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An on-site and remote study during the COVID-19 pandemic on virtual hand appearance and tactile feedback

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ABSTRACT

A virtual reality (VR) study was conducted both in our lab setting and remotely to investigate the effects of virtual hand appearance and tactile feedback on ownership, external appearance, and tactile sensation embodiment dimensions when participants were instructed to perform an assembly task in a virtual environment. Six experimental conditions that combine hand appearances (abstract, mannequin, and realistic) and tactile feedback (tactile and no tactile) levels were examined. The results of our study indicated that: (1) the more realistic hand had a stronger effect on tactile sensation and external appearance, while the mannequin hand was associated with a greater ownership effect; (2) tactile feedback was associated with a stronger effect on external appearance compared to no tactile feedback; (3) the realistic hand model in conjunction with tactile feedback significantly affected the tactile sensation of the participants; (4) the participants in the lab setting rated the external appearance of the realistic hand model higher than the remote participants; (5) the participants exposed for less than one hour per week to VR rated the tactile sensation in the presence of tactile feedback higher, while they similarly rated the external appearance of the virtual hand model in the presence of a realistic hand model higher when compared to those who were exposed for more than one hour per week to VR; and finally, (6) the younger participants rated the tactile sensation higher than the older participants in the presence of the realistic hand model. In this paper, we discuss our findings and provide design considerations for virtual reality applications that consider virtual hands and tactile feedback.

1. Introduction

Current virtual reality (VR) technologies allow users to not only observe virtual environments but also interact within them by performing a variety of tasks more efficiently and intuitively. Many virtual reality devices allow users to control 3D hand models and interact with virtual objects through using virtual reality controllers. It has been found that when users observe virtual hand models, the virtual reality experience becomes more appealing to them (Zell et al. 2015; Hoyet et al. 2016; Höll et al. 2018; Frinbourg et al. 2020). Moreover, since virtual reality controllers provide tactile feedback to users, a user can also sense the vibrotactile feedback of the controller when interacting (touching, grabbing, etc.) with virtual objects. These functionalities have made it possible for developers to create virtual reality applications that enable more realistic interactions since both visual and somatosensory cues of VR users are included.

Embodiment (Kilteni, Groten, and Slater 2012; Gonzalez-Franco and Peck 2018), or partial embodiment (Onishi, Tanaka, and Nakanishi 2016) in our case, i.e. the sense of virtual reality users possessing a virtual body or body part in a virtual environment, is a critical perceptual mechanism that needs to be explored. Gonzalez-Franco and Peck (2018) proposed six different embodiment dimensions: body ownership, agency and motor control, tactile sensations, location of the body, external appearance, and response to external stimuli. Our 3 (abstract, mannequin, and realistic hand models; see Figure 1) × 2 (tactile and no tactile feedback) study used a VR assembly application to investigate three embodiment dimensions (ownership, external appearance, and tactile sensation). We have taking into account previous research which indicates that identifying the design principles of avatars is a requirement (Schild et al. 2019) and that tactile feedback seems to aid task performance in immersive environments (Walker et al. 2015; Schiefer et al. 2018). However, the relationship between hand appearance and tactile sensation is not yet clear.

In our study, a virtual reality assembly application was developed, and participants were asked to interact...
with the examined conditions so we could explore the aforementioned embodiment dimensions. From our point of view, considering that there are various applications that use hand models and tactile feedback to help users assemble objects (Stork et al. 2012; Xia et al. 2012; Koumaditis et al. 2020), it was deemed essential to explore how the appearance of hand models and tactile feedback can affect the examined embodiment dimensions in a virtual environment. We considered that there are various applications used in the industry (e.g., manufacturing) aimed at training people to interact with different devices. For example, Toyota, one of the greatest automobile makers, uses VR for assembly line training. It seems that the use of virtual reality is coming to substitute the tasks that take place in the real-world setting; however, it may not provide a realistic experience when one is involved in dangerous situations. In such settings, understanding how people perceive a virtual hand could be considered quite important, to say the least. If, for example, such applications provide a high sense of embodiment, the trainees could become more aware of potential injuries that might be caused due to miscalculated decisions.

Participants in our study were recruited both from our campus as well as remotely during the COVID-19 pandemic. Based on our study design, we aim to answer the following research questions:

- **RQ1:** How do the three different hand models affect participants’ perceptions of ownership, external appearance, and tactile sensation?
- **RQ2:** Does having tactile feedback provide a stronger ownership, external appearance, and tactile sensation effect on participants?
- **RQ3:** How do remote participants rate ownership, external appearance, and tactile sensation compared to lab participants?
- **RQ4:** Does the prior virtual reality experience of the participants affect their ratings of ownership, external appearance, and tactile sensation?
- **RQ5:** Does the age of the participants affect their ratings of ownership, external appearance, and tactile sensation?

The paper is organised as follows: Section 2 presents the related work of our study. Section 3 provides details on the methodology that was followed. Section 4 presents the obtained results. In Section 5, we discuss our findings, limitations, and design guidelines. Finally, conclusions and potential future directions are presented in Section 6.

## 2. Related work

In an immersive environment, embodiment is the feeling of substituting an avatar into one’s first-person point of view (Argelaguet et al. 2016). The sense of embodiment has been studied in many different dimensions, including the effects of self-motion artifacts (Koilias, Mousas, and Anagnostopoulos 2019) and visuomotor calibration (Kokkinara, Slater, and López-Moliner 2015), the effects of tactile sensation (Krogmeier, Mousas, and Whittinghill 2019), and the effects of external appearance (Argelaguet et al. 2016; Fribourg et al. 2020). Additionally, studies that explore the effects on users’ embodiment in serious game (Chee 2007) or training (Slater 2017) and learning (Barmaki and Hughes 2018) domains have also been conducted. Although there are a number of elements (embodiment dimensions) that could affect self-avatar embodiment in virtual environments (Gonzalez-Franco and Peck 2018; Koilias, Mousas, and Anagnostopoulos 2020; Cui, Kao, and Mousas n.d.), it is important to understand what these elements are and how they interact with each other.

Body ownership is the sense of recognising one’s virtual body as his/her ‘real’ body (Slater et al. 2009). Botvinick and Cohen (1998) first proposed the rubber hand illusion (RHI), indicating body ownership could be induced through multisensory integration. The RHI is a simple illusion where participants perceive that a rubber hand belongs to their body (Yuan and Steed 2010). This perception was usually achieved with a synchronous stimulus on both the rubber hand and the participant’s real hand. Along with visual tactile stimuli, the participants could feel the virtual hand as ‘their own hand’ after a short period of time (Botvinick and Cohen 1998). Petkova et al. (2011) suggested that having a strong virtual sensation of a body part generates a whole-body ownership, and Tsakiris and Haggard (2005) and Costantini and Haggard (2007) provided evidence that a stronger sense of the RHI generated a stronger sense of embodiment in the presence of

![Figure 1](image-url). The three different hand models (from the left: abstract, mannequin, and realistic) used in this study.
visuo-tactile sensation. Finally, RHI studies have also found that the appearance of the hand can be an additional component of embodiment (Yuan and Steed 2010; Lin and Jörg 2016; Pyasik, Tieri, and Pia 2020).

Extending upon the RHI, studies have been conducted to investigate the participants’ ownership of other body parts, including the brain system (Ehrsson, Holmes, and Passingham 2005; Lopez, Halje, and Blanke 2008), skin colour and temperature (Haans, IJsselsteijn, and de Kort 2008; Farmer, Tajadura-Jiménez, and Tsakiris 2012), and foot movements (Kondo et al. 2018). Lopez, Halje, and Blanke (2008) found that performing caloric and galvanic vestibular stimulations on healthy subjects generated a strong sense of ownership. Ehrsson, Holmes, and Passingham (2005) suggested that body ownership is formed throughout fast and continuously occurring activities in the cerebellar area. Farmer, Tajadura-Jiménez, and Tsakiris (2012) investigated the effect of embodying different skin colours and found that embodying black skin increased embodiment and lowered racial bias. Haans, IJsselsteijn, and de Kort (2008) claimed that skin colours that do not resemble human skin decreased the perception of RHI. Finally, Kondo et al. (2018) suggested that a virtual foot could induce body ownership and the perceived ownership is considered to be as strong as using a whole-body avatar.

Besides the partial embodiment induced through RHI, studies investigating the whole body have also been conducted (Maselli and Slater 2013; Lugrin, Latt, and Latoschik 2015). Lugrin, Latt, and Latoschik (2015) investigated the effect of self-avatar appearance on ownership. They found that robot- and cartoon-like avatars elicited a stronger sense of ownership from their participants than human-like avatars. Maselli and Slater (2013) also studied full-body illusion. In their immersive VR study on identifying the building blocks of this ownership illusion, they asserted that the first-person perspective was essential in experiencing a sense of ownership.

In immersive environments, it is important to design a realistic body appearance in order to achieve the highest sense of ownership (Ding et al. 2020). Body appearance may affect embodiment in many ways, including racial, gender, age, and even cultural factors (Mishkind et al. 1986; Clarke, Hayfield, and Huxley 2012; Banakou, Groten, and Slater 2013). The level of body ownership illusion varies among different study participants and different situations. For example, embodying a black avatar reduces racial bias (Peck et al. 2013), while embodying a man/woman wearing a suit can lead to substantial behavioural changes (Kilteni, Bergstrom, and Slater 2013).

Besides just observing virtual content through the use of a head-mounted display, tactile feedback devices can be used to induce somatosensory sensations. Tactile feedback is the physical feedback of a device based on user input. Most electronic devices provide feedback to users through vibrations. In early studies, participants wore special equipment on their bodies to receive tactile feedback, such as haptic vests when making contact with other virtual characters in immersive environments (Krogmeier, Mousas, and Whittinghill 2019) or feedback-providing haptic gloves when using virtual hands to interact with other virtual objects and characters (Low et al. 2017). However, with the development of VR technology, tactile stimulation is available nowadays in almost all VR controller devices.

Various studies have proved that tactile sensation is also a factor contributing to embodiment (Kilteni, Groten, and Slater 2012; Haddadin, Johannsmeier, and Ledezma 2018). Kilteni, Groten, and Slater (2012) reviewed the factors that could enhance the sense of embodiment. Throughout their research, they found that synchronous tactile sensation enhanced the sense of self-location when a tactile event was seen visually on the self-avatar’s body from a first-person perspective. This strengthened the participants’ sense of self-location, which is considered to be a subcomponent of embodiment. It has also been found that the tactile feedback of a virtual hand increases individuals’ sense of hand and arm ownership (Guterstam, Gentile, and Ehrsson 2013; Fossataro et al. 2018), the touching of the self-body enhances the sense of embodiment (Gonzalez-Franco and Berger 2019), and the vibration sensations associated with specific stimuli on body parts promote an even a higher sense of embodiment when making contact or interacting with objects (D’Alonzo, Clemente, and Cipriani 2014). Finally, in another direction, Haddadin, Johannsmeier, and Ledezma (2018) suggested the use of tactile robots (i.e. smart wearables) could be a central embodiment component due to their realistic sense of touch and physical interaction, both essential elements of embodiment.

This study utilises knowledge from previous studies and extends upon them by investigating the effects of virtual hand appearance and tactile sensation on ownership, tactile sensation, and external appearance dimensions of embodiment. We conducted a 3 (abstract, mannequin, and realistic hand models) × 2 (tactile and no tactile feedback) study to determine the key factors contributing to the three above-mentioned embodiment dimensions. We think that our results contribute to further understanding how hand-appearance and tactile sensations will affect most study participants.
3. Materials and methods

This section presents all the details related to the methodology that was followed in our study.

3.1. Participants

We conducted an a priori power analysis to determine the sample size using G*Power 3.10 software (Cohen 2013). The calculation was based on 95% power, a medium-to-large effect size of .30 (Faul et al. 2009), six groups with six repeated measures, a non-sphericity correction of $\varepsilon = .60$, and an $\alpha = .05$. The analysis resulted in a recommended sample size of 48 participants. We recruited 48 participants (18–48 years-old) for the experiment. Specifically, 12 participants were recruited from the XR Distributed Research Network (XRDRN), which is a platform for researchers in the Cross-Reality (XR/VR/AR) discipline created in response to the COVID-19 emergency lockdown, and 36 participants were from our department. There were 16 female (age; $M = 23.12$, $SD = 3.30$) and 32 male (age; $M = 24.75$, $SD = 5.95$) participants. All participants had prior experiences with VR. No compensation was provided for participation.

3.2. Virtual reality application

For this study, we developed our VR application using Unreal Engine 4. The application runs on all Oculus devices. In this application, there were two sections: the tutorial level and the main level. Specifically, the tutorial level (see Figure 2) was a simple level with four assembly parts (two gears, one small ball, and one big ball). A table was placed in front of the participants, upon which the assembly parts (gears and balls) were placed. Instructions regarding the application’s operations were rendered on the wall of the virtual environment. There were no specific tasks the participants needed to complete. Participants were able to move around freely in the virtual environment and pick and assemble parts in the tutorial level to familiarise themselves with the operations of the application. It should be noted that for the tutorial level a 3D cube was used to represent the position of the controller in the virtual environment. In this level no tactile feedback was implemented. For the assembly process, participants needed to grab the parts using the side button on the controller and move them near to the corresponding semi-transparent slots of a similar shape. When the selected part was close enough to the corresponding semi-transparent slot, it automatically ‘snapped’ onto it. The instructions then directed the user to push the red button on the table to transition from the tutorial level to the main level.

We created six variations of the main level (see Figure 3), where each variation assigned one of the three hand models, with controller tactile feedback or not. For the hand models, an animation of a grabbing movement was included for each hand. Specifically, the mannequin and realistic hand models performed a grab animation with the fingers, while the abstract hand performed a simple bending motion (see Figure 4 for the three different hand models during the assembly task). There were two big balls, four small balls, and five gears to assemble as the main task. A table was placed in front of the participants in the virtual environment. All the parts were placed on the table in front of the user. The task for the participants was to assemble a 3D structure by placing all the individual parts into their slots. The task required the participants to successfully assemble the following parts: two big balls on the top of the structure, four small balls in the centre, four gears at the bottom, and one gear on a small cylinder. The cylinder was located at the centre of the large cube. Participants needed to push the gear from the outside slot of the cylinder into the inside. The parts did not need to be placed in any particular order, but there were two hidden slots (one small ball and one gear) that necessitated other slots be completed first. When all the parts were assembled, the participants would see a red button appear which they would have to press in order to continue to the next variation of the application. A hint regarding the final assembly was rendered on the wall.

3.3. Experimental conditions

Six experimental conditions were developed (abstract hand and tactile, abstract hand and no tactile, mannequin hand and tactile, mannequin hand and no tactile, realistic hand and tactile, and realistic hand and no tactile) by following a 3 (abstract, mannequin, and realistic
within-group design; meaning all participants experienced all conditions of the study. If the condition contained tactile feedback, the controller would vibrate when the participants grabbed the object. The conditions were randomised by following Graeco-Latin square so that each participant would experience the sequence of the conditions differently.

3.4. Measurements

We used the body ownership, tactile sensations, and external appearance dimensions of the embodiment questionnaire provided by Gonzalez-Franco and Peck (2018). The questionnaire was distributed to our participants using Qualtrics, which is an online survey tool. It should be noted that the questions were adjusted to fit the scope of this study. Finally, all questions were answered on a scale from 1 (strongly disagree) to 7 (strongly agree).

3.5. Procedure

To recruit remote participants, our study was posted on the XRDNR website. The remote participants were asked to visit the study’s Qualtrics webpage and read the consent form that was approved by the Institutional Review Board (IRB) of our university. Upon agreement, the remote participants filled out a demographics questionnaire. Then, a link to download the developed application was provided. Remote participants began the application at the tutorial level. At this stage, a text with detailed information on how to control the virtual hand by using the controller to grab an object, how to assemble the parts, how to move around, and what the goal of the tasks were, was all rendered on the wall behind the assembly parts. After the participants were confident enough with the set-up, they pressed the red button on the table to proceed to the main levels. We kept the text instructions on the wall of the main level in case the participants needed instructions for the tasks they were asked to perform. In addition, instructions regarding taking off the headset to complete the questionnaire on the Qualtrics webpage using their own personal computer were also provided at the rendered text. After completing all the variations of the experiment, the remote participants would need to record and input a passcode that was rendered on the wall. They needed to take a photo of their own equipment and upload it to the Qualtrics survey website. The last two steps were requested so that we could ensure that all remote participants had access to a head-mounted display as well as that all participants had completed the entire study.

For the on-site part of the study, upon arrival at the lab of our department in which the study was conducted, the participants were informed about the study and asked to read the consent form, which was approved by the IRB of our university. Upon participation agreement, the participants were asked to fill out a demographics questionnaire. Then, they were asked to put on the Oculus Quest head-mounted display and adjust it to their head accordingly. After the
adjustments, the participants started the study at the tutorial level. When the participants became familiarised with the operations, they pressed the red button on the table and continued to the main level, in which they experienced the experimental conditions (shown in Figure 5). As mentioned in the application section, participants were to finish the assembly tasks for each variation of the main level. In between each level variation, they took off their head-mounted displays and were asked to answer the provided questionnaire distributed to them in a computer-based format (in Qualtrics). After finishing the sixth variation of the main level, the researcher answered participant’s questions, and then the participants were thanked and dismissed. Both the remote and on-site participants spent no more than 60 minutes for the study.

For the on-site part of the study, in considering the current COVID-19 pandemic situation and following our institution’s instructions, we allowed a 60-minute gap in between each participant to ensure the risk of infection was minimised. All on-site participants were tested negative for COVID-19 before coming to the lab. Moreover, before and after each participant’s arrival at the lab, all equipment and furniture were carefully sanitised by the research team. Once participants arrived at the lab, we asked them to sanitise their hands, and during the study, all participants were asked to wear face masks and VR sanitary masks (HYPERKIN Universal VR Sanitary Mask V2.0).

4. Results

All results obtained from the study are summarised in this section. All analyses were performed using the IBM SPSS v.26.0 statistical analysis software. The normality assumption of the objective measurements and subjective ratings were evaluated with Shapiro-Wilk tests at the 5% level and graphically using Q-Q plots of the residuals. The measured items of the ownership, external appearance, and tactile sensation scales were tested for reliability (Cronbach’s alpha: .79 < α < .86), and due to sufficient correlation, we used the cumulative score of all items for each scale as the final result and treated them as continuous scales, a practice which is typically used. For all statistical tests, \( p < .05 \) was deemed as statistically significant.

4.1. Ownership

A two-way repeated measures analysis of variance (ANOVA), with the hand and tactile feedback types being the independent variables and the ownership being the dependent variables, was used to analyse the obtained data. We found a statistically significant main effect for hand appearance \([\Lambda = .714, F(2, 46) = 9.195, p = .000, \eta_p^2 = .286] \). Post hoc comparison using Bonferroni corrected estimates showed that the participants’ ownership when exposed to a mannequin hand \((M = 4.79, SD = .14)\) was significantly higher than when exposed to the realistic hand model \((M = 4.27, SD = .13)\). However, neither a statistically significant effect for tactile feedback \([\Lambda = .983, F(1, 47) = .798, p = .376, \eta_p^2 = .017] \) nor an interaction (hand appearance \times tactile feedback) were found on ownership \([\Lambda = .900, F(2, 46) = .027, p = .973, \eta_p^2 = .001] \). Figure 6 shows the plots of the estimated marginal means.

4.2. Tactile sensation

The two-way repeated measures ANOVA with the hand and tactile feedback types being the independent variables and the tactile sensation being the dependent variables revealed a significant main effect for hand appearance \([\Lambda = .740, F(2, 46) = 8.071, p = .001, \eta_p^2 = .260] \). Post hoc comparison using Bonferroni corrected estimates showed that the abstract hand model was rated lower \((M = 3.87, SD = .14)\) than the mannequin...
hand ($M = 4.39, SD = .10$) and realistic hand ($M = 4.46, SD = .11$) models. We did not find a statistically significant effect for tactile sensation on the tactile feedback conditions [F(1, 47) = 1.000, p = .347]. However, a significant interaction effect (hand appearance × tactile feedback) for tactile sensation was found [F(2, 46) = 3.038, p = .051, $\eta^2 = .082$]. The estimated marginal means (see Figure 7) showed that, in the presence of tactile feedback, participants rated the tactile sensation higher when exposed to either the mannequin or realistic hand models compared to when exposed to the abstract hand model.

4.3. External appearance

For the external appearance dimension of embodiment, the two-way repeated measures ANOVA showed a significant effect for hand appearance [F(2, 46) = 10.247, p = .001, $\eta^2 = .22$]. The post hoc comparison using Bonferroni corrected estimates showed that participants rated the abstract hand model ($M = 3.35, SD = .22$) lower than the mannequin hand ($M = 4.42, SD = .17$) and realistic hand ($M = 4.56, SD = .21$) models. Moreover, a significant effect for external appearance on tactile feedback was also found [F(1, 47) = 1.187, p = .283, $\eta^2 = .02$]. Post hoc comparison using Bonferroni corrected estimates showed that the participants rated the external appearance of the realistic hand model higher ($M = 4.89, SD = .23$) than that of the remote ($M = 3.60, SD = .41$) participants.

4.4. Experimental site

A three-way mixed ANOVA (hand appearance × tactile feedback × experimental site) was conducted to investigate the effects of the experimental site on the participants’ responses. A statistically significant interaction effect (hand appearance × experimental site) was found for the external appearance dimension of embodiment [F(2, 45) = 6.398, p = .004, $\eta^2 = .22$]. The estimated marginal means (see Figure 9) showed that the on-site participants’ rated the external appearance of the realistic hand model higher ($M = 4.89, SD = .23$) than that of the remote ($M = 3.60, SD = .41$) participants.

4.5. Virtual reality experience

We conducted three-way mixed ANOVA (hand appearance × tactile feedback × VR experience) on the participants’ prior VR experience (less than an hour per week vs. more than an hour per week) as a between-subject factor to investigate the effects of VR experience on the participant responses. Note that 33 participants experienced VR less than one hour per week, and 15 participants experienced VR more than one hour per week. A statistically significant interaction effect (tactile feedback × VR experience) was found for the perception setting (remote vs. on-site) as a between-subject factor.
of ownership \[\Lambda = .841, F(1, 46) = 8.718, p = .005, \]

The estimated marginal means (see Figure 10) showed that in the presence of tactile feedback, participants who were exposed for less than one hour per week with VR rated the tactile sensation higher \((M = 4.74, SD = .14)\) compared to the participants who were exposed for more than one hour with VR per week \((M = 4.01, SD = .21)\).

Additionally, a statistically significant interaction effect (hand appearance \(\times\) VR experience) was found for the external appearance dimension of embodiment \[\Lambda = .796, F(2, 45) = 8.718, p = .006, \eta^2_p = .204\]. The estimated marginal means (see Figure 10) showed that in the presence of a realistic hand model, the younger participants rated the tactile sensation higher \((M = 4.56, SD = .14)\) than the older participants \((M = 4.03, SD = .18)\).

4.6. Age groups

We explored whether age could affect the way the participants experienced the six experimental conditions. We conducted three-way mixed ANOVA (hand appearance \(\times\) tactile feedback \(\times\) age group) tests with age groups (younger; 29 participants aged between 18 and 24 vs. older; 19 participants aged between 25 and 48) set as a between-subject factor to investigate the effects of VR experience on the participants responses. A statistically significant interaction effect (hand appearance \(\times\) age) was found for the tactile sensation dimension of embodiment \[\Lambda = .851, F(2, 43) = 3.758, p = .031, \eta^2_p = .149\]. The estimated marginal means (see Figure 11) showed that in the presence of a realistic hand model, the younger participants rated the tactile sensation higher \((M = 4.56, SD = .14)\) than the older participants \((M = 4.03, SD = .18)\).

5. Discussion

In this study, we aimed to explore how the appearance of a virtual hand model and tactile sensation affected three embodiment dimensions: ownership, external appearance, and tactile sensation. The subsections below discuss our findings.

5.1. Hand appearance

We found significant results for the effect of hand appearance on all examined variables (RQ1). The mannequin hands were associated with a higher sense of ownership. On the other side, the realistic hand enhanced the participants’ perception of the tactile feedback as it felt more realistic. The abstract hand, being the least realistic, was scored lower by participants throughout the entire three embodiment dimensions (ownership, external appearance, and tactile sensation) compared to the other two styles.

The participants rated their sense of ownership for the mannequin hand as higher than for the realistic hand. This result deviates from previously conducted studies, which have indicated that the realistic hand generates higher levels of ownership in VR (Yuan and
Steed 2010; Ma and Hommel 2015; Zhang and Hommel 2016). Argelaguet et al. (2016) mentions that ownership is dependent on the appearance of the virtual hand and that morphological resemblance is needed to increase ownership. Hoyet et al. (2016) also found participants experiencing higher ownership when using more realistic hands and fingers. In this task, when considering the design of the environment, the mannequin hand appearance had the best resemblance to the virtual environment, since both the virtual environment and the mannequin hand model were low-poly with a semi-realistic appearance. Regenbrecht et al. (2017) has mentioned the importance of mimicking the real world in terms of realism in order to get close to visual coherence in an immersive environment. A coherent visual quality can maximise virtual visualisation and enhance embodiment. Participants in the present study reported that both abstract hands and realistic hands brought a sense of ‘style clash’ with the environment, which also supports our statement. A contradictory style of appearance (e.g. environment style vs. hand appearance) can reduce feelings of ownership (Argelaguet et al. 2016), which we think was the reason the participants’ ownership ratings were higher under the mannequin hand condition than the realistic hand condition. We should note that for the realistic hand conditions, a white male hand model was used. A previously conducted study by Peck et al. (2013) reported ethnicity-related changes in virtual body ownership. Moreover, Schwind et al. (2017) reported that female participants reacted in a more negative manner compared to male participants when interacting with male hand models. Therefore, we think that the ethnicity and gender of the participants could have an impact on our findings.

In terms of tactile sensation, both the mannequin hand and realistic hand received higher ratings than the abstract hand. This means that the abstract hand was associated with the lowest tactile sensation effect. Lougiakis et al. (2020) supports this claim in their study by indicating that in their task, controller and hand appearance were more effective than the abstract representation in terms of user performance and ownership. In our study, the mannequin and realistic hand animations looked more familiar to the participants, while the abstract hand did not really meet participants’ expectations. Longo, Mancini, and Haggard (2015) has mentioned that realistic hand appearance underlies tactile sensations because it allows better matching of tactile location and hand position. This statement also supports the reason why the participants’ ratings of the abstract hand were not impacted by the presence of tactile feedback in the present study. However, the tactile feedback was responsible for enhancing the tactile sensation of the participants when they were assigned a realistic hand model.

As for external appearance, the abstract hand was rated lower than the other two hand types. This result is reasonable because the abstract hand only featured the basic shape of a rectangular block. In addition, both the mannequin and realistic hands included finger animations of a grabbing movement, while the abstract hand’s shape simply bent and behaved like a 3D model with less detail and less precise movement compared to the other two hand models. Kokkinara and McDonnell (2015b, 2015a) found similar results when experimenting with the animation of virtual faces. Virtual faces were perceived as more appealing when higher levels of animation realism were provided. We think this was the main reason behind the participants perceiving the external appearance of the mannequin hand to be close to that of the realistic hand.

5.2. Tactile feedback

We found a significant effect of tactile feedback on the external appearance ratings of our participants (RQ2). Specifically, our finding proves that tactile feedback made our participants rate the external appearance of virtual hands higher. According to Hoffman (1998) and Hoffman et al. (1998) tactile augmentation enhances the realism of virtual environments and according to Haddadin, Johannsmeyer, and Ledezma (2018) touching a virtual object has an impact on participants’ perception of realism. The mentioned findings support our results.

Although Hillis et al. (2002) have mentioned in their earlier article that haptic and visual signals could be independently accessed in perceptual judgments, our study indicates that tactile feedback enhanced the tactile sensations when accompanied by the realistic hand compared to the other two hands. The significant interaction effect between hand appearance and tactile feedback on perceived tactile sensation suggests that when applying both factors, the rating of tactile sensation increases. Our finding goes along with Schwind et al. (2018), who found that tactile sensitivity was dependent on hand appearance and texture type, as also shown in our findings, indicating that hand appearance affected participants’ visual-haptic experience.

5.3. Study site

Our results also revealed a significant interaction effect between hand appearance and study site (RQ3). The in-lab participants rated the external appearance of the
realistic hand significantly higher than the remote participants. Although we do not have such evidence, presuming that attention is considered as an important factor in experimental studies (Carrasco, Ling, and Read 2004), we posit that a possible reason for this could be that the on-site participants were more focussed than the remote participants, resulting into taking the study more seriously and paying more attention to the hand appearances. Thus, we think that future remotely conducted studies need to consider screening participant’s attention.

Another possible reason for the effect of the study site on participants’ responses is that the on-site study was conducted in a more controlled environment. All the on-site participants completed the study at the lab where most external factors were controlled (e.g. similar environment, noise and temperature). Tiggemann and Boundy (2008) suggested that subtle factors can affect experimental studies. However, we were not able to control the experimental environment of the remote participants. We think that additional studies that explore environment-related factors should be conducted to more accurately understand such issues.

5.4. Virtual reality experience

Our results indicated that the prior VR experience of the participants could be considered as a factor that affected the participants’ ratings in terms of how they perceived the tactile feedback and appearance of the virtual hand models (RQ4). Specifically, in the presence of tactile feedback, the participants who were exposed for less than one hour per week with VR rated the perceived tactile sensation higher than the participants who were exposed for more than one hour in VR per week. Moreover, in the presence of a realistic hand model, participants who were exposed for less than one hour per week in VR rated the external appearance of the virtual hand model higher than the participants who spent more than one hour in VR per week. In a previous study by Mousas, Anastasiou, and Spantidi (2018), it was found that prior VR experience could affect the emotional reactivity of participants when interacting with virtual characters of different appearance, indicating that the VR experience of participants could potentially also contribute to understanding how participants perceive the appearance of a virtual hand model. We consider this a novel finding, since to the best of our knowledge, none of the previously conducted studies concerning the effects of virtual hand appearance (Ma and Hommel 2015; Argelaguet et al. 2016; Lin and Jörg 2016; Schwind et al. 2018; Lin et al. 2019; Lougiakis et al. 2020) have reported such findings. However, we argue that further experiments should be conducted to validate such findings.

5.5. Age groups

Another interesting finding revealed in our statistical analysis was that the age of participants could be a factor when affecting their perception of the tactile feedback (RQ5). In splitting our participants into two age groups (18–24 and 25–48 years old), the statistical analysis revealed that the younger participants rated the tactile sensation higher than the older participants in the presence of the realistic hand. Serino et al. (2018) found that older participants (aged 26–55 years-old) were more resistant to body changes induced by bodily illusions, while younger participants (ages 19–25 years-old) were more affected by such changes. Trautmann et al. (2017), who investigated the tactile sensation of participants by using cream products with small and large particles, found that the younger participants were more sensitive to the larger particles than the older participants, who did not sense any differences. Our results are in line with the aforementioned findings and revalidate that younger participants are more sensitive to tactile feedback than their older counterparts.

5.6. Limitations

There were a few study limitations that applied to both the on-site and remote experiment portions. We decided not to adjust the hand size for any of the hand models. Although this was a study limitation, we did so because we wanted to standardise the experiment, allowing all participants to experience the exact same hand sizes. Many on-site participants reported that the realistic and abstract hands were bigger than their own hands. Previously conducted research has found that different sizes of different virtual body parts can alter the participants’ perception of realism and appearance (Kilteni et al. 2012; Lin et al. 2019; Choudhary et al. 2020). Moreover, as mentioned the appearance of the realistic hand model that was used can be considered to be closer to that of a male adult hand. Unfortunately, we did not collect background information regarding the ethnicity of participants. We think that this information could have helped us further understand the potential effects of participants’ ethnicity on virtual hand appearance.

Another study limitation was the potential learning effects. While the conditions in this study varied, the assembly task was the same. By observing our in-lab participants, we realised that almost all participants spent more time in the first experimental condition to
which they were exposed compared to the rest five conditions. Although we did not capture the time that each participant spent in each condition, we think that this could have also impacted participants’ rating. In future studies, revisions regarding the assembly tasks could be made to avoid learning effects and ensure that all participants spend a similar amount of time in all experimental conditions. Furthermore, the design of the developed application could be improved. Some on-site participants provided feedback such as ‘I spent a lot of time figuring out where to put the objects’ or ‘I had some issues learning how to perform the assembly’. Based on these responses, it looks like the design of the levels needs to be more user-friendly so that the participants can be more focussed on the virtual hand model.

There were also some limitations in the remote study. It was an oversight of ours not to collect information on the study sites (e.g. office or home, size, external noise) in which the different participants were located. Moreover, we neglected to provide specific instructions to the participants as to how to engage in the experiment at their individual sites (e.g. controlling noise). Another limitation was related to the sample size. According to Casler, Bickel, and Hackett (2013), when conducting remote studies, a higher sample size is needed. However, in a three-month period during which our study was posted on the XRDRN, only 12 people decided to participate in this study, which was either due to the lack of compensation provided or because the XRDRN platform is not yet known across the research community.

The last limitation is related to the tactile feedback that was provided by the VR controller used in our study. Specifically, the Oculus controllers cannot provide rich contact and shape information when conducting assembly tasks. This is especially true when comparing fingertip and glove-based tactile feedback devices, which provide detailed tactile feedback, with hand-held controllers, which cannot provide as detailed tactile feedback to users. As Pacchierotti et al. (2017) mention, contact feedback is paramount toward body ownership and sensation of presence. Therefore, we think that lower levels of ownership might have been captured due to the low-quality tactile feedback that was used in our study.

5.7. Design considerations

We think that the knowledge obtained from this project should be documented by the authors to help the research community develop more efficient VR assembly applications that involve virtual hands and tactile feedback. Thus, we present in this section our reflections about designing virtual assembly tasks using virtual hands and tactile feedback.

Because hand appearances do affect ownership, external appearance, and tactile sensation, it is considered to be more appropriate to use either a mannequin or realistic style hand model. Hand and finger animation is also important. It is essential to have a realistic animation of finger and hand movement when grabbing different objects. Moreover, providing a tactile feedback (e.g. vibration feedback when grabbing objects) to users can also be an effective solution to enhancing the three dimensions of embodiment.

In terms of assembly applications, it is essential to provide indicators for the assembly tasks. In this study a few participants complained about the process being ‘frustrating’, ‘unclear’, or ‘time-consuming’, because the only guiding element was the semi-transparent target spots. Designs like an arrow indicator showing the corresponding slot for the part the participant is currently holding could be useful to decrease the amount of effort exerted toward finding the correct target. Moreover, other designs, like numbering the order of the parts and slots (e.g. part #1 needs to be assembled in slot #1) could also be effective for users.

6. Conclusions and future work

We developed a VR assembly application with different hand appearances and tactile feedback conditions to examine three embodiment dimensions (ownership, tactile sensation, and external appearance). As a result, the mannequin hand had a greater effect on ownership, and the realistic hand had a greater effect on tactile sensation and external appearance. We also found that the tactile feedback condition had a greater effect on external appearance than the no-tactile feedback condition, and the realistic hand appearance in conjunction with the tactile feedback had a significant effect on the perceived tactile sensation. Participants in the lab setting rated the external appearance of the realistic hand model higher than the remote participants. These results can be used as an essential design consideration for future virtual reality assembly-related virtual reality applications. Finally, participants with less VR experience rated higher the tactile sensation and the external appearance when exposed to the realistic hand model conditions.

In addition to the mentioned limitations, there are a few more directions that could be studied in the future, including different mannequin and realistic hand sizes, styles, genders, colours, and age. Future studies could investigate tactile feedback by manipulating patterns and intensity levels. Moreover, it is essential that the
XR research community explore more effective ways to both conduct remote studies and profile remote participants. It is assumed that by understanding the dynamics and profiles of participants, it could be possible to conduct highly effective remote studies. Despite our limited experience, we think remote research networks, such as the XRDNR, could be a key element in the era of COVID-19 pandemic; while we also think that there is a need for the research community to engage more in such platforms in order to help with the easy and rapid acquisition of the required data.

Notes
2. https://www.xrdrn.org/

Disclosure statement
No potential conflict of interest was reported by the authors.

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