HAL
open science

Object Touch by a Humanoid Robot Avatar Induces Haptic Sensation in the Real Hand

Laura Aymerich-Franch, Damien Petit, Gowrishankar Ganesh, Abderrahmane Kheddar

To cite this version:

Laura Aymerich-Franch, Damien Petit, Gowrishankar Ganesh, Abderrahmane Kheddar. Object Touch by a Humanoid Robot Avatar Induces Haptic Sensation in the Real Hand. Journal of Computer-Mediated Communication, 2017, 22 (4), pp.215-230. 10.1111/jcc4.12188 . lirmm-02155056

HAL Id: lirmm-02155056

https://hal-lirmm.ccsd.cnrs.fr/lirmm-02155056v1

Submitted on 13 Jun 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

JOURNAL OF COMPUTER-MEDIATED COMMUNICATION

Journal of Computer-Mediated Communication

Object Touch by a Humanoid Robot Avatar Induces Haptic Sensation in the Real Hand

Laura Aymerich-Franch
Damien Petit
Gowrishankar Ganesh
Abderrahmane Kheddar

Centre National de la Recherche Scientifiue (CNRS) - National Institute of Advanced Industrial Science and Technology (AIST) Joint Robotics Laboratory (JRL), 1-1-1 Umezono, 305-8560, Tsukuba, Japan

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

Humanoid robot embodiment is a recently developed form of mediated embodiment. In 2 studies, we report and quantify a new haptic (touch) illusion during embodiment of a humanoid robot. Around 60% of the users in our studies reported haptic sensations in their real hand when they observed their robot avatar touching a curtain with its hand. Critically, our study shows for the first time that users can experience haptic sensations from a nonanthropomorphic embodied limb/agent with visual feedback alone (i.e. no haptic feedback provided). The results have important implications for the understanding of the cognitive processes governing mediated embodiment and the design of avatar scenarios.

Keywords: humanoid robot embodiment, pseudohaptic feedback, virtual synesthesia, sense of embodiment, sense of touch, avatar.

doi:10.1111/jcc4.12188

It is generally assumed that the sensation of touch in mediated embodiment can only be elicited through haptic devices that artificially recreate this sensation. However, previous studies in virtual environments have shown that pseudo haptic sensations can also be induced in individuals by providing them with visual feedback of their avatars "touching" a virtual object in the presence of visuo-movement synchronization between their movements and those of the avatar. These illusory haptic sensations, that are explained by the so-called *pseudohaptic feedback model* (Lécuyer, 2009) include among others the illusions of stiffness (Lecuyer, Coquillart, Kheddar, Richard, & Coiffet, 2000; Paljic, Burkhardt, & Coquillart, 2004), texture (Lécuyer, Burkhardt, & Etienne, 2004), or mass (Dominjon, Lécuyer, Burkhardt, Richard, & Richir, 2005) of virtual objects. While the induction of these illusions do not require a haptic device, they do require some actual physical interaction, or touch. Most of the illusion experiments thus utilize a device such as a mouse, a Spaceball, or a joystick (Lécuyer et al., 2000, 2004; Dominjon et al., 2005; Paljic et al., 2004) to provide this interaction.

Editorial Record: First manuscript received on July 28, 2016. Revision received on January 18, 2017. Accepted by Matthew Lombard on May 4, 2017. Final manuscript received on May 11, 2017. First published online on July 10, 2017.

That said, few studies in virtual reality report that a visual image of an avatar limb touching and manipulating virtual objects can induce haptic sensations even in the absence of touch. In particular, Biocca and colleagues found that participants reported haptic sensations of physical resistance when a visual image of their hand manipulated a virtual spring in a virtual environment (Biocca, Kim, & Choi, 2001; Biocca, Inoue, Lee, Polinsky, & Tang, 2002). More recently, Brogni, Caldwell, and Slater (2011) described an experience of illusory touch in which some participants were able to experience sharpness when they touched sharp objects, but not when they touched smooth ones. Using Augmented Reality, Weir and colleagues (2013) reported an illusion in which some participants experienced a sensation of heating after seeing virtual flames overlaid on their hands. These findings have been suggested as a form of *virtual synesthesia*, which is characterized by a temporary experience of a sensation (either touch, smell, taste, or sound) that results from stimulating a different sense (most commonly vision) during immersion in a virtual environment (Rogowska, 2011). In a real environment, following the rubber hand illusion paradigm, striking the *embodied* fake (rubber) hand with a laser pointer beam (Durgin et al., 2007) or stroking it with a brush (Aymerich-Franch, Petit, Kheddar, & Ganesh, 2016) have been documented to produce tactile sensations in the participant's real hand. However, the visual feedback of the hand in all these studies was always anthropomorphic (i.e. human shape).

In this study, we investigated whether illusory noncontact haptic perception requires visual feedback of an anthropomorphic hand or limb. This question is critical for the development of embodiment and avatar studies with robots. An ability to induce haptic sensations during avatar scenarios is important for improved experience and improved control of the elements manipulated by the avatar, and the importance of corporality defines critical constraints in the design and choice of systems suitable for avatar scenarios. In this regard, it has been suggested that virtual synesthesia may contribute to increase the sense of presence in virtual reality (Biocca, et al., 2001) or be used to manipulate perception in order to compensate for missing components of the perceptual experience (Lederman & Jones, 2011). To investigate this issue, we used a setup developed by Aymerich-Franch and colleagues for whole-body humanoid robot embodiment (Aymerich-Franch, Petit, Ganesh, & Kheddar, 2015). Embodiment in robot avatars has emerged as a form of mediated embodiment (Aymerich-Franch, et al. 2015; Aymerich-Franch, Petit, Ganesh, & Kheddar, 2016; Becker-Asano, Arras, Nebel, & Ishiguro, 2012; Cohen et al., 2014; Kishore et al., 2014) that follows similar principles to those used in virtual reality to induce a sense of embodiment of the avatar body. In order to elicit a sense of embodiment to the robot body in the current study, we provided participants with a head-mounted display (HMD) that gave them first person visual feedback from the robot perspective. In addition, we provided head and arm movement synchronization between the participant and the robot (see the *System for humanoid robot embodiment* in our *Method* section).

While a resemblance of the shape of an artificial limb or body to a human body helps increase the sense of embodiment (Haans, IJsselsteijn, & de Kort, 2008), previous studies suggest that humans are also able to experience non-human looking avatar and robot bodies as their own (Ahn, et al., 2016; Aymerich-Franch, 2012; Aymerich-Franch et al., 2015, 2016, 2017; Steptoe, Steed, & Slater, 2013; Won, Bailenson, Lee, & Lanier, 2015). Thus, we hypothesized that an anthropomorphic limb is not essential for embodiment (Aymerich-Franch & Ganesh, 2016), and that a non-anthropomorphic limb can induce illusory haptic perceptions provided that a sense of embodiment is induced towards it. Our results support this hypothesis. In particular, we report an illusion in which participants experience a haptic sensation in their hands when they touch an object (a curtain) in the real environment through their embodied robot avatar. In addition to the standard questionnaires, we introduce a new illustrative measure to quantify the sensation the subjects feel. As far as we know, this is the first exhibition of haptic illusions with a avatar with non-anthropomorphic characteristics. In addition, this is the first

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

study to demonstrate that humans can feel illusory haptic sensations during touch in a real environment (i.e. not virtual) without any haptic stimulation (i.e. without the use of any contact device as in pseudohaptics).

Method

Participants

Twenty-two volunteers of different nationalities (13 females and 9 males), aged 21-37 (M = 28.27, SD = 5) took part in Experiment-1, while 14 volunteers of different nationalities (5 females and 9 males), aged 20-45 (M = 28.71, SD = 8.16) took part in Experiment-2. In both studies, one of the participants was left-handed and the rest were right-handed. Participants were recruited through a call for volunteers in a web page created ad-hoc for the experiments, which was allocated in a social network. The volunteers received 1500 JPY (Japanese yen) for their participation. Participants were naive to the purpose of the experiments. We used working in the robotics or the neuroscience fields as exclusion criteria. In addition, we pretested the experiments with five intern master students from our laboratory. All participants gave their written informed consent prior to participating. The study was conducted with ethical approval of the *National Institute of Advanced Industrial Science and Technology* (AIST) ethics committee.

System for humanoid robot embodiment

An HRP-2 humanoid robot unit was used as the robot avatar. Each arm of the robot had seven degrees of freedom. A RGB-D (red green blue - depth) camera (Asus XtionPRO live) was mounted on the robot's head, which sent monocular visual feedback to an Oculus Rift head-mounted display (HMD) that the user wore. Sensors integrated in the HMD allowed the tracking of the user's head motion in order to synchronize with the robot's head movement. A second RGB-D camera (similar to the previous one) was used externally to track the user's hand position. Open Natural Interface (OpenNI[1]), a vision-based framework to track body and hand motion, was used for this purpose. In our experiment, we only tracked the user's hand position (seven degrees of freedom). The hand tracker was initialized after detecting a waving motion of the user's hand. Once the hand was tracked, we asked participants to place their hand in a position which corresponded to the robot's hand position (see *Embodiment induction* section). Following that, the user hand motion was mapped on the robot hand (we trigger a tele-presence mode (Kheddar, 2001)). In order to control the robot arm and head together, we used the Stack-of-Task (SoT) controller (Mansard, Stasse, Evrard, & Kheddar, 2009), which took as input the hand position provided by OpenNI as well as the user's head orientation provided by the HMD. The SoT defines the tasks as state error vectors in the sensory space and projects them in the robot joint space through robot inverse kinematics computations. We used the Robot Operating System (ROS)[2], a flexible framework for writing robot software, to integrate the HMD, the robot's camera, the SoT and the human hand tracking.

Embodiment induction

After reading and signing the consent form, we instructed participants to stand in front of the hand-tracking RGB-D camera. They were located at a distance of 4 meters (approx. 13 feet) from the humanoid robot, opposite from it. In order to create the feeling of embodiment, participants wore the HMD, which displayed real-time video feedback from the camera located at the forefront of the robot's head, right above its eyes. The HMD tracked participants' head movement and synchronized it to the robot's head movement. In the synchronous condition, in which the participant

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

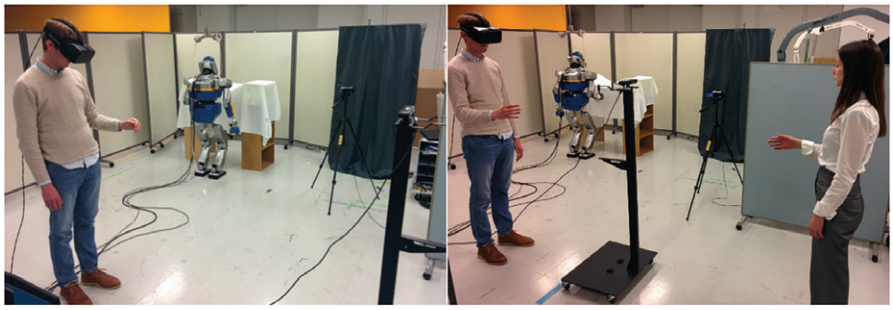

Figure 1 Setup for the synchronous (left) and asynchronous (right) conditions. The participant wears an HMD which displays visual feedback from the robot field-of-view. The participant's arm movement is tracked using the RGB-D camera (Asus XtionPRO live) and synchronized to the robot's arm movement in the synchronous condition. In the asynchronous condition, the RGB-D camera tracking the movement is turned toward the experimenter so that s/he can perform the control in place of the user.

controlled the humanoid arm movements, the camera faced the participant so that the participants' arm movement could be tracked and synchronized with the robot's arm movement (Figure 1, left). The first experiment also included an asynchronous condition, where the camera facing the participant was flipped and faced one of the researchers, who performed the control instead (Figure 1, right). Since the participants wore the HMD during the trials, they were unable to see that the researcher was performing the control of the arm, as their vision coincided with that of the robot, and both the participant and the researcher were out of its field of view. In both conditions, participants were instructed to place their arm (either left or right arm, in Experiment-1, and left arm in Experiment-2) creating a 90° angle between the arm and the forearm, with the elbow next to the hip, and the hand opened. They then looked to the front and waved the arm so the camera could track their movement (they were instructed to do the same in the asynchronous condition, even though the camera was not facing them). Following this, participants looked at the robot's arm and moved it by performing up and down and left and right movements for 30 seconds with their real arm. They were told not to perform sudden movements or drop the real arm during the task. To verify that the embodiment induction process worked, participants responded to the embodiment questionnaire (see *Measures* section).

Object exploration

After the embodiment induction procedure, the participants were required to look at a white curtain in front of them (Figure 2) and touch it with the robot arm for 2 minutes. The participants were instructed to use only up-and-down, and left-and-right movements but were free to choose when and which movement they made during the 2-minute period. For the asynchronous condition in Experiment-1, participants were also told to do the same (but this time the experimenter controlled the movements).

Measures

We measured the sense of embodiment and the haptic sensation with a questionnaire. In addition, we developed a hand painting measure to further assess the haptic illusory sensation.

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

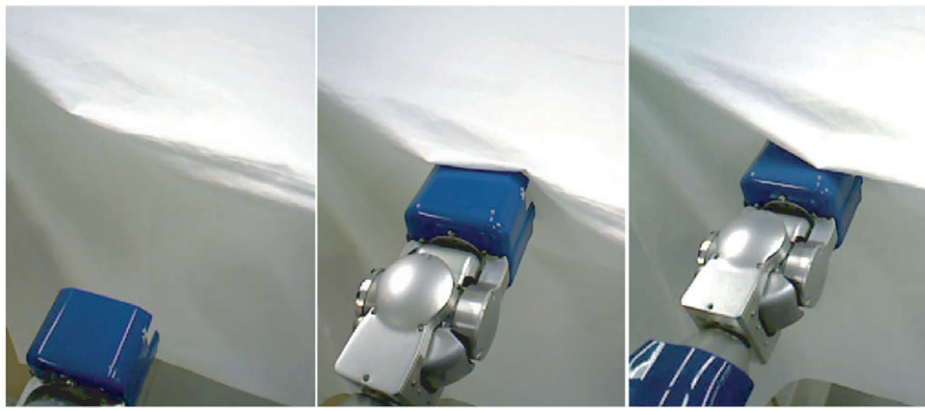

Figure 2 Participant's field-of-view during the experiment: The participant was able to see the robot's arm touching the curtain through the HMD, which provides visual feedback from the robot's embedded RGB-D camera.

Embodiment questionnaire

For Experiment-1, we adapted the embodiment questionnaire from Longo et al. (2008) to measure the sense of embodiment to the robot's arm. The questionnaire consisted of 12 items that participants rated on a 7-point scale that ranged from (1) *not at all* to (7) *very strongly*. The scale consisted of four subdimensions:

sense of body ownership (five items), sense of self-location (two items), sense of agency (three items), and sense of touch (two items). We added the last item (sense of touch) given its relevance for the experiment. The reliability was $\alpha = .83$ for the synchronous condition and $\alpha = .89$ for the asynchronous condition.

For Experiment-2, we developed a short-form embodiment questionnaire following previous studies (Aymerich-Franch et al., 2015; Longo et al., 2008) and Experiment-1, to measure the sense of embodiment of the robot's arm. We designed the questionnaire so that participants could complete it verbally during the experience. The questionnaire consisted of four items that participants rated on a 7-point scale ranging from (1) *not at all* to (7) *very strongly*. As in Experiment-1, each item evaluated a different subdimension of embodiment (i.e. sense of body ownership, sense of self-location, sense of agency; Kilteni, Groten, & Slater, 2012). Moreover, as in the previous experiment, we added an item to examine sense of touch. Reliability was $\alpha = .83$. Appendix A presents the complete list of items for both questionnaires.

Haptic sensation

Based on preliminary findings, which indicated that subjects reported the sensation of "missing touch" of the curtain as tickling, we assessed the haptic sensation by asking participants to rate whether they experienced real tickling on the fingers that were virtually touching the curtain on a 7-point scale which ranged from (1) *not at all* to (7) *very strongly*.

Hand painting measure

Participants also painted the location in which they experienced the tickling on a paper that graphically represented both sides of a human left hand. They were given three colors — red, orange, and yellow — to

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

indicate whether the feeling was strong, medium, or mild, respectively. The areas in which they did not experience any sensation were left blank. Also, if they did not experience any sensation at all they left the figure blank. To obtain the final plot (see Figure 6), average mean by areas was calculated from each individual pictorial representation among the participants that experienced the haptic sensation in Experiment-2. We assigned coloring in the individual representation the following number by area: 0 for white, 1 for yellow, 2 for orange, and 3 for red. We obtained the average for each area from the resulting values. In the final plot, white areas represent zones of no sensation reported (overall mean < 0.1), yellow areas represent a mild sensation (overall mean range between 0.1 and 0.4), orange areas represent a medium sensation (overall mean range between 0.5 and 0.7), and red areas represent a strong sensation (overall mean ≥ 0.8).

Demographic measures

Participants completed information about age and gender, and about being left- or right-handed.

Manipulation check

We asked participants in each condition whether the robot arm was synchronized to their movements or not. All participants passed the manipulation check question for all conditions.

Experiment-1

Experiment-1 was designed to analyze the role of embodiment in inducing the haptic sensation in the human users when touch was actually performed by the humanoid robot. Following previous studies (Gonzalez-Franco, Perez-Marcos, Spanlang, & Slater, 2010; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010), we included a control condition in which the participant's arm movements were not synchronized to the movement of the robot arm (asynchronous condition) but it still touched the curtain. We expected that the lack of synchrony between the two arms would significantly reduce the embodiment to it, and subsequently affect the touch perception. In other words, this experiment confirmed that the visual feedback of the robot arm alone is not enough to induce the haptic illusion, and that embodiment is essential for it.

We carried out a within-subject experimental design with 14 subjects who experienced two conditions, repeated once for each arm:

- synchronous: the movements of the robot arm were synchronized to those of the participant
- asynchronous: the movements of the robot arm were not synchronized to those of the participant and were controlled by the experimenter instead

Thus in total, the participants experienced four trials/conditions:

$$(\text{synchronous, asynchronous}) \times (\text{left arm, right arm})$$

After finishing each condition, the HMD was removed. Participants completed a PC-based questionnaire on sense of embodiment and haptic feedback (see *Measures* section). After that, they carried out the next condition following the same procedure until completing the four conditions. Half of the participants started with the left arm and the other half started with the right arm. They experienced both conditions (synchronous and asynchronous) before switching to the other arm. The controlled robot hand (i.e. either left or right) always corresponded to the hand they used to control it. We randomized the order for starting with one or the other arm and for experiencing either

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

Table 1 Mean (SD) for embodiment, its subcomponents, and haptic sensation, for synchronous and asynchronous conditions for Experiment-1

n = 22	Synchronous	Asynchronous
Embodiment	4.81(.99)	2.31(.94)
Ownership	4.41(1.23)	2.23(1.23)
Self-location	4.59(1.52)	3.06(1.73)
Agency	5.98(.85)	2.02(1.21)
Touch	4.24(1.75)	2.22(1.3)
Haptic sensation	2.52(1.66)	1.57(.92)

synchronous or asynchronous condition first, for each arm. At the end, they answered demographic questions and were also given the possibility to add any comments they might have and were paid for their participation. The haptic sensation was only assessed by questionnaire in the first round of participants. To further understand the nature of the subject experience and reinforce our results, we then developed the new hand painting measure (see *Measures* section). We ran eight additional participants who, in addition to the procedure mentioned above, completed the hand painting measure after completing each condition. Given that there were no significant differences between left and right arm in the previous participants, these participants completed the two experimental conditions only with the left arm, for being the arm used in the original rubber hand illusion experiment (Botvinick & Cohen, 1998).

Results

Table 1 shows mean and SD for embodiment and each subcomponent, as well as for the haptic sensation, for each experimental condition. No significant differences were found for left (M = 5.14, SD = .87) and right (M = 5.14, SD = 1) arms in the synchronous condition ($F(1, 13) = .00$, $p = .979$, $\eta p^2 = .00$) or for left (M = 2.35, SD = 1.08) and right (M = 2.59, SD = 1.38) arms in the asynchronous condition ($F(1, 13) = .43$, $p = .525$, $\eta p^2 = .03$) for embodiment in the first round of participants. Thus, we were able to average both trials in each experimental condition and considered the additional participants together with the earlier ones in a single sample, with two experimental conditions: synchronous and asynchronous.

Participants reported a significantly higher sense of embodiment of the robot arm in the synchronous condition than in the asynchronous condition ($F(1, 21) = 217.13$, $p < .001$, $\eta p^2 = .91$), which validated the experimental design. To examine the different levels of haptic sensation experienced in each condition, we ran a paired-sample T-test. Participants reported a significantly higher haptic sensation in their fingers and hand (expressed as tickling) in the synchronous condition, compared to the asynchronous condition ($F(1, 21) = 12.22$, $p = .002$, $\eta p^2 = .37$). Of the total sample, 59.1% of the participants experienced haptic sensation (>1) at least in one of the conditions in which they controlled the robot's arm (synchronous condition). Of the participants that reported the sensation, 46% reported a *medium* to *very strong* haptic sensation (≥4). Figure 3 represents the haptic sensation experienced by participant through Experiment-1. The additional participants that reported haptic sensation, consistently reported this feeling both in the questionnaire and in the hand painting. Figure 4 shows the pictorial representations drawn by the additional participants that experienced the haptic sensation.

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

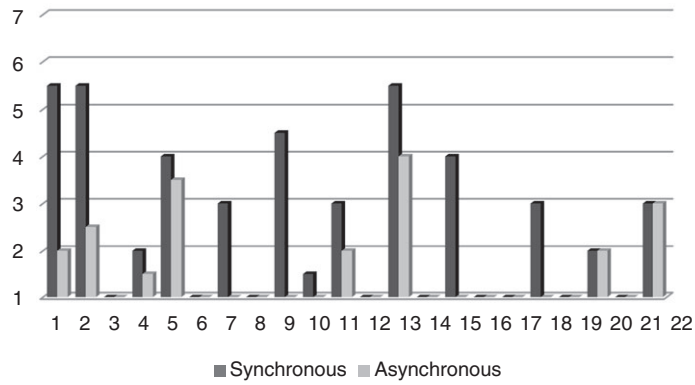

Figure 3 Haptic sensation by participant in the synchronous and asynchronous condition (average) in Experiment-1.

Experiment-2

Experiment-2 aimed to use our new hand painting measure to investigate the spatial characteristics and intensity of the illusory haptic perception experienced by the subjects. This experiment used a similar design and procedure as Experiment-1 but used only the synchronous condition.

Since we found no differences in intensity of the illusion between left and right hand in the previous experiment, participants completed the experiment only with the left arm (i.e. for being the arm used in the original rubber-hand illusion experiment; Botvinick & Cohen, 1998) and repeated it twice. In the first trial, after 2 minutes of performing curtain touch (see *Object exploration* section), and while they were still doing this task and wearing the HMD, participants verbally responded to the short form of the embodiment questionnaire and the haptic feedback question (see *Measures* section). Following this, the HMD was removed and participants completed the hand painting measure.

Subsequently, the subjects repeated the same procedure for a second time. At the end, they answered demographic questions and also had the opportunity to add any comments they might have and were paid for their participation.

Results

Table 2 shows mean and SD for embodiment (average of the two trials). A frequency analysis showed that, of 14 participants, eight (~57% of the sample) experienced haptic sensation (reported as tickling) in at least one of the trials. Figure 5 contains all the pictorial representations of the participants that experienced the haptic sensation. Of the participants who reported the sensation, 62.5% reported a *medium* to *very strong* haptic sensation (≥4) at least in one of the trials. Figure 6 shows a pictorial display of the localization of the feeling by intensity, as an average across the participants that experienced the haptic sensation. The sensation was localized on both sides of the fingers and hand. Participants reported the strongest sensation on the area of the knuckles and the middle area of the index finger on the back-of-hand side, followed by the superior area of the palm; the middle area of the pinky, ring, and middle finger on the back-of-hand side; the superior area of the index finger also on the back-of-hand side; and the superior area of the pinky finger on the palm side. Participants experienced a mild sensation in the superior area of ring and middle fingers on the back-of-hand side and inferior area of the back of the hand as well as in all fingers on the palm side and the inferior right area of the palm.

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

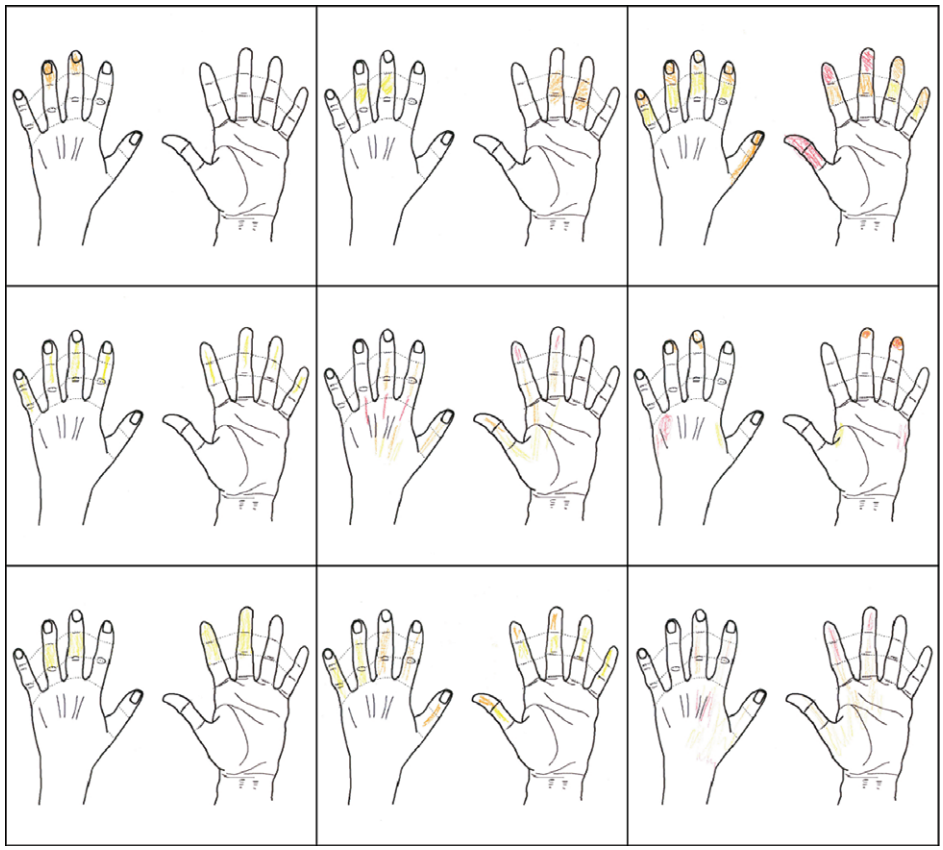

Figure 4 Graphical representation of the haptic feedback drawn by the participants for the synchronous condition (top six figures) of Experiment-1. Some participants also reported haptic feedback in the asynchronous condition (bottom three figures).

Discussion

In our studies, participants embodied in a humanoid robot experienced a haptic illusion, which they reported as perceiving tickling in their fingers and hands when they saw the robot arm touching a curtain. The haptic sensation was reported even though the setup did not include any haptic or pseudohaptic feedback device of any form. The results support embodiment as a modus to enable people to experience haptic sensation resulting from the stimulation of another sensory channel, specifically vision, resulting in a sort of "virtual synesthesia" (Biocca et al., 2001, 2002; Rogowska, 2011). Our results also support findings in neuroscience which suggest that manipulating tactile and visual information can induce referred sensations (Schaefer, Noennig, Heinze, & Rotte, 2006, see also relevant work of Klatzky & Lederman, 2011 on the spatial dimensionality and object property perception in touch and vision).

In both our experiments, around 60% of the subjects experienced the haptic sensation when they touched the curtain through the robot arm. This percentage is similar to that obtained in related experiments with illusions. In particular, Ehrsson (2012) has highlighted that around 30% of the population does not experience the well-known rubber hand illusion. In our case, of the ones who experienced the

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

Table 2 Mean (SD) for embodiment, its subcomponents, and haptic sensation, for Experiment-2 (average of the two trials)

n = 14	Synchronous
Embodiment	4.81(1.03)
Ownership	5.04(1.24)
Self-location	4.65(1.61)
Agency	5.85(.96)
Touch	3.69(1.56)
Haptic sensation	1.93(1.17)

illusion, half of the participants in the first experiment and almost two-thirds in the second experiment rated it at least 4 on a 7-point scale. The hand map that represents the location and intensity of the feeling in the second experiment shows that the strongest sensation on average, was located on and around the knuckles. The humanoid robot used in the experiment did not have fingers (see Fig. 2). Thus, the hand map might indicate that participants identified the end of the robot hand with the area corresponding to the knuckles in a clenched fist. In support of this suggestion, we observed that some participants tended to curl their hands as the experiment proceeded, even though the initial instructions were to keep the hand relaxed and slightly opened.

It is important to remark that we explicitly asked our participants to report tickling only if they experienced a real feeling of tickling, and not *as if* they felt tickled. We specifically point out this issue because, generally, experiments in body ownership -such as the rubber hand illusion experiments (Botvinick & Cohen, 1998)– or experiments on *Presence* in virtual reality –i.e. the feeling of really "being there," in the virtual environment (Lombard & Ditton, 1997) – normally assess these aspects using *as if* type questions (e.g. I felt *as if* the rubber hand was my hand (Botvinick & Cohen, 1998)), which we also followed to develop our embodiment questionnaire.

Our results demonstrate that nonanthropomorphic humanoid robots, when embodied, are able to induce haptic sensations in real environments. This result agrees with a recent proposal that the functional characteristics of a limb are more important than the physical features for embodiment (Aymerich-Franch & Ganesh, 2016). The finding is also in line with previous studies that suggest that humans are able to embody avatar bodies that depart from the humanoid form (Ahn et al., 2016; Aymerich-Franch, 2012; Aymerich-Franch et al., 2015, 2016, 2017; Kilteni, Normand, Sanchez-Vives, & Slater, 2012; Steptoe, et al., 2013; Won, et al., 2015).

There are several limitations in the current study to be addressed in future work. First, behavioral and physiological measures need to be included in future research. Follow-up studies need to look at whether and how the strength of the illusion is affected by behavioral features, such as the type of movement that users make during the experiment. Also, further work is needed to examine whether the sensation of touch differs with the textures and materials of the touched object. The interaction of motion and morphology is another issue that needs to be checked in regard to virtual synesthesia perception. Specifically, we need to examine how the illusion changes with a nonanthropomorphic robot arm controlled by visuo-movement synchronization, compared to a less active, but human-looking robot arm.

In the second experiment, some participants reported that the curtain was not clearly visible (i.e. slightly blurry) and they could not see it properly through the visor. We speculate that this limitation was due to the fact that we positioned the robot closer to the curtain compared to the previous experiment. Thus, while embodiment was equally high in both experiments, the touch illusion might have been

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

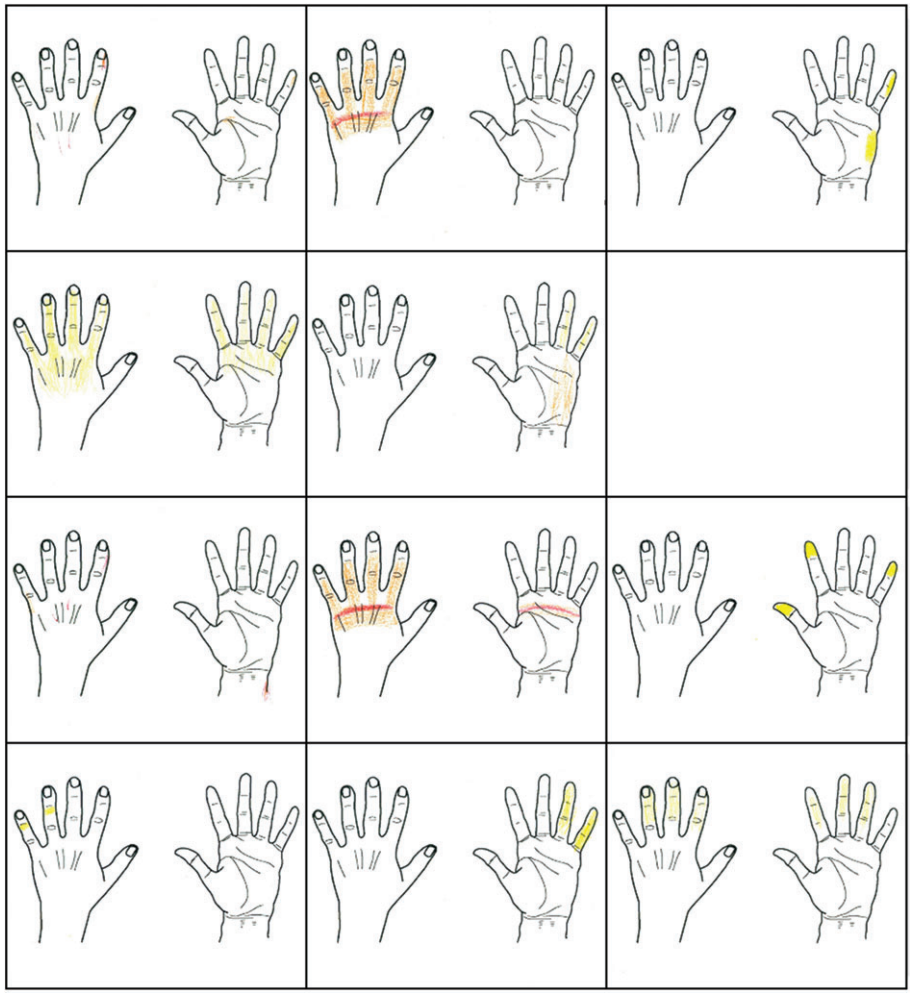

Figure 5 Graphical representation of the haptic feedback drawn by the subjects in trial 1 (top five figures) and trial 2 (bottom six figures) of Experiment-2.

reduced due to this limitation in our set-up. The quality of the visual feedback, the lack of stereo vision, and the related delays are factors that can be still optimized to possibly further improve the illusion.

The possibility to induce haptic sensations by using humanoid robots promises remote (haptic) sensor-less haptic feedback. Recent studies have shown that tactile feedback is important not just as a sensory modality but also in motor coordination and specifically effort perception (Ganesh, Osu, & Naito, 2013). Our findings thus have important implications in regard to user experience and task control in virtual reality systems and thought-based teleoperated robots (Petit, Gergondet, Cherubini, & Kheddar, 2015). We believe that contactless pseudohaptic feedback stemming from the stimulation of other sensory modalities might be an important alternative to the limited haptic displays currently available in these systems. It also highlights the importance of haptics in embodiment science. While there have been significant advances in haptic technology in the last years, the implementation of this sensory modality

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

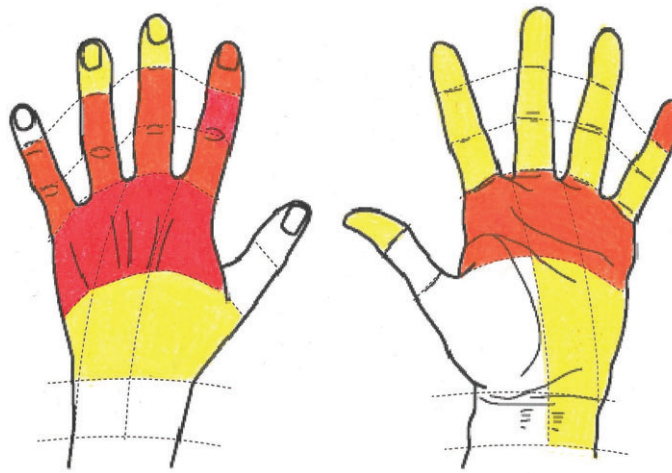

Figure 6 Pictorial report of the haptic sensation by subjects in Experiment-2 (average): White areas represent no sensation ($M < 0.1$), yellow areas represent a mild sensation ($M = 0.1$ to 0.4), orange areas represent a medium sensation ($M = 0.5$ to 0.7), and red areas represent a strong sensation ($M \geq 0.8$).

is still the least developed in embodiment systems (Slater, 2014). While there exist devices which give haptic feedback for specific situations, providing generalized haptics in avatar embodiment might be a highly complex solution (Slater, 2014). Touch illusions might constitute an important alternative to solve this problem.

Finally, how the changing representation of the body in mediated embodiment modifies the self is a highly relevant issue for computer-mediated communication (Biocca, 1997). An important number of works have demonstrated that the visual characteristics of virtual avatars with human appearance are able to influence attitudes and behavior (Aymerich-Franch, Kizilcec, & Bailenson, 2014; Groom, Bailenson, & Nass, 2009; Hershfield, et al., 2011; Peck, Seinfeld, Aglioti, & Slater, 2013; Rosenberg, Baughman, & Bailenson, 2013; Yee & Bailenson, 2007). The potential transformations at the cognitive and behavioral level resulting from embodying nonanthropomorphic robot avatars is therefore an important issue that requires further examination.

Acknowledgments

LA is supported by the EU Research Funding, 7th Framework Programme (FP7) with the EU Marie Skłodowska-Curie actions, project HumRobCooperation under grant agreement No PIOF-CT-622764. AK and DP were partially supported from the EU FP7 Integrated Project VERE No. 257695 and GG was partially supported by the Kakenhi 'houga' grant 15616710 from the Japan Society for the Promotion of Science (JSPS). We especially thank Prof. Mel Slater for his feedback and Dr. Eiichi Yoshida for his support in the ethical procedures.

Notes

1 https://github.com/occipital/openni2
2 http://www.ros.org

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

References

Ahn, S. J., Bostick, J., Ogle, E., Nowak, K., McGillicuddy, K., & Bailenson, J. N. (2016). Experiencing nature: Embodying animals in immersive virtual environments increases inclusion of nature in self and involvement with nature. *Journal of Computer-Mediated Communication,* 21(6), 399–419.

Aymerich-Franch, L. (2012). Can we identify with a block? Identification with non-anthropomorphic avatars in virtual reality games. *Proceedings of the International Society for Presence Research Annual Conference.* October 24–26, Philadelphia, Pennsylvania, USA.

Aymerich-Franch, L., & Ganesh, G. (2016). The role of functionality in the body model for self-attribution. *Neuroscience research,* 104, 31–37. https://doi.org/10.1016/j.neures.2015.11.001

Aymerich-Franch, L., Kizilcec, R. F., & Bailenson, J. N. (2014). The relationship between virtual self similarity and social anxiety. *Frontiers in Human Neuroscience,* 8*(November)*, 1–10.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2015). Embodiment of a humanoid robot is preserved during partial and delayed control. *Proceedings of the IEEE International Workshop on Advanced Robotics and its Social Impacts (ARSO 2015)*. July, 1–3, Lyon, France.

Aymerich-Franch, L., Petit, D., Kheddar, A., & Ganesh, G. (2016). Forward modeling the rubber hand: illusion of ownership modifies motor-sensory predictions by the brain. *Royal Society Open Science*.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2016). The second me: Seeing the real body during humanoid robot embodiment produces an illusion of bi-location. *Consciousness and Cognition,* 46, 99–109.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2017). Non-human looking robot arms induce illusion of embodiment. *International Journal of Social Robotics*, 1–12. https://doi.org/10.1007/s12369-017-0397-8

Becker-Asano, C., Arras, K., Nebel, B., & Ishiguro, H. (2012). The effect of anthropomorphism on social tele-embodiment. *IROS 2012 Workshop on Human-Agent Interaction.*

Biocca, F. (1997). The cyborg's dilemma: Progressive embodiment in virtual environments. *Journal of Computer-Mediated Communication,* 3(2).

Biocca, F., Inoue, Y., Lee, A., Polinsky, H., & Tang, A. (2002). Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence. *Proceedings of Presence*, 410–428.

Biocca, F., Kim, J., & Choi, Y. (2001). Visual touch in virtual environments: An exploratory study of presence, multimodal interfaces, and cross-modal sensory illusions. *Presence,* 10(3), 247–265. https://doi.org/10.1162/105474601300343595

Botvinick, M., & Cohen, J. (1998). Rubber hands "feel" touch that eyes see. *Nature,* 391(6669), 756. https://doi.org/10.1038/35784

Brogni, A., Caldwell, D. G., & Slater, M. (2011). Touching sharp virtual objects produces a haptic illusion. *Lecture Notes in Computer Science* (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6773 LNCS(PART 1), 234–242. https://doi.org/10.1007/978-3-642-22021-0_26

Cohen, O., Druon, S., Lengagne, S., Mendelsohn, A., Malach, R., Kheddar, A., & Friedman, D. (2014). fMRI-based robotic embodiment: Controlling a humanoid robot by thought using real-time fMRI. *Presence: Teleoperators and Virtual Environments,* 23(3), 229–241. https://doi.org/10.1162/PRES_a_00191

Dominjon, L., Lécuyer, A., Burkhardt, J. M., Richard, P., & Richir, S. (2005). Influence of control/display ratio on perception of mass of manipulated objects in virtual environments. *Proceedings of the IEEE International Conference on Virtual Reality.*

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

Durgin, F. H., Evans, L., Dunphy, N., Klostermann, S., & Simmons, K. (2007). Rubber hands feel the touch of light. *Psychological Science,* 18(2), 152–157. https://doi.org/10.1111/j.1467-9280.2007.01865.x

Ehrsson, H. H. (2012). The concept of body ownership and its relation to multisensory integration. In B.E. Stein (Ed.), *The new handbook of multisensory processes* (pp. 775–792. Cambridge, MA: MIT Press.

Ganesh, G., Osu, R., & Naito, E. (2013). Feeling the force: Returning haptic signals influence effort inference during motor coordination. *Scientific reports,* 3.

González-Franco, M., Pérez-Marcos, D., Spanlang, B., & Slater, M. (2010, March). The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. *Virtual Reality Conference (VR), 2010 IEEE* (pp. 111–114). IEEE.

Groom, V., Bailenson, J. N., & Nass, C. (2009). The influence of racial embodiment on racial bias in immersive virtual environments. *Social Influence,* 4(3), 231–248.

Haans, A., IJsselsteijn, W. A., & de Kort, Y. A. (2008). The effect of similarities in skin texture and hand shape on perceived ownership of a fake limb. *Body Image,* 5(4), 389–394.

Hershfield, H. E., Goldstein, D. G., Sharpe, W. F., Fox, J., Yeykelis, L., Carstensen, L. L., & Bailenson, J. N. (2011). Increasing saving behavior through age-progressed renderings of the future self. *Journal of Marketing Research,* 48(SPL), S23–S37.

Kheddar A. (2001), Teleoperation based on the hidden robot concept, *IEEE Transactions on Systems Man and Cybernetics,* Part A, 31(1), 1–13.

Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments,* 21(4), 373–387. https://doi.org/10.1162/PRES_a_00124

Kilteni, K., Normand, J. M., Sanchez-Vives, M. V., & Slater, M. (2012). Extending body space in immersive virtual reality: a very long arm illusion. *PloS ONE*, 7(7), e40867.

Kishore, S., González-Franco, M., Hintemüller, C., Kapeller, C., Guger, C., Slater, M., & Blom, K. J. (2014). Comparison of ssvep bci and eye tracking for controlling a humanoid robot in a social environment. *Presence: Teleoperators and Virtual Environments,* 23(3), 242–252. https://doi.org/10.1162/PRES_a_00192

Klatzky, R. L., & Lederman, S. J. (2011). Haptic object perception: spatial dimensionality and relation to vision. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 366(1581), 3097–3105. https://doi.org/10.1098/rstb.2011.0153

Lécuyer, A. (2009). Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback. *Presence: Teleoperators and Virtual Environments,* 18(1), 39–53. https://doi.org/10.1162/pres.18.1.39

Lécuyer, A., Burkhardt, J.-M., & Etienne, L. (2004). Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '04,* 6(1), 239–246. https://doi.org/10.1145/985692.985723

Lecuyer, A., Coquillart, S., Kheddar, A., Richard, P., & Coiffet, P. (2000). Pseudo-haptic feedback: can isometric input devices simulate forcefeedback? *Proceedings IEEE Virtual Reality 2000* (Cat. No.00CB37048). https://doi.org/10.1109/VR.2000.840369

Lederman, S. J., & Jones, L. A. (2011). Tactile and haptic illusions. *IEEE Transactions on Haptics,* 4(4), 273–294.

Lombard, M., & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication,* 3(2), 20. https://doi.org/10.1111/j.1083-6101.1997.tb00072.x

Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition,* 107(3), 978–98. https://doi.org/10.1016/j.cognition.2007.12.004

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

Mansard, N., Stasse, O., Evrard, P., & Kheddar, A. (2009, 22-26 June). *A versatile generalized inverted kinematics implementation for collaborative working humanoid robots: The Stack of Tasks.* Paper presented at the International Conference in Advanced Robotics (ICAR), Munich, Germany.

Paljic, A., Burkhardt, J. M., & Coquillart, S. (2004). Evaluation of pseudo-haptic feedback for simulating torque: A comparison between isometric and elastic input devices. *Proceedings - 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS* (pp. 216–223). https://doi.org/10.1109/HAPTIC.2004.1287199

Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and cognition,* 22(3), 779–787.

Petit, P., Gergondet, P., Cherubini, A., & Kheddar, A. (2015). An integrated framework for humanoid embodiment with a BCI. *IEEE International Conference on Robotics and Automation (ICRA)*, May 26-30, 2015, Seattle, Washington.

Rogowska, A. (2011). Categorization of synaesthesia. *Review of General Psychology,* 15(3), 213.

Rosenberg, R. S., Baughman, S. L., & Bailenson, J. N. (2013). Virtual superheroes: Using superpowers in virtual reality to encourage prosocial behavior. *PLoS ONE,* 8(1), 1–9.

Sanchez-Vives, M. V., Spanlang, B., Frisoli, A., Bergamasco, M., & Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. *PloS ONE,* 5(4), e10381. https://doi.org/10.1371/journal.pone.0010381

Schaefer, M., Noennig, N., Heinze, H. J., & Rotte, M. (2006). Fooling your feelings: Artificially induced referred sensations are linked to a modulation of the primary somatosensory cortex. *NeuroImage,* 29(1), 67–73. https://doi.org/10.1016/j.neuroimage.2005.07.001

Slater, M. (2014). Grand challenges in virtual environments. *Frontiers in Robotics and AI,* 1, 3.

Steptoe, W., Steed, A., & Slater, M. (2013). Human tails: Ownership and control of extended humanoid avatars. *IEEE Transactions on Visualization and Computer Graphics,* 19(4), 583–90.

Weir, P., Sandor, C., Swoboda, M., Nguyen, T., Eck, U., Reitmayr, G., & Day, A. (2013). Burnar: Involuntary heat sensations in augmented reality. *IEEE Virtual Reality*, 43–46.

Won, A.S., Bailenson, J.N., Lee, J.D., Lanier, J. (2015). Homuncular flexibility in virtual reality. *Journal of Computer-Mediated Communication,* 20, 241–259.

Yee, N. & Bailenson, J.N. (2007). The proteus effect: Self transformations in virtual reality. *Human Communication Research,* 33 (3), 271–290.

About the Authors

Laura Aymerich-Franch is currently a Marie Curie IOF fellow at *The Experimental Virtual Environments (EVENT) Lab for Neuroscience and Technology* at the University of Barcelona. She studies the behavioral consequences of virtual and robot embodiment on humans. Address: Departament de Personalitat, Avaluació i Tractaments Psicològics, Facultat de Psicologia, Campus de Mundet, Universitat de Barcelona, Passeig de la Vall d'Hebron 171, 08035 Barcelona, Spain. E-mail: laura.aymerich@gmail.com

Damien Petit has a Ph.D. in Robotics from the University of Montpellier. His research interests include humanoid robotics, robotic embodiment, robot-human interactions and thought-based control of humanoids. Address: CNRS-AIST JRL, 1-1-1 Umezono, 305-8560, Tsukuba, Japan. E-mail: damien.gerard.petit@gmail.com

Ganesh Gowrishankar is a CR1 Researcher at the *Centre National de la Recherche Scientifique* (CNRS) and is currently located at the CNRS-AIST Joint Robotics Laboratory (JRL) in Japan. His research

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019

interests include human sensori-motor control and learning, robot control, social neuroscience and robot-human interactions. Address: CNRS-AIST JRL, 1-1-1 Umezono, 305-8560, Tsukuba, Japan. E-mail: gans_gs@hotmail.com

Abderrahmane Kheddar is *Directeur de Recherche* at CNRS in France and the Director of the CNRS-AIST Joint Robotic Laboratory (JRL) in Japan. He is also leading the Interactive Digital Humans (IDH) team at CNRS-University of Montpellier LIRMM, France. His research interests include haptics, humanoids and thought-based control using brain machine interfaces. Address: CNRS-AIST JRL, 1-1-1 Umezono, 305-8560, Tsukuba, Japan. E-mail: kheddar@lirmm.fr

Appendix

Embodiment questionnaire Experiment-1

It seemed like … (1- *not at all*, 7- *very much*)

1. I was looking directly at my own arm, rather than at a robot's arm (O)
2. The robot's arm began to resemble my real arm (O)
3. The robot's arm belonged to me (O)
4. The robot's arm was my arm (O)
5. The robot's arm was part of my body (O)
6. My arm was in the location where the robot's arm was (L)
7. The robot's arm was in the location where my arm was (L)
8. I moved the robot's arm (A)
9. I was in control of the robot's arm (A)
10. I was responsible for the actions of the robot's arm (A)
11. I could really touch the white sheet (T)
12. I could feel the touch of the white sheet (T)

Embodiment questionnaire Experiment-2

I feel as if … (1- *not at all*, 7- *very much*)

1. The robot arm belonged to me (O)
2. The robot arm was in the location of my real arm (L)
3. I was responsible for the actions of the robot arm (A)
4. I could really touch the curtain (T)

where "O" are ownership items; "L" are self-location items; "A" are agency items; and "T" are touch items.

Downloaded from https://academic.oup.com/jcmc/article-abstract/22/4/215/4666428 by guest on 13 June 2019