Social attitude towards a robot is promoted by motor-induced embodiment independently of spatial perspective

David Farizon, Peter Ford Dominey, Jocelyne Ventre-Dominey

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Abstract— **Humans can enter into social relations with robots through different spatial perspectives. In the telepresence perspective, the human sees through the eyes of the robot. In the face-to-face perspective the human faces the robot and interacts in a self-other relation. During robotic telepresence, we have shown that embodiment into robots can be promoted by reciprocal and synchronous stimuli in the form of intentional movements or passive tactile stimulations. Here we investigate the impact of different spatial perspectives coupled to these sensory-motor manipulations on human subjects' social perception of robots. Through a series of experiments, we demonstrate that independent of the telepresence vs. face-to-face self-perspective, the sense of agency as induced by synchronous human-robot movements is crucial for generating positive changes of robot acceptability. We suggest that motor intentionality most clearly influences our social perception of robots.**

I. INTRODUCTION

As the presence of robots in real-life situations with humans increases, it is important for robots to be socially acceptable, insuring hence the quality of human-robot interactions. Research in cognitive neuroscience that addresses the foundations of the phenomenology of embodiment suggest that a novel and largely unexplored approach to robot social acceptance may be possible.

A. Psychological foundations of embodiment

Numerous studies on the phenomenology of embodiment demonstrate the importance of 1st-person-perspective and synchrony during sensory-motor manipulations applied to single body-parts, other humans or virtual reality avatars to be embodied. [1-7]. For example, a pioneering experiment called the rubber hand illusion paradigm (RHI) demonstrated subjects' ability to develop a sensation of embodiment including ownership toward a fake hand that is stroked with a paintbrush simultaneously with the subject's non-visible hand [8]. The multimodal congruence of seeing the rubber hand and feeling one's own hand being stroked simultaneously produces a strong feeling that the rubber hand is one's own. Researchers extended these observations to the face showing a sensation of enfacement by synchronous tactile stimulation of a same area of the face in two human subjects facing each other [7, 9-11]. In parallel the authors described correlations between the sensation of enfacement and positive social features of the other. The link between the illusory sensation of embodiment and changes in social perception are likely grounded in overlapping internal body representations of self and other [7, 11]. This idea receives strong support from the finding of the mirror neuron system coding for our own actions and emotions as well as for the perception of others' action, intention and social traits [12-14].

B. Related work on embodiment into a Robot

In the robotic telepresence domain, physical embodiment of subject into a robot has already been considered as an important factor to make human interactions with robots more successful [15-19]. Aldageirsson et al. [15] showed that people felt more psychologically involved and more engaged in the interaction with a remote robot-mediated operator when they felt embodied in a socially expressive way. Higher levels of cooperation enjoyment in the interaction was also reported. Based on this theoretical and empirical background, we investigated the ability to enhance subjects' social perception of a robot by eliciting a sensation of embodiment during robot-human interaction.

In our research [20, 21], we went further in the understanding of the beneficial effects of robotic embodiment to enhance acceptance of robots in a human society. For this purpose, we used a telepresence setup where the subject is teleported into a robot that is facing a mirror so that the subject sees the own face as the robot face. Embodiment was promoted by synchronous sensory-motor manipulations where subject and robot either received synchronized tactile stimulation on the face or moved in synchrony [20, 21]. Only during visuo-motor manipulations, we showed that the sensation of embodiment, especially agency, takes place with increased positive social attitudes toward the robot. Indeed, during robotic telepresence, while synchronized visuo-tactile facial stimulations did produce an illusory sensation of robotic embodiment, including ownership, location and

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agency, they do not induce change in subjects' emotional perception of the robot.

While telepresence is an interesting medium to study how embodiment into robots can enhance other social feelings towards the robot, including moral attributes [20-22], it does constitute an unusual human-robot interaction where the subject is teleported in another body. Moreover, in our experience using a mirror in front of the robot, the subject interacts with another, as being oneself, as a robot. Such an experimental situation promotes the embodiment as well as emotional feelings toward the robot as one's own body self. However, it is not clear whether our findings obtained in such a specific experimental framework coupling mirroring and robotic telepresence can be generalized to other more prevalent human-robot interactions, such as face-to-face interaction.

C. Hypotheses:

In order to address this issue, here we investigate the face to face human-robot interaction using similar paradigm than during our previous telepresence experiments. In particular, we test the following hypotheses : 1) that embodiment can indeed occur in face-to-face human-robot interactions, 2) if so, that embodiment scores depend on the modality (motor vs sensory) of the embodiment induction as in our previous research, and 3) that embodiment scores are coupled or not with changes in social judgements depending on the sensory-motor manipulations. If successful, we will reveal a common generalized process underlying robotic embodiment and changes in social acceptability towards these robots.
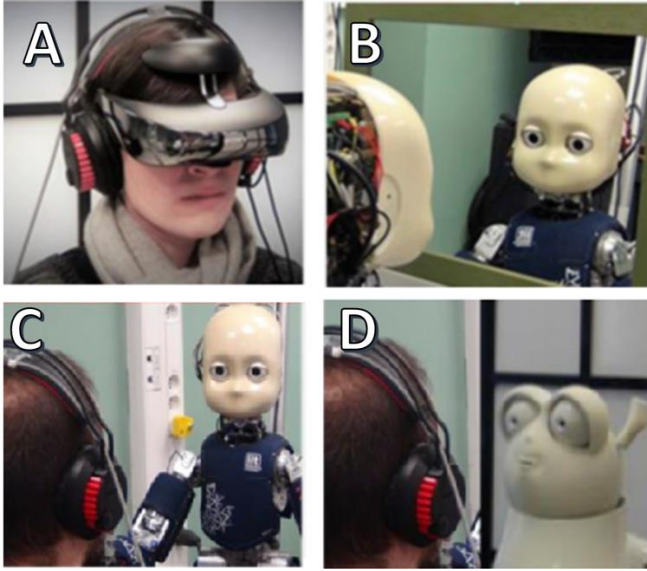

Figure 1. Robot experimental setups. A-B. Telepresence Self-Perspective: A, the subject wears a HMD headset and sees through the robots eye-cameras- B, the robot is in front of the mirror, so that the subject sees the own face in the mirror as the robot. C-D. Face-to-face Self-perspective: the subject sees the robot in front of him, with iCub (C), and with Reeti (D). All conditons are realized with Reeti and iCub, balanced across subjects.

In the current research, we hence perform a new set of experiments, and compare our previous findings obtained in telepresence to these new results obtained from the face-to-face interactions, corresponding to those most frequently used in daily life robot-human exchanges. The two modalities of

sensory and motor manipulations are investigated when the subjects face the robot in these more ecological conditions.

II. MATERIAL & METHODS

In our experiments, each subject experiences conditions that involve synchronous and asynchronous stimulations with respect to the robot. By using two different robots in the successive experiments with each subject, we can thus avoid any contamination from one condition to the next.

A. Robots and Control Architecture

This study was performed with the robots iCub [23], and the robot Reeti (http://www.reeti.fr/index.php/en/). Both robots had a mobile head and eyes, with facial features including eyes and nose. Video cameras in the robot eyes allowed the robot to perceive the visual environment. While the robot iCub had a humanoid structure (size of a 3 year-old child), the robot Reeti resembled a cartoon character.

The robots were controlled by the Super Wizard of Oz (SWoOZ) system [24]. SWoOZ collects real-time data from position sensors on the subject's headset in order to allow the subject to control the robot's head in real-time. For telepresence, a Head-Mounted Display (HMD) placed on the subject's head and connected to the robot cameras allows the subject to see the visual environment of the robot. Thus SWoOZ monitors real-time signals of head positions and visual cameras to provide smooth and simultaneous visuo-motor human-robot interactions. This is built on top of the robot communication infrastructure YARP [25].

B. Experimental Conditions

Our experimental conditions are constructed along two dimensions (see Table 1): Self-perspective (Telepresence vs. Face-to-Face) and Embodiment-induction (Intentional motor, vs. Passive tactile). In the current research we perform new experiments in the face-to-face conditions. For comparison, we also briefly explain the telepresence conditions and results from our previous work [20, 21].

<div align="center">Self-Perspective</div>

	Telepresence	Face-to-Face
Motor	Ventre-Dominey 2019	New Exp 1
Tactile	Farizon 2021	New Exp 2

(Embodiment Induction)

Table 1. Experimental conditions.

1) Telepresence Self-Perspective

In the Telepresence Self-perspective conditions that we explored in [20, 21] , the subject who is teleported into the robot is sitting in the experimental room in a location several meters from the robots in order not to be visible for the robot and not to see the robot. As shown in Figure 1A, the subject wears a HMD with a stereo visual display (SONY HMZ-3WT 3D Viewer) connected to the video cameras located in the robot eyes, and an audio headset to isolate the subject from environmental noise. The subject thus sees a stereo image through the eyes of the robot. A mirror is placed in front of the robot (Figure1B), and thus, through the stereo image from the robot cameras into the HMD, the subject sees him/herself

in the mirror as a robot. As seen in Table 1, this Telepresence condition allows two forms of embodiment induction, described in B below.

2) Face-to-Face Self-Perspective

In the face-to-face condition that we use in the current experiments, the subject no longer wears a HMD vison system, and the subject and the robot are facing each other in a face-to-face configuration (Figure 1 C-D). This condition is of particular interest, as it is more typical of classic cooperative human robot interaction [26-29]

In the current study, we perform 2 new experiments in the Face-to-Face conditions. Subjects gave their informed consent prior to the experiment. Experiment 1 tests a group of 16 subjects (mean age=26, SD=4.65) in the Motor induction condition, and Experiment 2 tests a group of 24 subjects (mean age= 24, SD=4.3) in the Tactile induction condition. The number N of subjects was established for each group using a power analysis to allow effect size d $\geq$ 0.75. We report results for these new experiments on the 40 subjects, and we compare these with the corresponding results from the Motor and Passive Tactile induction experiments with Telepresence. As indicated in Table 1, we previously explored the Telepresence conditions with Motor and Tactile induction [20, 21].

C. Modality of the Embodiment Induction

1) Intentional Motor Embodiment Induction

In the Intentional Motor induction mode, a small head mounted motion sensor (Polhemus Fastrak TM, 05446 Vermont, USA) is fixed on the subject's headset and coupled to a transducer located in the close proximity of the subject. The source emits an electromagnetic field and the sensor is tracked in full 6DOF (position and orientation). In the synchronous (SYN) condition, subjects' head motion signals are used to pilot the robot head movements, with imperceptible latency (136 $\pm$ 28 msec) via the SWoOz system [24, 30]. In the asynchronous condition, the robot head moves in a manner that is decoupled from the subject's head movement. While the subject moved the head in a slow, self-paced exploratory manner, the robot's head was autonomously directed by a pre-recorded pseudo-random motion trajectory made to match the same spatio-temporal features.

2) Passive Tactile Embodiment Induction

In the Passive tactile induction condition, the subject's face is stroked with a paintbrush synchronously (SYN), or asynchronously (ASYN) with the stroking of the robot's face. For this, two experimenters hidden from the participant delivered manually the tactile stimulations: one experimenter was sitting next to the subject and the other one next to the robot. A computer screen visible only to the experimenters displayed a moving target that reflects the starting point, the direction (horizontal or vertical) and the frequency of the tactile stimulation. Previously trained, both experimenters started to stroke the subject and robot faces at the time of the target onset and maintained the paintbrush displacement synchronous to the target motion (frequency 0.33 Hz). In the synchronous condition the two experimenters were moving

the paintbrush synchronously to the visual target and in the asynchronous condition one experimenter was displacing the paintbrush with a delay of about one second with respect to the other experimenter. Thus, with passive tactile induction, the subject feels the tactile stimulation on the cheek and only sees a paintbrush stroking the robot's cheek.

D. Experimental procedure

In the current experiments, each subject is exposed to two human-robot interaction sessions, one with iCub and one with Reeti, respectively. One session uses synchronous stimulation and the other uses asynchronous stimulation. The order of the robot type and stimulation synchrony is balanced across subjects. In Experiment 1, one group of subjects (N=16) is exposed to the intentional motor conditions. In Experiment 2, another groups (N=24) is exposed to tactile conditions.

At the beginning of each experiment, the subject responds to a questionnaire evaluating feeling of likeability towards both robots. Then the first interaction session begins. The session consists of four blocks of stimulation (intentional motor or passive tactile), that are either synchronous or asynchronous between the human and robot. The subject then responds to questionnaires evaluating the feeling of closeness towards the robot (IOS) and the sensations of embodiment (based on 18 sentences describing a sensation). After a short pause, the second interaction session begin with the other robot, and the other synchrony condition. The second session is followed by the closeness and embodiment questionnaires, and finally the likeability questionnaire. Details on these questionnaires can be found in [20, 21]. This same organization of the experimental procedure was previously used in the telepresence experiments [20, 21].

E. Data Analysis

As stated, the sensation of Embodiment and the Closeness were measured after each session of human-robot interaction while the Likeability was measured before and after the experiment. The Embodiment scores were quantified on the individual quote of a subjective scale (0:no sensation to 100: very strong sensation) for each sentence of the questionnaire. Then a mean score was calculated for each category: Enfacement (Sensation to resemble the robot), Location (Sensation to be in place of the robot) and Agency (Sensation to control the robot) by pooling the corresponding sentences. The score of Likeability was established on a subjective scale between 0 (not likeable) and 100 (very likeable). A Self-Other Closeness task was performed on the basis of the IOS test developed by Aron et al [31] and the score of Closeness was measured on a graphic 7-point scale (1: no closeness and 7: very strong closeness).

The different variables of Embodiment (Enfacement, Location, Agency) and of the social features including Likeability and Closeness were computed for statistical analysis with Statistica software package. For Likeability and IOS Closeness analysis, we used a mixed repeated measures ANOVA design with the within-subject factor Synchrony (SYN: Synchronous vs ASYN: Asynchronous)

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and a between-subject factor Perspective (Telepresence vs Face-to-Face). For the Embodiment scores, a mixed repeated-measures ANOVA was used with two within-subject factors, Synchrony (SYN: Synchronous vs ASYN: Asynchronous) and Embodiment Category (Enfacement, Location, Agency), and a between-subject factor Perspective (Telepresence vs Face-to-Face). Post-hoc specific pairwise comparisons were realized with a Bonferroni test and the significance was established at 95% of confidence interval.

III. RESULTS

A. Experiment 1 - Motor Induced Embodiment

Here we consider the effects of motor induced embodiment in the Face-to-Face perspective, and we compare these results with our previous results in the Telepresence perspective.

1) Embodiment Effects

a) Effects of Synchrony

In Figure 2 we see that for the Face-to-Face perspective, when the subject controls the movement of the robot in a synchronous manner, embodiment scores are increased. This is also the case for the Telepresence perspective. These observations are confirmed both for Telepresence (Syn effect : $F_{(1, 14)} = 38.46$, $p < 0.001$; partial $\eta^2 = 0.73$; Syn x Cat interactions : $F_{(2,28)} = 9.20$, $p < 0.001$; partial $\eta^2 = 0.40$), and Face-to-face (Syn effect: $F_{(1,15)} = 24.14$, $p < 0.001$, partial η^2; Cat x Syn interactions : $F_{(2,30)} = 31.42$, $p<0.001$, partial $\eta^2 = 0.68$) situations. The sensation scores for Location (TELE : p= 0.18 ; FF :p=0.05) and more significantly for Agency (TELE and FF $p < 0.001$) are increased during Synchronous vs. Asynchronous motor interactions. There is no effect of Synchrony on Enfacement in either Telepresence or Face-to-face.
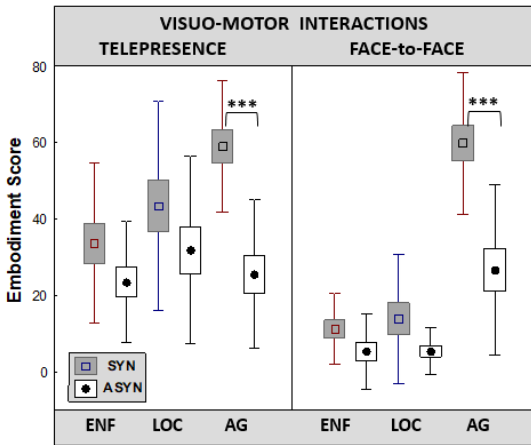

Figure 2. Embodiment effects induced by intentional movement in Telepresence vs Face-to-Face perspectives. Enf: Enfacement, Loc: Location, Ag: Agency. SYN: Synchronous, ASYN: Asynchronous. *** p< 0.001.

b) Effect of Self-Perspective

In Figure 2 we observe that there is a strong effect of synchrony on Agency for both Telepresence and Face-to-Face Perspectives. In contrast, the effects on Enfacement and Location are more important in Telepresence as compared to Face-to-Face perspective (Pers effect : $F_{(1,30)} = 4.20$, p=0.049, partial $\eta^2 = 0.12$; Syn x Pers interactions : $F_{(1,30)} = 5.00$ p= 0.033, partial $\eta^2 = 0.14$). This yields a more global sensation of embodiment in Telepresence.

2) Social/Affective Effects

In Figure 3A we see that more for Telepresence than Face-to-Face perspectives, when the subject controls the movement of the robot in a synchronous manner, Likeability scores are increased. This was confirmed by the statistical analysis. Likeability significantly depends on Perspective (Pers effect : $F_{(1,30)} = 4.20$, p=0.049, partial $\eta^2 = 0.12$; Syn x Pers interactions : $F_{(1,30)} = 5.00$ p= 0.033, partial $\eta^2 = 0.14$) as it was significantly more increased in Synchronous vs Aynchronous (p=0.001) interactions in Telepresence (Syn effect : $F_{(1,14)} = 18,37$, $p < 0.001$; partial $\eta^2 = 0.57$) than in Face-to-Face (Syn effect : $F_{(1,15)} = 4.0$ 4, p=0.063, partial $\eta^2 = 0.21$).
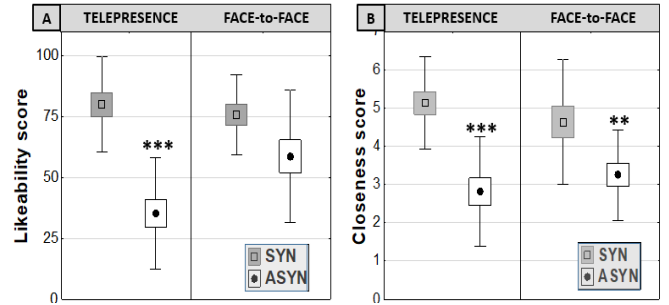

Figure 3. Likeability and closeness effects induced by intentional movement in Telepresence vs Face-to-Face perspectives. SYN: Synchronous, ASYN: Asynchronous. *** p<0.001, ** p< 0.01

In contrast, in Figure 3B we see that the Closeness was significantly increased in the Synchronous interactions in both Telepresence (Syn effect : ($F_{(1,14)} = 52.37$, $p < 0.001$; partial $\eta^2 = 0.79$) and Face-to-Face (Syn effect : $F_{(1,15)} = 8.77$, p=0.0097, partial $\eta^2 = 0.37$) and there was no difference between these two spatial Perspectives (Pers effect : $F_{(1,30)} = 0.006$, p> 0.25, partial $\eta^2 = 0$; Syn x Pers interactions : $F_{(1,30)} = 2.8$ p= 0.10, partial $\eta^2 = 0.08$). Thus, the perception of Closeness to a robot is enhanced by Synchronous movement, independent of the self-perspective, Telepresence or Face-to-Face.

B. Experiment 2 - Tactile Induced Embodiment

We now consider the effects of tactile stimulation in the Face-to-Face perspective, and we compare these results with our previous results in the Telepresence perspective.
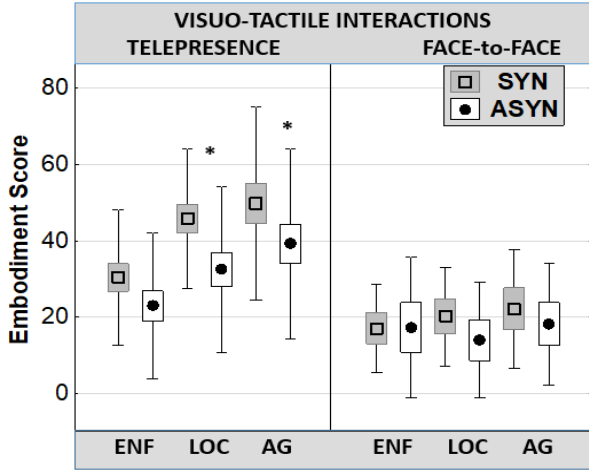
Figure 4. Embodiment effects induced by passive visuotactile stimulation in Telepresence vs Face-to-Face perspectives. Enf: Enfacement, Loc: Location, Ag: Agency. SYN: Synchronous, ASYN: Asynchronous. * p< 0.05.

1) Embodiment Effects

a) Effects of Synchrony

In Figure 4, we observe that in the Face-to-Face perspective, there were no effects of synchrony on the embodiment sensation (Syn effect: $F(1,23)= 2.37$, p= 0.14, partial $\eta^2 = 0.09$). This is in contrast with Telepresence, where tactile stimulation induces a significantly increased embodiment in Synchronous vs Asynchronous interactions (Syn effect : $F(1,22) = 17.23$, $p < 0.001$, partial $\eta^2 = 0.439$) in all categories but Enfacement (Syn $\times$ Cat interactions $(F(3,66) = 1.27$, $p > 0.25$, partial $\eta^2 = 0.054$).

b) Effects of Self-Perspective

Indeed, Figure 4 demonstrates that overall, while for Face-to-Face there are minimal effects of tactile stimulation on embodiment, for Telepresence, there is a visible effect of tactile stimulation on the sensation of embodiment. This is confirmed by the differential effect of Perspectives on the embodiment scores (Pers effect : $F(1,30)= 11.24$, p= 0.0022, partial $\eta^2 = 0.27$) which depends on the category (Cat x Pers interactions : $F(1,30)= 14.69$, p< 0.001, partial $\eta^2 = 0.33$) independently of the Synchrony (Syn x Cat x Pers interactions : $F(2,60)= 0.23$ P> 0.25, partial $\eta^2 = 0.007$). Posthoc Bonferroni analysis showed a significant decrease of Location (p= 0.037) and an almost significant decrease of Agency (p= 0.056) in Face-to-Face as compared to Telepresence Self-perspective.

2) Social/Affective Effects

In Figure 5 we see that for the social/affective measures, there is little effect of tactile stimulation. Thus, in contrast to Motor induction, the social attributes including Likeability (Syn effect: $F(1,23)= 0.86$, p> 0.25, partial $\eta^2 = 0.04$) and Closeness (Syn effect : $F(1,23)= 0.03$, p> 0.25, partial $\eta^2 = 0.0$) are independent of the synchrony of the visuo-tactile stimulations during robot interactions. This is valid in both Telepresence and Face-to-face and there is no effect of Perspective neither for Likeability (Pers effect: $F(1,46)= 0.94$, p> 0.25, partial $\eta^2 = 0.02$) nor for Closeness (Pers effect : $F(1,46)= 0.13$, p> 0.25, partial $\eta^2 = 0$).
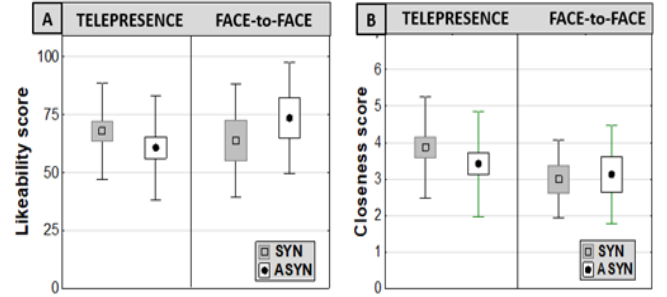

Figure 5. Likeability and closeness effects induced by passive visuotactile stimulation in Telepresence vs Face-to-Face perspectives. SYN: Synchronous, ASYN: Asynchronous.

3) Synthesis : Major points

The most remarkable finding in these experiments is that in Face-to-Face interactions, motor synchrony produced reliable effects of embodiment as revealed by significant effects for agency. This is in accordance with our previous results in the telepresence perspective. Furthermore, these effects were coupled to reliable positive social/affective effects as revealed by the significant effect for closeness.

IV. DISCUSSION

If robots are to enter into meaningful relationships with people, then these robots must be acceptable. In this study we investigated the ability of human subjects to develop positive emotional states toward a robot as they feel to be embodied into this robot. We previously characterized these effects in the atypical condition where the human was teleported into the robot. While these were remarkable results, it was not clear how they would generalize to the more ecological condition where the human and robot share the same space in a face-to-face interaction. Thus, in the current study we performed new experiments examining the effects of motor vs. tactile embodiment induction in the face-to-face spatial perspective. This allows us to compare the two spatial self-perspectives: telepresence and face-to-face, and two methods for inducing embodiment: intentional motor synchrony and passive tactile synchrony.

A. Importance of the Induction Modality

We previously demonstrated that in telepresence, the key point for enhancing the affective feelings toward the robot was the subject's intentional actions that were effected in a synchronized manner between human and robot [21].

In the current study, we extended this observation to the domain of face-to-face interaction, where the human and robot are in a self-other relation. Confirming our hypotheses, we observed that synchronous motor activity between the human and the robot facing each other produces a significant sensation of agency, and a significant feeling of closeness to the robot. This important finding argues in favour of a generalized mechanism involved in the generation of emotional traits toward robots during motor driven embodiment whatever the type of human-robot interactions.

In contrast, we previously demonstrated that in telepresence perspective affective feelings towards a robot were not significantly improved during synchronized tactile stimulation [20]. This was despite the significant sensations

of embodiment into the robot described by the subject. It is important to recall that in our previous work, human subjects teleported into the robot were facing a mirror and thus facing themselves as a robot. Thus, in this condition the robot's face being touched or moving at the same time as one's own face likely evoked changes in the internal representation of the own face [9, 10]. Here, in the face-to-face perspective, we observed that synchronous tactile stimulation produced weak embodiment into the robot as well as weak effect on affective feelings. This further argues that efforts to increase positive affect towards robots should focus on coordinated motion rather than tactile stimulation.

B. Importance of Synchrony: Psychology

In the current study, we provide new insights on the impact of synchronous intentional action during interpersonal human-robot interactions. Interestingly, while our telepresence condition using a mirror reinforces self-identification, the face-to-face condition constitutes the basis of interpersonal communication with a well distinct self and other. We thus might expect less illusory embodiment and less social changes toward robots in the face-to-face condition. Interestingly for both telepresence and face-to-face, the subjects reported the same significant sense of agency as well as increased affective feelings toward the robot only in synchronized motor interaction. This finding reveals the importance of the synchrony and of intentional action in robotic social cognition. As we know in human psychology, the synchrony of movements, including mimicry and imitation plays an important role in social cognition [32]. In communication, the synchronization of mutual movements and posture sharing are determinant in the perception of social similarity and human interpersonal relationship [32, 33]. The neurophysiological basis of such interaction between motor and social process resides in changes in mental representation of the subject's face shifting the self-other boundary [9, 10, 34, 35].

This recalls the observations of Merleau-Ponty regarding the inseparability of the representation of self and other. As characterized by Rochat, Merleau-Ponty's intuition is that the own body perception and representation is fundamentally inseparable from the perception and representation of others [36], providing a basis for cooperative interaction. The current research provides evidence that under appropriate conditions, this type of co-representation can be attained between humans and robots.

Another important parameter is the sense of agency that is strongly augmented during synchronized head movements between human and robots. Indeed, the sense of ownership (enfacement) and location was very weak during motor manipulations in face-to-face as compared to telepresence. During sensory manipulation a sensation of embodiment was observed only in telepresence but not in face-to-face and weak affective feelings were reported in both interactions. Thus, only the motor driven interactions yields a significant sense of agency with increased affective feelings for the robot. Accordingly, during human-robot collaborations in shared building tasks, it has been reported that when a subject feels to be an agent of the robot behaviour the feelings toward the robot are positive [37]. In contrast, when a robot is perceived autonomous, as in our asynchronous motor manipulations, the subject develops negative feelings. Our findings and those of

the literature are suggestive of the importance of the sensation of controlling the robot in relation with the motor system to make a robot more agreeable. To explain the link between motor processing and social acceptability of robots, we suggest that the high-order intentional process related to motor control is crucial in the generation of the sense of agency and the consecutive changes in social feelings [20]. We know that the sense of agency relies on the comparison between the motor command issued from the intentional process and the feedback signal informing on the sensory outcome of an action [38-42]. In case of interacting agents either during telepresence or face-to-face, shared synchronous movements might trigger the resonance mechanisms supported by the mirror neuron system responsible for a number of social features, including theory of mind, empathy and self-recognition [12-14].

Based on these findings, we suggest that independently of the spatial perspectives, the crucial key of social changes co-occurring with illusory sensation of agency resides in the intentional causality and the consecutive resonance processing in play during shared human-robot action representation.

C. Towards Human-Robot Symbiotic through Synchrony

These results have clear impact on the future development of symbiotic relations between humans and robots. As clearly noted by Levinson, one of the key elements of the human "interaction engine" is our capacity to physically synchronize and anticipate during interactions with others [43]. We previously observed that humans are capable of perceiving and exploiting robot motoric cues in order to anticipate and optimize their joint behavior in real-time [26], and to improve cooperative interaction [27]. The current results demonstrate that in face-to-face interaction, synchrony between the human and robot promotes acceptance and positive affect toward the robot. These observations can be transferred into practical considerations for future robot implementations.

We observed that the greatest impact of tactile stimulation is in the increase of sensation of embodiment in the telepresence condition. Future robot design for telepresence and embodied avatars must exploit these findings, and generate tactile stimuli on the user that are synchronized with those that are perceived visually. The crucial element for robot design in the context of telepresence is the synchrony between what the user sees and what they feel.

In applied robotic settings using face-to-face interactions it will be important to facilitate human social attitudes towards robots through the use of synchronized motor and tactile responses, and additional cues such as eye-blink synchrony [44] and gaze coordination [45] will also contribute to these effects. We can generalize these results and consider that a crucial element for robot design in the context of face to face interaction is the coordination and synchrony between human behavior, including gesture, gaze, posture, speech, and the robot's responses and mimicry. Thus, future developments in human-robot interaction systems should benefit from these observations of the social benefits of synchronous face-to-face intentional interactions.

experiments were carried out at the Stem Cell and Brain Research Institute—SBRI (INSERM 1208, 69500, Bron, France) during the prior affiliation of DF, PFD and JVD with SBRI.

LEGAL DISCLAIMER

The study was approved (Rhône-Alpes Préfecture: Authorization No. 10028) by the Regional Health Agency (Agence Régionale de Santé-ARS) review board authorizing biomedical research at the Stem Cell and Brain Research Institute where the experiments were carried out in accordance with the principles of the revised Helsinki Declaration (World Medical Association, 2013).

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