire. Q1-Q10 and Q11-Q18 were adapted from [2] and formulated ad-hoc, respectively.

Ownership	
Q1	It seemed that I was looking directly at my own hand instead of a virtual one.
Q2	It seemed that the virtual hand was beginning to look like my real hand.
Q3	It seemed to me that the virtual hand belonged to me.
Q4	It seemed that the virtual hand was my hand.
Q5	It seemed that the virtual hand was part of my body.
Location	
Q6	It seemed that my hand was where the virtual hand was.
Q7	It seemed that the virtual hand was in the place where my hand was.
Q8	It seemed that the touch I felt was caused by the brush touching the virtual hand.
Agency	
Q9	It seemed to me that I could have moved the virtual hand if I had wanted to.
Q10	It seemed to me that I was in control of the virtual hand.
Tactile sensation	
Q11	I had a tactile sensation when the brush touched me
Q12	The tactile sensation felt realistic to me
Q13	I felt that the brush touched my fingers.
Q14	I felt physical resistance (e.g., hard or soft) when the brush touched me.
Q15	I felt some texture (e.g., rough or smooth) when the brush touched me.
Q16	I felt any thermal sensation (e.g., hot or cold) when the brush touched me.
Realism and presence	
Q17	Overall, the VR experience seemed close to a real experience.
Q18	I felt like I was physically inside the VR environment.

was more realistic, the no tactile stimulation type was ranked 1 and the tactile stimulation types were both ranked 2.5. This, however, happened in only one case. The order of the conditions (all-fingers and single-finger) and the stimulation types (no feedback, simple, and complex) within conditions were pseudorandomized, respectively, resulting in twelve unique trial sequences. A single trial was tested per stimulation type as this showed to be enough to produce an effect [33] while minimizing confounding factors such as boredom, discomfort, and distraction.

E. Outcome measures

The embodiment of the virtual hand was assessed by measuring proprioceptive drift (objective measure) and by asking the subjects to respond to questionnaires (subjective measure). The proprioceptive drift is a behavioral correlate of the feeling of ownership [32] and is implemented by measuring the change in the perceived sense of proprioception of the participant's physical hand before the experiment and after each intervention. As explained in the previous section, the participants' physical hand was moved away from the reported position of the virtual hand and following each experimental trial, the participant was asked to report the perceived position of the physical hand. Specifically, the participant used their left hand to point pointed on the top table (see *Fig. 2*) the perceived position of the physical right index fingertip (single-point position reference). The experimenter then measured the distance from the initially perceived position to the pointed position using a measuring tape shown in Fig. 2. If the perceived position of the physical hand drifted towards the virtual one, this indicated an increase in the feeling of ownership of the virtual hand. To quantify this effect, the initially perceived position of the physical hand was normalized with respect to the position of the virtual hand, so that the physical and virtual hand positions corresponded to 0 and 1, respectively. Thus, positive and negative values implied drift towards and away from the virtual hand, respectively. The normalization was included as the perceived position differed from the actual position of the physical hand in all subjects (proprioception bias).

Subjective measures were acquired from an 18-item questionnaire (see *Table 1*). Items Q1-Q10 assessed embodiment (ownership, location, and agency) and were adapted from Longo's scale [2], while items Q11-Q18 assessed tactile sensations, presence, and realism and were created ad-hoc to ensure comprehensive assessment. Following each experimental trial, the participant reported on a 7-point Likert scale how much they agreed with each statement (0 is "strongly disagree" and 6 is "strongly agree"). As all participants were Spanish native speakers, the questionnaire items were translated into Spanish. All items from the questionnaire were analyzed individually, but the subjective ratings of ownership (Q1-Q5), location (Q6-Q8), and agency (Q9-Q10) were additionally averaged within trials and analyzed as pooled measures [34]. Q1-Q5 considered to which extent the participants felt like the virtual hand belonged to their physical body (body ownership). Q6-Q7 asked about the correspondence in the location between the virtual and physical hand, whereas Q8 explored the correspondence in the location of tactile sensation. Q9 and Q10 considered to which extent the participants felt that they were able to initiate movement of and actively control the virtual hand, respectively (agency). As the present experiment did not include movement, these questions required the participants to envision moving the hand (i.e., to "extrapolate" outside immediate experience). Q11 to Q16 evaluated the perception, realism, feeling of resistance of the brush when being touched, texture, and temperature, respectively. Q17 and Q18 considered whether the VR experience was overall realistic to the subjects and whether the subjects felt like being present inside the virtual environment.

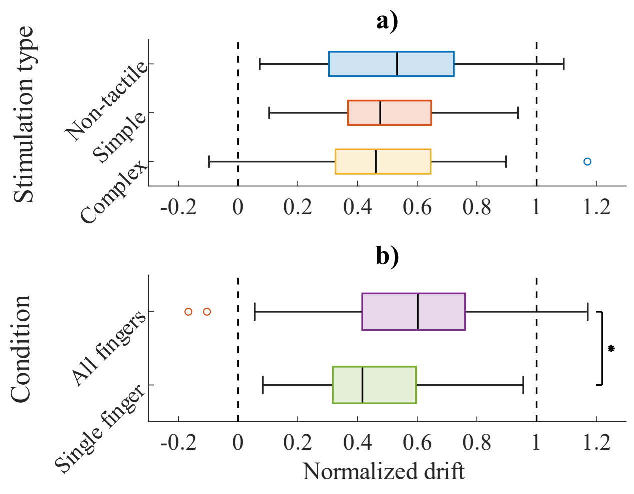

Fig. 4. Summary results of the of the proprioceptive drift measure. The main effect of stimulation types and conditions are shown in (**a**) and (**b**), respectively. The blue, orange, and yellow box plots show the results from the non-tactile, simple and complex feedback conditions, respectively, and the purple and green box plots show the results from the all-fingers and single finger conditions, respectively. The vertical black line, box limits, whiskers, and colored circles indicate median, interquartile range, extreme values and outlies, respectively. The vertical dashed lines at 0 and 1 represent the physical and virtual hand position, respectively. The asterisk indicates a p-value of $p<0.05$. The significance level was $p<0.05$.

F. Statistical analysis

The data for each measure were first tested for normality using Lilliefors tests. If the data were normally distributed, a two-way ANOVA was applied to assess the effect of conditions and stimulation types. However, the only normally distributed measure was proprioceptive drift. For the remaining measures, the main effects of stimulation type and condition were manually computed by averaging across the other factor: to assess the difference between stimulation types, the outcome measures for each stimulation type were averaged across the two conditions and vice versa. Then, depending on the normality of the averaged data (Lilliefors tests), the three stimulation types (no feedback, simple and complex feedback) were compared using a repeated measures ANOVA (rmANOVA) or Friedman test (non-parametric equivalent), followed by the Tukey-Kramer honestly significant difference criterion for posthoc pairwise comparisons. In fact, Friedman test was applied for all multiple comparisons except for the ownership measure in the all-fingers condition in which rmANOVA was used. The two conditions (all-fingers and single-finger) were compared using a paired t-test or Wilcoxon signed rank (non-parametric equivalent), again depending on the normality of the data distributions. The results are reported only if a significant difference between the two conditions was detected. To check for the interaction between the factors (stimulation type * condition), the stimulation types were also compared for each condition individually. First, we run Friedman or rmANOVA depending on the normality of the data, and then we performed a pairwise comparison with Tukey-Kramer honestly significant difference criterion. We then observed the pattern of significant differences between the stimulation types for each condition. If this pattern was different between conditions, the results were reported individually for each condition, otherwise, the results of the main effect of stimulation types (regardless of the condition) were presented. The significance level was set to $p<0.05$. For consistency, all results in the text were reported as median/interquartile range (IQR). Only the most important outcomes are reported and visualized in the paper. Additional results can be accessed in the Supplementary material file. The statistical analyses were conducted using Matlab 2022b (MathWorks, Massachusetts, USA).

III. RESULTS

A. Proprioceptive drift

A two-way ANOVA revealed that there was no interaction between conditions and stimulation types (see *Fig. 4*). The main effect of the stimulation type was also not significant (non-tactile: 0.5/0.4 vs simple: 0.5/0.3 vs complex: 0.5/0.3). Nevertheless, for all stimulation types, the subject's estimate of the real hand position clearly drifted toward the virtual hand, and the amount of drift was similar across stimulation types. However, the main effect of the condition was significant ($p<0.05$), with a larger drift in the all-finger condition compared to the single-finger condition (all-fingers: 0.6/0.3 vs single-finger: 0.4/0.3).

B. Stimulation type ranking (realism)

The stimulation type with no tactile feedback was ranked significantly lower compared to both tactile stimulation types ($p<0.0001$, non-tactile: 1.0/0.0 vs simple: 2.5/0.5 and $p<0.0001$, non-tactile vs complex: 2.5/0.5, over both conditions), see *Fig. 5* (individual condition results). However, despite a weak trend, where the median rating of simple was lower than complex in both conditions, the difference between the two tactile stimulation types was not significant.

C. Ownership

When the stimulation types were compared within each condition individually as pooled measure (averaging within-subject ratings from items Q1-Q5), there was a significant difference between the no tactile and both tactile stimulation types ($p<0.01$, non-tactile: 3.6/2.6 vs simple: 4.4/1.7 and $p<0.05$, non-tactile vs complex: 4.2/1.4) for all-fingers condition, with no significant difference between the tactile stimulation types, as visualized in *Fig. 6*. In the single-finger condition, however, the feeling of ownership was similar across stimulation types (non-tactile: 4.0/3.0 vs simple: 4.2/2.2 and non-tactile vs complex: 4.4/1.6).

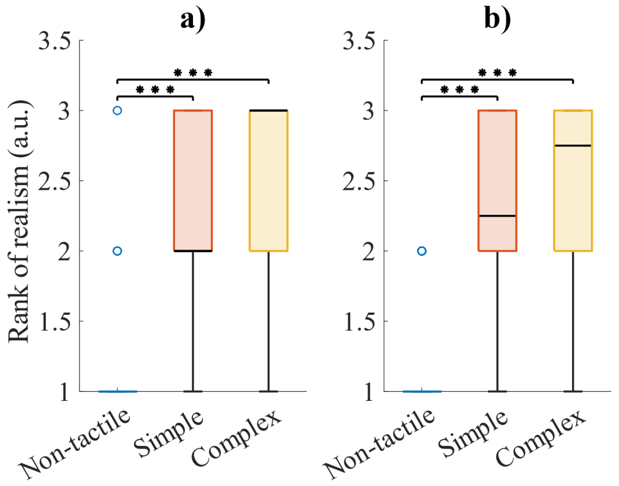

Fig. 5. Stimulation type ranking results per stimulation type for the all-fingers, **a)**, and single finger condition, **b)**. The blue, orange, and yellow box plots are the results from the non-tactile, simple, and complex stimulation types, respectively. The box plot annotations are the same as in *Fig. 4*. The asterisks *** indicates a p-value of $p<0.0001$.

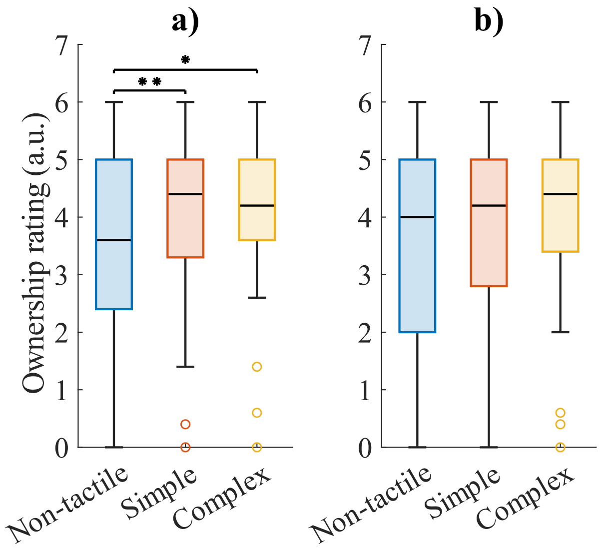

Fig. 6. Ownership rating results per stimulation type for the all-fingers, **a)**, and single finger condition, **b)**. The blue, orange, and yellow box plots are the results from the non-tactile, simple, and complex stimulation types, respectively. The box plot annotations are the same as in *Fig. 4*. The asterisks * and ** indicate a p-value of $p<0.05$ and $p<0.01$, respectively.

D. Location

There was a significant difference in ratings between the no tactile and tactile stimulation types when considering Q6-Q8 as a pooled measure (averaging within-subject ratings across items) ($p<0.0001$, non-tactile: 3.6/1.8 vs simple: 4.8/1.6 and $p<0.0001$, non-tactile vs complex: 5.0/1.1, see *Fig. S2*). Not surprisingly, the lower rating of the stimulation type with no tactile feedback was especially expressed for item Q8 (all fingers: 1.0/3.0, single-finger: 1.0/3.5), as this question is related to the location of tactile sensation, which was missing in that type of stimulation. Therefore, we repeated the comparison but only for Q6-Q7, which examined the matching in the location of the virtual and physical hand. Even in this case, the subjects rated the tactile stimulation types significantly higher compared to the no tactile stimulation (*p<0.01*, non-tactile: 4.0/2.5 vs simple: 5.0/2.0 and *p<0.0001*, non-tactile vs complex: 5.0/1.5), but again, only in the all-fingers condition. In the single-finger condition, no significant differences were detected (non-tactile: 4.75/2.5 vs. simple: 5.0/2.0 and non-tactile vs. complex: 5.0/2.0).

E. Agency

When the stimulation types were compared within conditions individually and considering Q9-Q10 as a pooled measure (averaging within-subject ratings across items, see *Fig. S3*), tactile feedback significantly improved the feeling of agency compared to no tactile stimulation in the all-finger condition (*p<0.001*, non-tactile: 2.5/3.3 vs simple: 4.0/2.5 and *p<0.0001*, non-tactile vs complex: 4.5/2.8, see *Fig S3*), whereas in the single-finger condition, the significant difference was only detected between the no tactile and complex stimulation types (non-tactile: 2.5/4.0 vs simple: 3.8/3.0 and *p<0.0001*, non-tactile vs complex: 4.0/2.5).

F. Tactile sensation

Expectedly, when asked whether they perceived tactile sensation (Q11), the tactile stimulation types were rated significantly higher compared to no tactile stimulation (*p<0.0001*, non-tactile: 1.0/3.0 vs simple: 6.0/1.5 and *p<0.0001*, non-tactile vs complex: 6.0/0.5, see *Fig. S4*). The same result was obtained for items regarding the perceived realism Q12 (non-tactile: 1.0/2, simple: 4.5/2.0, complex: 4.5/2.5, see *Fig. S5*) and accuracy of the tactile sensation (non-tactile: 1.0/2.8, simple: 5.0/1.8, complex: 5.5/1.5, see *Fig. S6*). However, the simple and complex feedback were rated similarly. Also, the tactile stimulation types induced a significantly greater feeling of resistance Q14 (non-tactile: 0.0/1.5, simple: 2.8/2.8, complex 3.0/3.3, see *Fig. S7*) and texture Q15 (non-tactile: 0.0/1.5, simple: 2.5/2.5, complex: 3.0/4.0, see *Fig. S8*) during brush stroking, with no significant difference between the two tactile stimulation types. When comparing the conditions, the all-fingers resulted in higher ratings for perceiving resistance (*p<0.01*, all-fingers: 2.5/2.2 vs. single finger: 2.0/2.2). Expectedly, for the item asking about the perceived thermal sensation (Q16), the median/IQR was low for all stimulation types, see *Fig. S9*. However, the simple stimulation (1.3/2.3) was rated significantly higher than no tactile stimulation (0.0/1.3) whereas no difference was detected between complex (1.0/2.8) and no tactile stimulation.

G. Realism and presence

Regarding realism (Q17), the complex feedback was rated significantly higher than no tactile stimulation (*p<0.05*, non-tactile: 3.5/2.8 vs complex: 4.5/1.0, see *Fig. S10*), while there was no significant difference between no tactile and simple stimulation (non-tactile vs simple: 4.0/1.5). For the feeling of presence (Q18), the comparison between stimulation types in the all-fingers condition showed that both tactile stimulation types were rated higher than no tactile stimulation (*p<0.0001*, non-tactile: 3.0/3.0 vs. simple: 5.0/2.0 and *p<0.01*, non-tactile vs complex: 4.5/2.0, see *Fig. S11*). However, in the single-finger condition, all stimulation types were rated similarly (non-tactile: 4.0/3.0 vs. simple: 4.0/2.0 and non-tactile vs. complex: 4.0/2.0).

IV. DISCUSSION

The objective of the present study was to test if and how the embodiment of a virtual hand is affected by the fidelity of electrotactile feedback and the extent of skin area to which the stimulation was applied when the subjects performed a virtual equivalent of the rubber hand illusion experiment. Three electrotactile stimulation types, namely, no stimulation, simple (single point), and complex stimulation (sliding motion) were delivered to the subjects using a tactile glove with multiple stimulation pads on each finger. The stimulation was delivered to either a single finger (fingertip and middle phalange of the index finger) or all fingertips synchronized with visual feedback of a virtual brush stroking the skin of a virtual hand in a smooth motion. The initial hypotheses were that the complex stimulation pattern would induce a greater sense of embodiment of the virtual hand in both conditions, as the complex feedback presumably better replicates the natural tactile sensation. We also expected that the embodiment would be facilitated when stimulating all fingers compared to a single finger.

The results demonstrated that modulating the spatial extent of the stimulation, from single to all fingers, was indeed an effective strategy. When analyzing the subjective measures (stimulation type rankings and questionnaire items) obtained in the all-fingers condition, tactile feedback induced a greater embodiment compared to no tactile stimulation. The tactile feedback resulted in significantly higher ratings in all analyzed questionnaire items, producing a substantial impact on ownership, agency, location, realism, and presence. These results are in line with previous studies which also showed a significant improvement in subjective measures [15], [35], as well as the ability to localize an unseen hand [36] when tactile feedback was provided. This is an encouraging result demonstrating that the addition of tactile stimulation in VR can indeed improve multiple aspects of the user experience. Importantly, to maximize the effect, the feedback should be delivered over a larger area (all fingers vs. single finger). However, the introduction of tactile feedback did not significantly increase the proprioceptive drift compared to only visual feedback. Nevertheless, the results imply that this is not because the stimulation was not an important addition to the user experience, but more because of the "ceiling" effect of the visual feedback. As demonstrated before [15], visual feedback on its own is already enough to produce a high level of immersion and induce the embodiment in VR when measured objectively. Indeed, whether there was tactile stimulation or not, the subjects reported substantial proprioceptive drift towards the virtual hand. The fact that proprioceptive drift does not always match other embodiment measures, e.g., ownership, was reported before [37].

The fact that the tactile stimulation had a most pronounced impact in the all-finger block (see ownership, location, agency, realism and presence measures) can also be related to the more dynamic interaction in that scenario. It could be that the subjects anticipated tactile feedback when the stimulation was switching from finger to finger, and when the stimulation was active, the experience matched the prediction (the brush contacted the finger, and the stimulation was felt). In the single-finger condition, such making and breaking of contact occurred less frequently and always over the same finger during a trial (distal overshoot of brush once per loop) and the lack of tactile input was thereby less perceived. This could indicate that such dynamic interactions might have particular importance for the user experience of tactile feedback in VR. It remains to be seen if visuotactile stimulation of even broader portions of the hand, including the proximal phalanges and palm, could further enhance the level of embodiment. VR can be used for rehabilitation and training of stroke patients [38], [39] and amputees [40], and therefore, the addition of tactile feedback might be useful in the clinical context. The present study shows that to maximize the effect of feedback in such training protocols, one should focus on increasing the area and dynamism of interaction.

Surprisingly, the second strategy, that of increasing the fidelity of the feedback by delivering a more complex profile designed to better mimic a smooth progression of the natural feedback, did not have the expected effect. The embodiment in this type of tactile stimulation was not stronger compared to that when providing simple single-point tactile stimulation. There was no significant difference between the simple and complex stimulation in any of the outcome measures. Nevertheless, some items did provide a weak indication of the effect of the complex versus simple stimulation. For instance, the complex tactile stimulation significantly improved the feeling of agency (Q9-Q10) and realism (Q17) in the single-finger condition compared to the baseline of no tactile stimulation, whereas the simple feedback failed to show a significant effect in these cases.

The lack of a stronger effect of a complex stimulation pattern could be due to several factors that should be investigated in future studies. The added value of the complex feedback was perhaps not sufficiently strong because simple tactile stimulation was already enough to produce an improvement in user experience, which was then difficult to increase further with the more complex pattern. Indeed, it has been demonstrated before that simple stimulation can facilitate the feeling of embodiment [13], [15], [35]. In the present study, the simple tactile stimulation involved activating all pads, which produced a non-specific but spatially distributed tingling sensation, and this effect could already emulate the contact with a brush. However, it could also be that the complex stimulation was still not realistic enough to make a substantial difference. The latter point is somewhat supported by the results, as there was no significant difference between the two feedback schemes, even when the subjects were asked to explicitly rank the stimulation types. When introducing the subjects to the two methods, before starting the experiments, we performed a careful calibration (as explained in Methods, section *Experimental procedure*) and all of them confirmed that they could feel the gradual progression in the complex stimulation. Nevertheless, the fidelity of complex feedback might need to be further improved to translate into a detectable difference in user experience and feeling of embodiment compared to a simple approach. For instance, the effect of complex feedback might be more pronounced if the brush movements would have been slower. Also, introducing a slight stimulation overlap between the consecutive segments (pad rows and columns) might have induced a stronger and smoother illusion of apparent motion [41]. Furthermore, maybe the resolution of the spatial stimulation was not high enough. More segments per finger might need to be activated to imitate the sliding sensation of the brush stoking more effectively. Lastly, it could be that the simple feedback was felt as stronger compared to the complex feedback. The higher intensity might have compensated for the missing illusion of motion when inducing an immersive tactile effect. Additionally, the trial duration in the present study was selected based on the literature [22], [42] and to avoid excessive experiment duration and confounding factors (e.g., fatigue and loss of focus). Nevertheless, it remains to be investigated if and how the duration of tactile-enhanced interactions in VR impacts user experience.

The fact that the questionnaire items evaluating the presence (Q11-Q13) and quality (Q14 and Q15) of tactile sensations showed significantly higher ratings for the active tactile stimulation compared to no tactile stimulation was expected. This can be regarded as a "control measurement" confirming that the subjects actually perceived the sensation. Interestingly, the ratings for the thermal measure (Q16) were different from zero in all stimulation types, and the active tactile stimulation types were rated significantly higher than no tactile stimulation, especially for the simple feedback approach. Perhaps this effect was elicited because many pads were simultaneously active when delivering simple feedback, thereby creating a "larger" and more "tingling/warm" sensation. Overall, these outcomes demonstrate that while tactile feedback indeed creates a more versatile (richer) interaction in VR, by allowing the subjects to feel, for instance, texture and resistance during brush stroking, the "unnatural" aspects of electrical stimulation can produce spurious sensations that are not "supported" by the virtual scene (thermal sensation).

Integrating tactile stimulation within virtual reality is still in its nascent stages. A recent meta-analysis [16] has identified several key gaps in this field and the current study tried to address some of them. A notable limitation in existing research is the tendency to utilize small sample sizes. In contrast, our study expands on this by incorporating a larger sample, thereby enhancing the reliability and generalizability of our findings. Furthermore, while most studies in this field have typically focused on stimulating a single area, often the index finger, our research takes a more comprehensive approach. We explore and compare the effects of stimulating multiple fingers, thereby aiming to better understand if and how such diverse tactile inputs can enhance the sensation of embodiment within VR environments. Nevertheless, this is an emerging area of research, and many questions still need to be answered to fully understand how the type, precision, and quality of stimulation impact embodiment. For instance, it would be interesting to investigate if modulating the intensity or frequency of stimulation would further facilitate embodiment. Also, it would be of interest to verify whether being able to freely move the hand and voluntarily touch the object increases the impact of tactile stimulation.

V. CONCLUSION

Overall, the results of the present study confirmed that the inclusion of tactile stimulation in the virtual environment subjectively improved the embodiment of the virtual hand. Interestingly, the stimulation of a larger extent of the hand (sequential stimulation of all fingers) induced a larger proprioceptive drift than stimulating only a single finger both with and without tactile stimulation. Furthermore, the addition of tactile feedback seemed to produce an effect only when the stimulation was delivered over a larger area and in a more dynamic scenario (all fingers vs. single finger). Unexpectedly, the feedback of higher fidelity (sliding motion stimulation) did not improve the embodiment compared to simple single-point stimulation. It remains to be seen if further improvement in the feedback realism and naturalness to better approximate natural sensations when using electrotactile stimulation in immersive VR would produce a significant impact when compared to simple all-at-once feedback.

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