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Social perception of others shapes one's own multisensory peripersonal space

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Abstract

The perception of our self is not restricted to our physical boundaries, but it extends beyond the body to incorporate the space where individual-environment interactions occur, i.e. the peripersonal space (PPS). PPS is generally conceived as a low-level multisensory-motor interface mediating hand-object interactions. Recent studies, however, showed that PPS representation is affected by higher-level cognitive factors, suggesting that it may underlie also individual-environment interactions. Here we asked whether the multisensory representation of PPS is influenced by high-level mechanisms implied in social interactions, such as the social perception of others. To this aim, in Experiment 1, we developed and validated a new multisensory interaction task in mixed reality (i.e., the Social PPS task). This task allows measuring the boundaries of PPS between one self and another person in a fully controlled, yet highly ecological, set-up. In the Experiment 2, we used this task to measure how participants' PPS varied when facing another person. The social perception of this person was manipulated via a classic social psychology procedure, so that, in two conditions, she was perceived either as a moral or an immoral character. We found that PPS representation is sensitive to the social perception of the other, being more extended when participants were facing a moral than when facing an immoral person. This effect was specific for social context, as no change in PPS was found if participants were facing an object, instead of the person. Interestingly, the social manipulation affected also attitude, identification, willingness to interact with the other, so as interpersonal distance. Together these findings show that social perception of others affects both the psychological representation of the others in relation to oneself and the multisensory representations of the space between oneself and the other, offering new insights about the role of social cognition in bodily representation.

Highlights

- We validated a new multisensory interaction task to measure the multisensory representation of the space between the self and another person in a controlled and highly ecological set-up.
- One’s own multisensory Peripersonal space is shaped by the social context.
- One’ own multisensory PPS is more extended toward the body of a person perceived as moral than immoral.
- PPS modulation occurs when we form a first impression of another person.
- Higher-level cognitive and social mechanisms, such as social perception, affect the representation of the body in space.

Keywords
Peripersonal space, social perception, morality, body representation, interpersonal distance

1. Introduction

The neural representation of our body does not end with its physical boundaries. Studies have shown that the multisensory representation of our body includes also the area surrounding it – the peri-personal space (hereafter, PPS) - where physical interactions between the body and the environment normally occur. Neurophysiological studies on monkeys (Rizzolatti, Scandolara, Matelli, and Gentilucci, 1981; Graziano, Yap, and Gross, 1994; Duhamel, Colby, and Goldberg 1998; Graziano & Cooke, 2006) described special populations of multisensory neurons responding to somatosensory stimuli on the body and visual and/or auditory stimuli related to external objects, specifically occurring close to (and not far from) the body. In keeping with this, further neuropsychological (di Pellegrino, Làdavas, and Farnè, 1997; Ladavas, 2002; di Pellegrino & Ladavas, 2014), neuroimaging (e.g., Bremmer, Duhamel, Ben Hamed, & Graf, 2002; Blanke, Slater, & Serino, 2015; Clery, Guipponi, Wardak, & Hamed, 2015) and psychophysical (see Maravita, Spence, Kennet, & Driver, 2002; Maravita, Spence, & Driver, 2003) studies on humans have shown that processing of tactile bodily stimuli is more strongly affected by external stimuli presented near the body, as compared to when the same stimuli occur father apart, suggesting that multisensory bodily cues are specially integrated within a spatial region close to the body, defining the extent of PPS.

One of the most intriguing aspects of PPS representation is its plasticity. Plastic properties of PPS have been largely investigated in the context of the sensory-motor processes involved in individual-objects interactions. For example, it has been shown that the PPS representation dynamically projects toward the end goal of an action, such as reaching (Brozzoli, Cardinali, Pavani, & Farnè, 2010) or walking (Noel et al., 2015a). PPS plastically extends after using tools to act in the far space (Maravita & Iriki, 2004) and it conversely contracts if actions are impeded, such as after a period of immobilization (Bassolino, Finisguerra, Canzoneri, Serino, & Pozzo, 2015) or in amputee patients (without prostheses; Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013). Other studies both in monkeys (Graziano & Cooke, 2002) and humans (Serino, Annella, & Avenanti, 2009; Makin, Holmes, Brozzoli, Rossetti, & Farne, 2009; Avenanti, Annela, & Serino, 2012) have also demonstrated that brain regions hosting multisensory PPS neurons directly project to the motor system, allowing faster and appropriate reactions to external objects. Together, these findings suggest that PPS representation should be considered a multisensory-motor representation of the body in space whose ultimately goal is mediating interactions between the individual and the environment (Serino, 2016; Graziano & Cooke, 2006; Clery et al., 2015, Brozzoli et al., 2014).

While the sensory-motor nature of PPS representation has been largely studied, much less is known about the role of higher-level cognitive and social mechanisms in this process. In particular, in the view of PPS as an interface for individual-environment interactions, the role of social modulators of PPS representation is particularly intriguing, considering that other people are probably the most relevant external stimulus we interact with. Indeed, it has been recently shown that areas representing the PPS are also activated by stimuli in the space close to another person (Brozzoli et al., 2013). However, relatively few studies have examined whether the social context affects PPS representation. For instance, Heed, Habets, Sebanz, & Knoblich (2010) showed that the integration of tactile stimuli on one's own hand and visual stimuli close to the hand varies depending on whether another person is present, facing the participants, suggesting that the physical presence of another person in the far space impacts on PPS. In addition, Teneggi, Canzoneri, di Pellegrino, & Serino (2013) showed that not only the presence, but also the nature of the interaction with another person affects' PPS. By using an audio-tactile interaction to measure the extent of PPS, these authors first found that participants' PPS boundary shrunk back towards their own body when they shared the space with another unknown person, as compared to when facing an inanimate body, i.e., a mannequin. Interestingly, such social modulation of PPS boundaries depended of the relationship with the other person. They measured PPS representation before and after participants were treated fairly (vs. unfairly) by the other person in an economic game (i.e. receiving equal vs. unequal payoff). An extension of the participants' PPS toward the body of the fair (but not of the unfair) other was found. Similar changes in PPS were shown by Maister, Cardini, Zamariola, Serino, & Tsakiris (2015) by using another form of social manipulation. PPS was tested after participants received synchronous (vs. asynchronous, as a control condition) multisensory stimulations on their own and on another person face. This manipulation, which is used to induce the so-called enfacement effect (Tsakiris et al., 2008; Sforza, Bufalari, Haggard, Aglioti, 2010), has been shown to induce also a feeling of trust and closeness towards the other person (Paladino, Mazzurega, Pavani, & Schubert, 2010; Mazzurega, Pavani, Paladino, & Schubert, 2011). Maister et al. (2015) showed that these effects are also associated to a remapping of the space where the other person was placed as one's own PPS after the synchronous (and not the asynchronous) stimulation. Taken together, these studies demonstrate that people' PPS representation is sensitive to the social contexts; however, they do not point to the higher-level cognitive and social mechanisms responsible for it.

If we conceive PPS as an interface for individual-environment interactions, one could hypothesize that social perception – that is the ability to quickly form an impression of other people – is a key process to link the social environment with the one's own bodily representation. This account is intriguing as, on the one hand, it may shed some light on the interplay between social, cognitive and bodily processing and, on the other hand, it may provide some insights about the functions of PPS regulation in social interactions. We know from research in social cognition that action is the ultimate function of social perception; that is, we quickly form an impression of other persons, as this would guide our behaviour toward them (Fiske & Taylor, 2013). Following this line of reasoning, previous studies suggest that one's own PPS extends toward a person, when she/he is perceived as a fair and trustworthy (Teneggi et al., 2013) or a close partner (Maister et al. 2015). However, the manipulations used in these studies (and reviewed above) did not directly vary, nor assessed, the social perception of the partner. Teneggi et al. (2013), for instance, varied the money payoff received by the participant during an economic game, whereas Maister et al. (2015) delivered a synchronous (vs. asynchronous) interpersonal multisensory stimulation, which reduces self-other distinction (Paladino et al., 2010). Other elements of the experimental context (e.g. the rewarding experience of receiving an equal payoff, or the pleasantness of receiving a synchronous stimulation, etc.), rather than the impression of the person present in the far space, could have been responsible for the PPS change. These potential confounding factors, combined with the absence of a control condition in which PPS was assessed in a non-social context (e.g., when facing an object), leave unanswered a series of fundamental questions concerning the relation between social cognition and PPS representation. For instance, does PPS representation change depending on the impression we have of a person we are facing? Does such social modulation induce a contraction of PPS towards one's own body or an extension toward the other person's body? If this is the case, which social psychological processes may trigger these effects on PPS? What is the ultimate function of the PPS regulation in social contexts?

Thus, in the present research we aim to further investigate the contribution of higher-level cognitive and social mechanisms in PPS regulation by directly manipulating the impression participants form of the person they are facing. Specifically, we relied on a standard procedure used in studies on social perception in order to make participants form an impression of a person character on the basis of her responses to a questionnaire. These responses were varied so as the other person behaved as a moral or an immoral individual. We manipulated the perceived morality of the other, as several studies have shown that morality is one of the (if not "the") fundamental dimensions of social perception (Goodwin, 2015). When forming an impression of individuals and groups, people appears to pay special attention to moral characteristics (as compared to other factors such as warmth and competence, equivalent in terms of valence) (Brambilla, Rusconi, Sacchi, & Cherubini, 2011). In addition, person morality best predicts the overall evaluation and attitude (e.g., Brambilla, Sacchi, Rusconi, Cherubini, & Yzerbyt, 2012; Goodwin, Piazza, & Rozin, 2014), so as the behavioural tendencies toward the other (Brambilla, Sacchi, Pagliaro, & Ellemers, 2013). This centrality of morality traits in person perception is related to the fact that these characteristics provide unique information on the person intention, whether these are good or bad and also his/her qualities as human being (Goodwin, 2015). This theoretically driven social manipulation allows to better investigate the top-down role of social processes in shaping PPS.

A previous study by Iachini and colleagues (2015) used a conceptually similar manipulation (the persons were described as moral or immoral). However, in their study, they relied on a reachability judgement (i.e. judging whether an external stimulus is reachable) as a proxy of PPS boundary. In our research we are interested in the multisensory nature of PPS, as a general form of individual-environment interaction (Serino, 2016; Ferri, Costantini, Tajadura-Jiménez, Väljamäe, & Vastano, 2016). For this reason, we developed a new task, directly inspired by the neurophysiological findings regarding the surrounding space around the body (Rizzolati et al., 1981). This allowed us verifying whether the social perception of others induces a change in the representation of one's own body in space.

To this aim, we tested PPS representation after the social manipulation by means of a new multisensory interaction task: we developed a visuo-tactile version of the audio-tactile task used by Teneggi et al. (2013) and Maister et al. (2015), (see Serino et al., 2015), and adapted it to immersive virtual reality, in order to assess PPS in the context of social interactions. More specifically, this task measures reaction times to a tactile stimulation on the body, while a virtual object, approaching the participants' face, is located at six possible distances between the body of the participant and that of another person facing her. To this aim, immersive augmented reality is used so that virtual objects are presented, via a head-mounted display (HMD), within pre-recorded real scene of the environment and of the other person.

Thus, in Experiment 1, we first validated this task and then applied it in Experiment 2 to assess participants' multisensory representation of the area between their body and the body of another person (i.e. the social PPS task), of whom they had formed an impression as either a moral or an immoral person. In line with previous research on the social modulation of PPS (Teneggi et al., 2013), we expect that PPS representation would differ when facing the moral as compared to the immoral other, being, in particular, more extended toward the body of the former than the latter individual. As a control condition, in order to show that perceived morality specifically affected PPS representation when in presence of the partner, and to exclude generic effect on multisensory processing (due for instance to arousal and emotional changes after modulation of social impression), participants also completed a visual-tactile task where an object, instead of the person, was presented (Non-Social PPS task).

In addition, in order to gain a better understanding of the interplay between social cognition processes and PPS representation, we also assessed several social outcomes in play while forming an impression of the partner as a moral vs. immoral person. First, in line with previous research, we expect to find more positive attitude and overall judgment, stronger behavioral intention to interact, identification and similarities toward the moral than the immoral other. The relation between the PPS boundary, on the one hand, and the overall attitude, the extent of identification and the willingness to interact with the partner, on the other hand, will provide some indications on which of these social psychological processes affect one's own PPS.

A final goal of the present research is to explore the relation between the regulation of the PPS boundary and of the physical distance toward the partner that the participant feels as comfortable, i.e., interpersonal distance (ID). This distance has been used in many researches in social psychology to measure the personal space, that is the area around the body that people feel is “their space” (Sommer, 1959). To measure ID, we implemented in the same immersive augmented reality environment, a stop distance paradigm, whereby the other person moves towards the participant until the latter feels the distance between oneself and the other as comfortable. This paradigm was administered after the PPS task so as to prevent any carry over effect of the stop distance on the main dependent variable of interest for the present research, that is the performance on the visuo-tactile task. Along with Iachini et al. (2015), we expect closer interpersonal distance with the moral, than the immoral partner. The comparison between the effects of the social manipulation on PPS boundaries and ID, the relationships between these effects and other social psychological factors (i.e., attitude overall judgment, and intention to interact with the other) will be explored.

2. Experiment 1: Validating the social visuo-tactile interaction task.

The aim of this experiment was to validate a new task to assess participant PPS representation when facing a person. This task is an adaptation to social context of the audio-tactile PPS task developed by Canzoneri et al., 2012 (see Serino et al., 2015). Participants were immersed in an augmented reality environment, consisting in a pre-recorded movie, where another person was sitting in front of them along a corridor. Their task was to respond a fast as possible when they felt a vibro-tactile stimulation at their hand, while ignoring virtual objects, presented by means of a head-mounted display, moving from the location of the other person, towards their face. Tactile stimuli were administered at different time delays from the onset of the virtual object movements, so that touch was processed when the visual stimulus was at a different distance from the participants' body. In order to demonstrate that the task captures the multisensory PPS, we aimed at showing a speeding effect in the detection of the tactile target stimuli when the virtual object occurred at closer distances from the participant's body, as compared to farther distances (see e.g., Canzoneri et al., 2012; Serino et al., 2015)

2.1. Method

2.1.1. Participants

Eighteen students (11 females, Mean age = 22.44, SD = 3.2, range = 19–29; with normal or corrected-to-normal vision) from the University of Trento participated in the experiment. Course credits were offered to volunteers and informed consent was obtained from all of them.

2.1.2. Materials

The PPS task was administered by the aid of a virtual reality headset (Oculus Rift DK2; 900x1080 per eye, ~105° FOV) and the RealiSM software (Reality Substitution Machine, http://lnco.epfl.ch/realism), a new augmented-reality technology developed at the Laboratory of Cognitive Neuroscience at the École Polytechnique Fédérale de Lausanne. This technology allowed us to integrate a pre-recorded real scene (a photo of a person in a corridor, see below) with a virtual element, a cube, and to administer the PPS task.

2.1.3. Procedure

The study was presented as a research on the role of social and cognitive factors in social interactions. Once arrived to the lab, participants first read the informed consent and then were introduced to the virtual environment and to the social PPS task by a female experimenter.

2.1.3.1. The social PPS task.

The task was an adaptation of the visuo-tactile PPS task (Serino et al., 2015) to a social context. Participants, sitting at a desk, were asked to wear an head-mounted display and to hold in their hands a computer mouse - used to register the response with the right hand - and a vibrotactile stimulator - used to administer tactile stimuli to left hand. Participants were instructed to respond to the tactile stimulation as fast as possible, by pressing the button of the mouse and to ignore visual stimuli presented on the head-mounted display.

The tasks consisted of three types of trial, namely bimodal visuo-tactile, unimodal tactile and catch trials. The critical bimodal visuo-tactile trials started with a white fixation cross in the centre of a black screen that disappeared after 300 ms. Then, participants saw a white corridor, where an actress (age 27 years old, neutral expression and wearing a white T-shirt and jeans) stood at a far location, at a distance of approximately 1.5 m (see below). After 700 ms from her appearance, a tridimensional brown virtual cube (0.2 m x 0.2 m x 0.2 m) appeared, at the level of the neck of the actress. Then the cube started to move approaching the participant with a speed of 0.75 m/s, it moved for 2600 ms and then remained still for 400 ms at the end of its trajectory. The face of the actress was always visible. Together with the visual stimulus, a tactile stimulation - clearly above perceptual threshold and lasting 350 ms - was delivered via a single vibro-tactile device that the participant hold in his/her left hand for the duration of the task. Importantly, the tactile stimulation was given at 6 different temporal delays from the appearance of the cube (after 325, 650, 975, 1300, 1625, and 1950 ms) and thus perceived by the participant when the virtual object was placed at 6 distances from her/him (D1-D6). Specifically, when the vibro-tactile stimulation was delivered after 325 ms from the beginning of the movement of the cube, the cube was perceived at the farthest distance from the participant (D6). Conversely, when the vibro-tactile stimulation was given after 1950 ms, the cube was at the closest distance (D1). Differently stated, a longer delay correspond to a closer object distance. In catch trials, the moving virtual cube and the other person in the corridor were shown, but no tactile stimulation was administered. In the uni-modal tactile trials the participants received the tactile stimulation at the same time intervals, while facing the other person, but no cube was presented. The whole task consisted of two blocks of 75 trials, each including 48 bi-modal visuo tactile, 12 uni-modal tactile, and 15 catch trials, presented in random order to the participants. Each block lasted for about 5 minutes and the two blocks were intermingled with a 5-minutes break.

At the end of the visuo-tactile task. the perceived distance of the other person in the real world was estimated. Once the headset was removed, participants were asked to reproduce in the real environment the distance at which they perceived the person in the immersive reality. Specifically, they were asked to stop the experimenter, while she was approaching them, at the distance where the person in the immersive reality was located in the virtual reality environment. Mean estimated distance was 1.42 m from the participant (SD = .33, *N* = 13).

Finally, in order to assess the perceived distance of the virtual objects from the body, in a pilot study we asked 7 participants (M_{age} = 29.14, SD_{age} = 6.89, range = 23-44, 3 male, 4 female) to estimate the distance of the virtual object at each of the 6 temporal intervals at which the tactile stimulation of a multimodal trial was delivered. Participants received 36 multimodal trials (6 per each distance/temporal delays from the appearance of the cube). At the end of each trial, they were asked to verbally estimate the distance of the cube when they received the tactile stimulus, on a scale ranging from 0 (very close) to 100 (very far). The trials were randomly presented. The responses and the statistical analyses are reported in Figure 1B. The shorter the temporal delay of the tactile stimulation, the larger the estimated distances of the virtual cube from the body was.

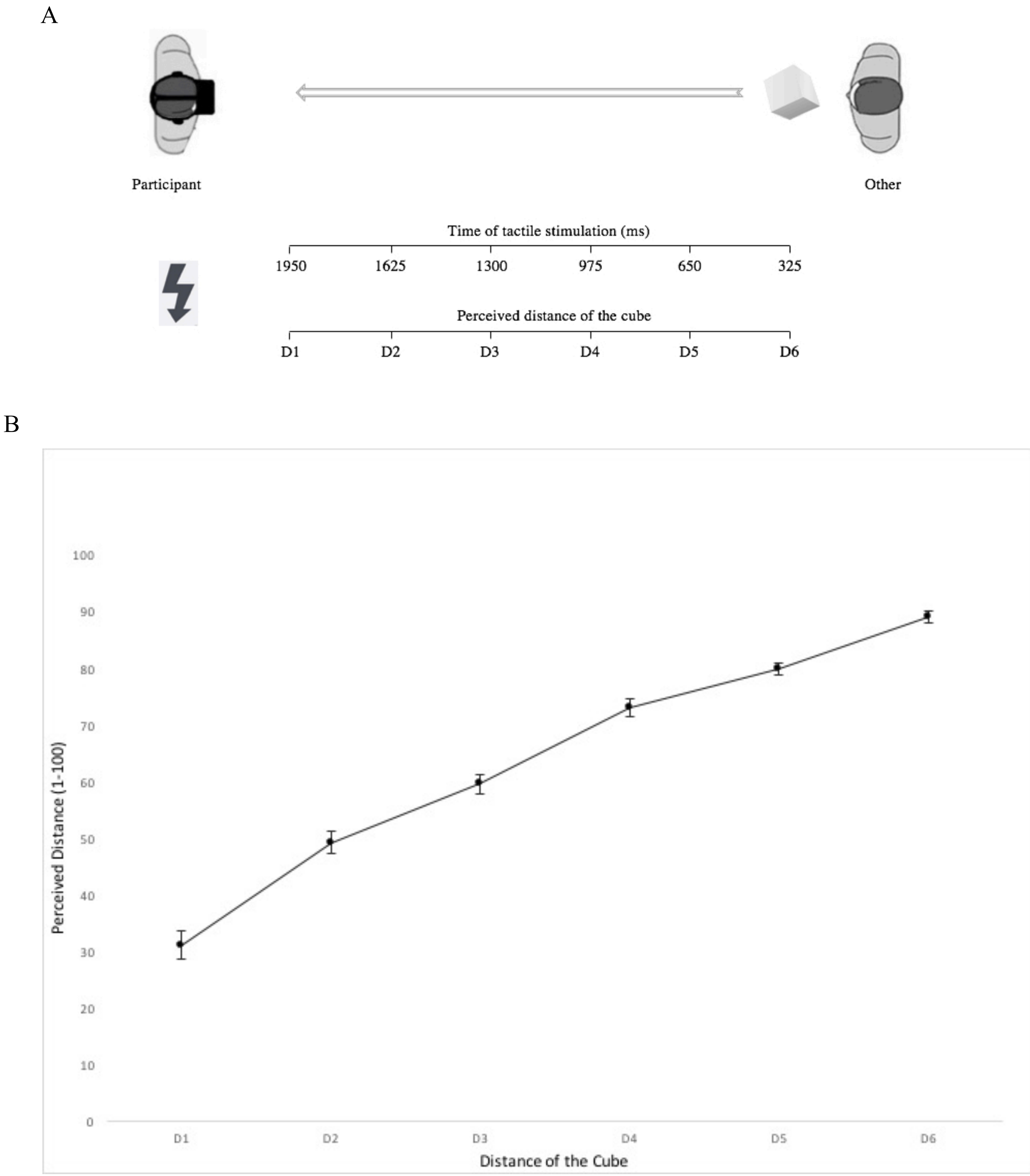


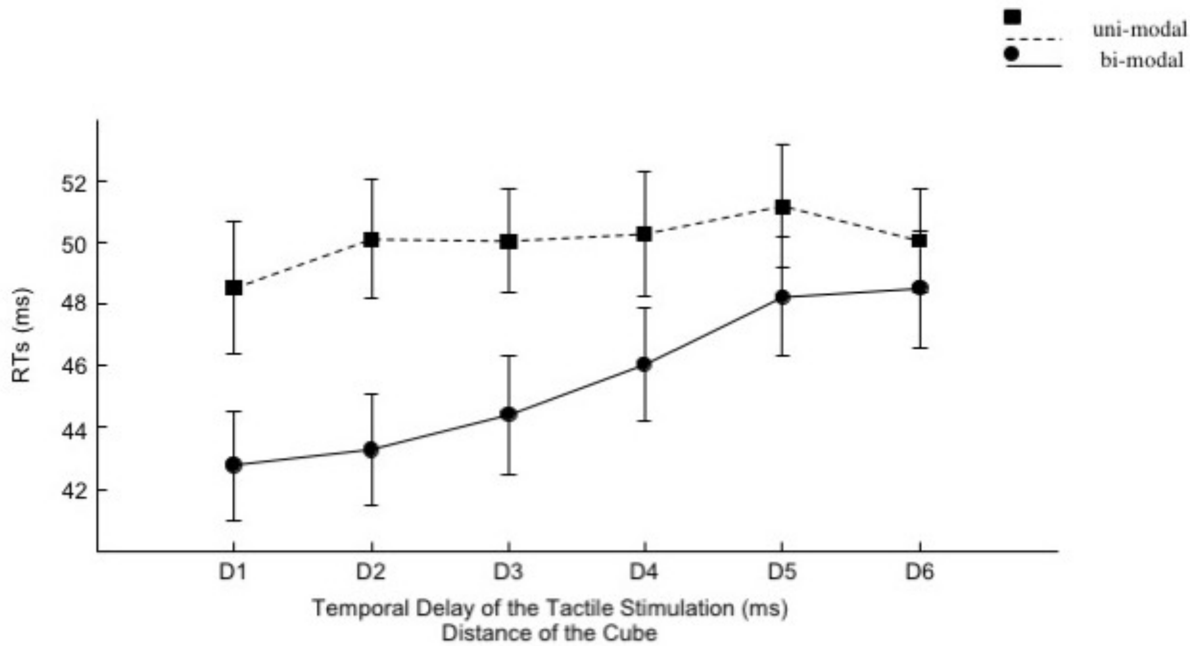
Figure 1.
Panel A. Participants wore a head-mounted display through which they saw a pre-recorded movie of a person, standing in front of them. During the experimental PPS trials, they received a tactile stimulation at their left hand while a task-irrelevant object (i.e., a virtual cube) approached their face. The tactile stimuli were delivered at different temporal delays (range: 325-1950 ms) from the beginning of the object movement, and were thus perceived when the cube was at 6 different distances from the participants' face (respectively, D6-D1). Participants were asked to ignore the visual stimulation and to respond to the tactile stimulation by pressing the mouse button. Panel B. The graph shows the estimated distances of virtual object as a function of the temporal delays of tactile stimulation (T1 to T6), B = 10.36, SE = .74, t(26.27) = 14.09, $p < .001$. Error bars represent SEM.

2.2. Results and discussion

As tactile stimulation was administered well above threshold, accuracy was very high (mean omission rate = 2; S.E.M. ± 0.662). Therefore, in line with previous studies using the same task (e.g., Canzoneri et al., 2012; Serino et al., 2015), we only analysed reaction times (RT) to the tactile stimulations as depended measure. RTs higher or lower than the 2 standard deviations from the mean RT were considered outlier responses and excluded from the analysis. The mean RTs to uni-modal and bi-modal trials for each time interval of the tactile stimulation (hereafter "distance") were calculated and entered in a repeated measure ANOVA with Modality (uni-modal tactile vs. bi-modal visuo-tactile trials) and Distance of the virtual object (D1, D2, D3, D4, D5, D6) as within-subject factors. The main effect of Modality was significant ($F(1, 17) = 49.737$, $p < .001$, $\eta_p^2 = 0.745$), and, as expected, qualified by a two-way Modality X Distances interaction ($F(5, 85) = 4.553$, $p = .001$, $\eta_p^2 = 0.211$). To better understand the interaction, a one-way ANOVA was run separately for bi-modal and uni-modal trails with Distance as within-subjects factor. As expected, the main effect of Distances was significant only for bi-modal trials ($F(5, 85) = 43.312$, $p < .001$, $\eta_p^2 = 0.718$; for uni-modal trials $F(5, 85) = .928$, $p = .467$, $\eta_p^2 = .052$). For bi-modal trials, the RTs were significantly faster at D1, D2, D3, and D4 compared to D5 and D6 (all $p < .002$, Bonferroni correction, see Figure 2A). Differently stated, the processing of the tactile stimulations was facilitated when the cube (i.e. the visual stimulation) was closer to the participant body, namely within a distance ranging from D1 and D4, confirming that visuo-tactile stimuli especially interact in a region of space close to the body, a finding consistent with the definition of PPS and previous studies assessing its boundary using a similar task (see e.g., Serino et al., 2015).

In order to better represent the facilitation effect induced by visual stimulation, while controlling for a possible expectation effect due to the temporal delay of tactile stimulation, for each subject, the fastest RT in the uni-modal condition was subtracted from mean RTs in the multimodal trials at each distance of the visual stimulus. In this way, a multisensory effect is represented by a speeding effect of RT in the multisensory condition as compared to the fastest uni-modal response, thus adopting a most conservative criterion to identify a facilitation effect. This representation is shown in Figure 2B, whereby, by definition, uni-modal tactile RT considered as a baseline is equal to zero and negative values indicate a RT facilitation in the bi-modal condition. Single-sample t-test against 0 showed that RT at D1 was significantly lower than 0 ($p < .05$, one-tail Bonferroni corrected; indicating a significant facilitation), whereas RT at D5 and D6 were higher than 0 ($p < .05$, one-tail Bonferroni corrected; potentially indicating an additional cost of visual information far from the body). To summarize, Experiment 1 validated this VR version of visuo-tactile interaction task to assess the extent of PPS social context, i.e. the presence of another person.

A



B

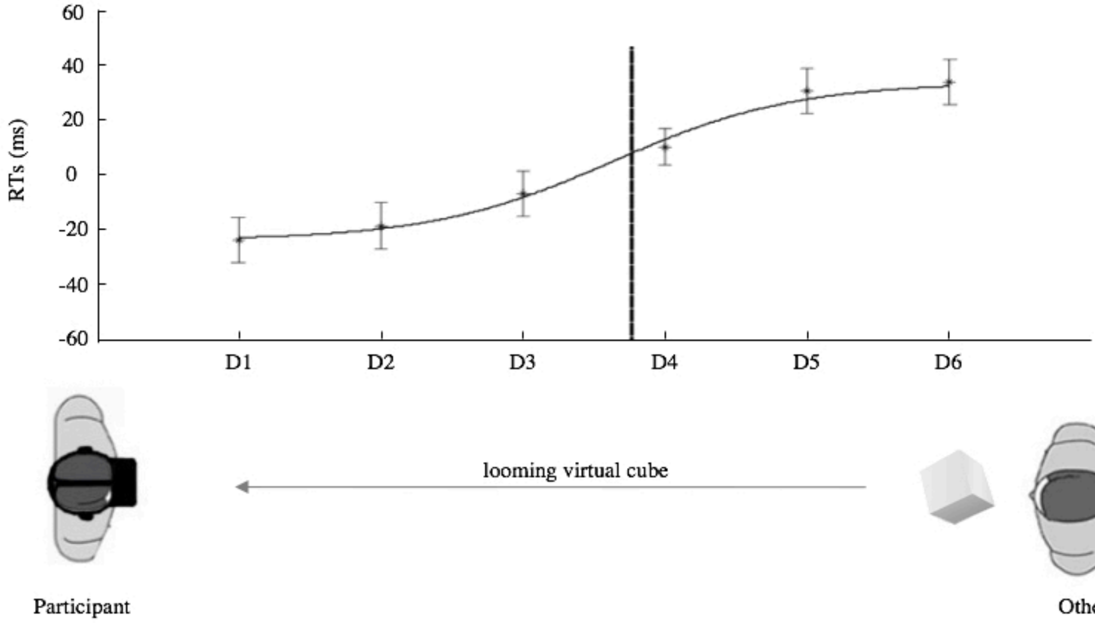


Figure 2.
Panel A. The graph shows the mean RTs (error bars represent SEM) at the different times of tactile stimulation for the bi-modal (i.e., when the cube was presented as approaching the participants' face, and thus at different distances from the participants' face; black line) and the uni-modal (i.e., when the cube was not presented; red line) trials.
Panel B. The graph plots the mean baseline-corrected RTs (error bars represent SEM) at different times of tactile target delivery (corresponding to the different distance of the cube, D1-D6) and the best fitting sigmoidal functions describing the relationship between the cube distance and the tactile processing (see experiment 2 for details). The central point of the sigmoidal function indicates the middle point of the spatial range where the pattern of RTs changes from slow to fast, and can be considered a single-value proxy of the location of the PPS boundary (see PPS Analysis).

3. Experiment 2: Social modulation of PPS.

The goal of experiment 2 was to examine the influence of top-down factors on PPS representation, and specifically the impact of perception of the other as a moral vs. immoral person in shaping the PPS boundaries. To this aim, we manipulated and measured the social perception of the other and then we assessed the extent of the participants' PPS when facing the moral vs. immoral person (experimental condition; social PPS task), or an inanimate object (control condition; non-social PPS task). In addition, we also measured the preferred interpersonal distance, in order to test whether the social manipulation influenced in the same way the social interpersonal space and the multisensory PPS. These effects were also studied in relationship with different social psychological factors such as attitude overall judgment, and intention to interact with the other.

3.1 Methods

3.1.1. Participants

Sixty healthy female students (M_{age} = 20.97, SD_{age} = 2.285; range = 19–30, all female, 54 right-handed, 5 left-handed, 1 both-hands, with normal or corrected-to-normal vision) at the University of Trento volunteered to participate in the experiment in exchange of course credits. Participants (4) who judged the virtual reality as highly annoying, as assessed by a questionnaire (see Final questionnaire), were not included in the final analysis.

3.1.2. Procedure and tasks.

Similarly to the Experiment 1, this study was presented as a research on the role of social and cognitive factors in social interactions. Once arrived to the lab, participants read the informed consent. Then they filled-in some questionnaires, including one that was relevant for the present research, as it served to increase the credibility of the social manipulation task. In this questionnaire participants rated the frequency of 17 behaviors (see, for a full description, the manipulation paragraph). Then participants completed the following tasks: the impression formation task that served as a social manipulation (see below), a series of questionnaire to assess this impression, the Social (i.e., facing a person) and Non-Social (i.e., facing an object) PPS task, the Interpersonal Distance (ID) task, the final questionnaires (see below). Finally, the participants were thanked and debriefed. The tasks were administered always in the order presented above, except for the Social and Non-Social PPS task, whose order was counterbalanced across participants. In order to guarantee that the effect of of the social manipulation was long enough, irrespective of the order of the two PPS tasks, the social manipulation always preceded the social PPS task, independently of the tasks order. Therefore, half of the participants started the experiment with the impression formation task, and then completed, in order, the Social PPS task and the Non-Social PPS task. The rest of the participants performed the Non-Social PPS task, afterwards they completed the impression formation task and the Social PPS task. For an overview of the procedure see Figure 3.

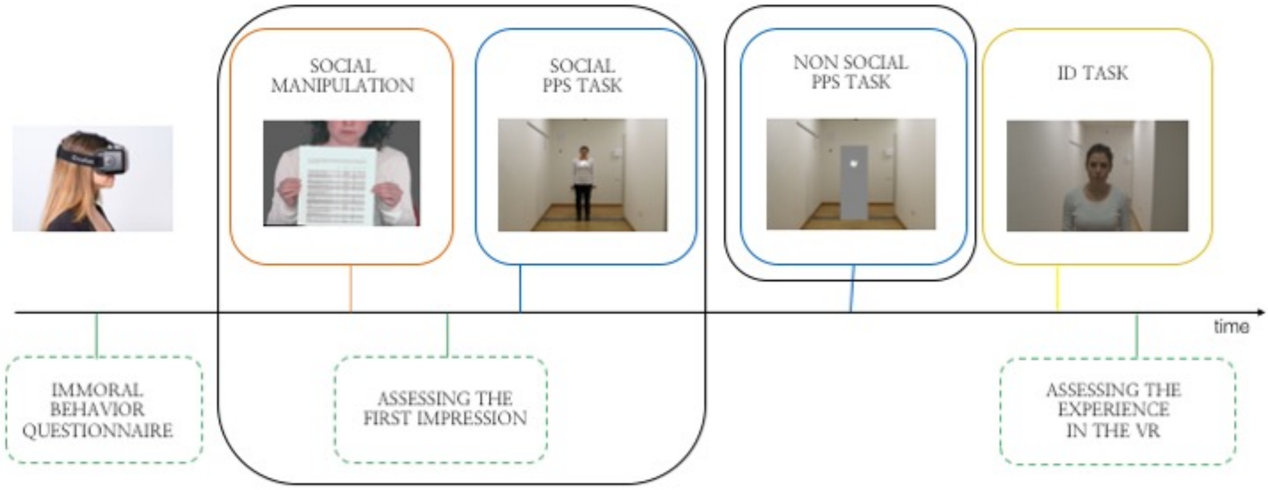


Figure 3. Experiment 2: Overview of the procedure.
Social manipulation: Participants saw in virtual reality the responses of the other person to the immoral behavior questionnaire. They were asked to form an impression of her.
Assessing the first impression: Participants responded to a series of questions concerning their impression on the morality of the other person, their attitude, identification and behavioral intentions to interact with her.
* The order of the Social PPS task and the Non-Social PPS task was counterbalanced between participants.
* The distance of the person and of the object was varied: half of the participants performed the task with the target presented close, the other half with the target presented far.

3.1.2.1 The Social manipulation: forming a first impression on the morality of the other person.

Participants watched a brief video in VR in which a female target (the same actress of Experiment 1 was shown, in the moral and the immoral condition) while she was sitting at a desk filling in a paper-and-pencil questionnaire, and then when she was holding the one-page questionnaire in her hands so as her responses were clearly visible. Note that the questionnaire was identical to the one that the participants filled in when arrived to the lab. Participants were asked to carefully read the items and the ratings given by the person in the video, so as to form an opinion of her. In the immoral behavior questionnaire, 17 behaviors were listed along with the responses allegedly reported by the person on a frequency scale ("*Never*" - "*Often*" - "*Always*" - "*I don't remember*"). Five items described immoral behaviors (i.e., "*Speaking ill of some friends*", "*Flirting with the boss in exchange of a favor*", "*Posting embarrassing pictures or videos of friends on the web, without their permission*", "*Revealing a secret of a friend without her/his permission*"), while the others were neutral and not related to morality (e.g., "*Eating always the same food at the restaurant*", "*Planning a trip with some friends*", "*Tidy up weekly*"). The frequency ratings to the five immoral behaviors of the female target were varied between participants to give an impression of the other as an immoral (i.e., high frequency of the immoral behaviors, e.g., *How often have you revealed a secret of a friend without her/his permission?,* response = "Often") or a moral person (i.e., low frequency of the immoral behaviors, response = "Never"). The allegedly paper-and-pencil questionnaire completed by the other person was also available for the participant on the desk during the full duration of the experiment.

This manipulation was tested in a separate pilot study in which participants (N = 24) were asked first to form an impression of two targets (in counterbalanced order) on the basis of their responses to the questionnaire and then to rate the two targets on a series of dimension used also in the main study (for a full description of the questions see the following paragraph). The participants judged the person who reported no immoral behaviors as more moral on three (i.e. fair (M_m = 5.46, DS_m = 1.10, and M_I = 2.25, DS_I = .74, for the moral and the immoral condition respectively), honest (M_m = 5.13, DS_m = 1.19, and M_I = 2.50, DS_I = 1.25) and loyal (M_m = 5.29, DS_m = 1.12, and M_I = 2.00, DS_I = .66), all $ts(23)$ all $ps < .001$) out the four traits (sincerity, (M_m = 4.83, DS_m = 1.13, and M_i = 4.38, DS_i = 1.56), $p = .25$) related to moral identity (Aquino and Reed, 2002). In addition, this target was also rated as more competent (M_m = 4.79, DS_m = 1.06, and M_i = 3.58, DS_i = .88), sociable (M_m = 5.08, DS_m = 1.14, and M_i = 3.71, DS_i = 1.33), and similar to the self (M_m = 4.42, DS_m = 1.38, and M_i = 1.78, DS_i = 1.24). Finally, the participants reported a more positive attitude (M_m = 52.04, DS_m = 32.18, and M_i = -19.17, DS_i = 41.06) and greater willingness to meet (M_m = 5.13, DS_m = 1.30, and M_i = 2.30, DS_i = 1.18) and interact (M_m = 4.75, DS_m = 1.26, and M_i = 2.41, DS_i = 1.25) with the person who never performed immoral behaviors (all $ts(23)$ all $ps < .001$).

3.1.2.2. Assessing the first impression, attitude, behavioral intentions and identification with the partner.

After watching the video, participants removed the headset and were asked to answer a series of questions. These are described here below. Note that the responses to these questions, if not differently specified, were registered on a 7-points scale (Likert scale, 1 = “not at all”, 7 = “completely”).

The first impression: target morality. To assess the perception of the social target, they rated the target on three traits related to morality (“*To what extent is she ..... fair, honest and loyal?”*) and other three positive traits (sincere, competent, sociable).

Identification. The identification with the target was tested by asking participants to evaluate the similarity with the target *(“To what extent is she similar to you?”*) and by the aid of a pictorial item, namely the Other in the Self Scale, or IOS). This scale is based on the concept of inclusion of the other into the self (Aron, Aron, & Smollan, 1992) that is the idea that close others are cognitively represented as included in the self-representation. The IOS has been widely used in social psychological studies as both a measure of identification (Schubert & Otten, 2002) and as a measure of interpersonal closeness (Gächter, Starmer, & Tufano, 2015).

Attitude. The attitude or overall evaluation was rated on two items (“*To what extent was she pleasant?*”; “*Please report your overall attitude toward her*”; responses were registered on a 21-

point scale (-100 = totally negative, 0 = neither positive or negative, +100 = totally positive).

Behavioral intention to interact. Finally, participants rated their "willingness to meet" and "willingness to interact" with the target as proxy of behavioral intention to interact ("*To what extent would you like to meet her? To what extent would you like to interact with her?*"). The participants completed also a paper-and pencil graphic version of a seating distance scale (Mehrabian & Diamond, 1971). This scale consists in eight chairs in a row. The participants' task was to choose the chair where they would like the target to be seated among the seven others that differed in terms of distance (1 = "closest", 7 = "furthest") from the chair they were supposedly seated.

3.1.2.3. Assessing the PPS

Participants performed the two different versions of the visuo-tactile interaction tasks developed in Experiment 1, namely the Social PPS task, when facing the other person they just formed their impression on, and the Non-Social PPS task, when facing an object.

The Social PPS task

The task was identical (number of trials, etc.) to the one described in Experiment 1 with a few exceptions. For about half of the participants the person appeared at a perceived distance of approximately 1.5 m (as in study 1), for the rest this distance was reduced and perceived about 0.9 m ($M_{estimation}$ = 0.9 mt away from the participant, SD = 15.46, N = 28). According to the Hall (1966) model of interpersonal distance, these distances correspond to social (interactions among acquaintances) and personal distance (interactions among friends and family), respectively. This variation was introduced with an exploratory intent.

The Non-Social PPS task

In this task the other person was replaced by a neutral object (i.e., a rectangular grey shape, whose size was matched to that of the other person in the social task). Again, the distance of the target was manipulated between-subjects, that is when the person appeared at a far (close) distance in the Social PPS task so appeared the object in the Non-Social PPS task. For the rest, the task was identical to that described in Experiment 1.

PPS analysis

In order to further study the change in PPS representation induced by the social manipulation and to provide more synthetic measures of PPS space representation, reaction time data in the social PPS task were also analyzed by means of fitting function. In particular, in line with previous studies (Canzoneri et al., 2012; Serino et al., 2015), we compared a linear or a sigmoidal function fitting the relationship between reaction time and the temporal delay of the tactile stimulation when the cube was perceived at different distances from the participants. The linear function was described by the following equation: $y(x) = y_0 + k * x$, where *x* represents the independent variable (i.e., the timing of touch delivery in ms), *y* the dependent variable (i.e., the reaction time), y_0 represents the intercept at x = 0 and k is the slope of the linear function. The sigmoidal function was the following:

$$y(x) = \frac{y_{min} + y_{max} \bullet e^{(x-x_c)/b}}{1 + e^{(x-x_c)/b}}$$

where *x* and y represents the same parameters as above, whereas y_{min} and y_{max} indicate the lower and upper saturation levels of the sigmoid, x_c the value of the abscissa at the central point of the sigmoid (i.e., the value of x at which $y = (y_{min} + y_{max})/2$) and *b* establishes the slope of the sigmoid at the central point. We firstly compared the goodness of fit the two functions, in order to select the more appropriate one, by comparing the coefficient of determination (R^2) of the sigmoid and linear functions for each situation (social PPS*moral; social PPS*immoral; non social

PPS*moral; non social PPS*immoral). Note that for this analysis, y_{min} and y_{max} values were fixated at the minimum and maximum possible RT, in order to estimate the same number of parameters. T-tests showed better fit (i.e., higher R^2) for the sigmoid than the linear function (all *ps* > .001). Thus, we chose the sigmoidal function for further analysis. This analysis allowed us to estimate the central position of the sigmoid, which is a single-value proxy of the location where the multisensory facilitation effect occurs (i.e., the distance of the PPS boundary) and the slope (*b* in the formula) as an index of the sharpness of the transition between the extrapersonal and the peripersonal space (see Serino et al., 2015). Importantly, lower values of the central point correspond to a less extended PPS, defined by borders that lie closer to the participant's body. On the other hand, higher values of the central point describe a wider PPS, with larger boundaries. Note that central point values are meaningless if the fitting of the sigmoidal function is too low. Thus, following the procedure of previous studies (e.g., Canzoneri et al., 2012; Teneggi et al., 2013; Ferri et al., 2015), when reporting this result, we excluded participants with $R^2 < .2$ for the sigmoidal fitting (N=7).

3.1.2.4. The interpersonal distance (ID)

We implemented the Stop Distance Paradigm (Hayduk, 1978) in augmented reality. Participants were asked to wear the head-mounted display, through which they saw a video showing the same person they formed the impression on. After 2 seconds the person, originally standing at a distance of approximately 4 mt, started approaching them walking at a constant velocity. Participants were asked to press the button of the mouse to stop the person at the distance they judge 'no more comfortable'. The task was repeated 6 times. The button press times were registered as proxy of Interpersonal distance (longer time, closer distance).

3.1.2.5. Final questionnaire: evaluating the immersive reality experience.

At the end of the experiment participants were to evaluate to what extent the experience in the immersive reality was annoying and realistic. The responses were given on a 7-point scale (1 =

not at all; 7 = very much).

4. Results

The social manipulation was effective in modulating multiple dimensions of social processing assessed in the present study. In particular, it affected attitudes, identification and behavioral intention to interact with the target.

4.1. The first impression: target morality. The manipulation was successful. The target was judged as a more moral person in the moral (i.e., no immoral behaviors, M = 5.89, DS = .93) as compared to the immoral condition (i.e., frequent immoral behaviors, M = 1.74, DS = .81), ($t(54) = 17.797$, $p < .001$). Interestingly this negative impression also influenced the rating of the target competences ($M_m = 5.57$, $DS_m = .92$, and $M_i = 4.00$, $DS_i = 1.36$, for the moral and the immoral condition respectively $t(54) = 5.062$, $p < .001$) and sincerity ($M_m = 5.64$, $DS_m = 1.13$, and $M_i = 3.68$, $DS_i = 2.13$, for the moral and the immoral condition respectively, $t(54) = 4.317$, $p < .001$), but not of sociability, that did not differ across conditions ($M_m = 5.50$, $DS_m = 1.23$, and $M_i = 5.36$, $DS_i = 1.37$, for the moral and the immoral condition respectively, $t(54) = .411$, $p = .683$).

4.2. Attitude. The target was perceived as more pleasant in the moral ($M_m = 5.04$, $DS_m = .99$) than in the immoral ($M_i = 2.25$, $DS_i = 1.01$) condition ($t(54) = 10.403$, $p < .001$). Coherently, the overall attitude toward the target was more positive in the moral ($M_m = 60.71$, $DS_m = 26.38$) than in the immoral ($M_i = -46.43$, $DS_i = 29.34$) condition ($t(54) = 14.370$, $p < .001$).

4.3. Identification. Participants reported stronger similarity toward the moral ($M_m = 5.43$, $DS_m = 1.17$) than the immoral ($M_i = 1.86$, $DS_i = .76$) person ($t(54) = 13.580$, $p < .001$). A similar effect emerged also for the IOS, with stronger inclusion of the other into the self for the moral other ($M_m = 3.39$, $DS_m = 1.40$), and $M_i = 1.89$, $DS_i = .79$, $t(54) = 4.952$, $p < .001$).

4.4. Behavioral intention to interact. Finally, participants reported more willingness to meet (M_m = 4.89, DS_m = 1.10, and M_I = 2.14, DS_I = 1.11), $t(54) = 9.300$, $p < .001$) and to interact (M_m = 4.96, DS_m = 1.04, and M_I = 2.18, DS_I = 1.12), $t(54) = 9.645$, $p < .001$), and smaller seating distance (M_m = 1.64, DS_m = .73, and M_I = 4.14, DS_I = 1.48), $t(54) = -7.998$, $p < .001$) with the person perceived as moral than to the one perceived as immoral.

4.5. PPS representation

In line with previous studies (e.g., Noel et al., 2015a; Noel et al., 2015b; Serino et al., 2015; see also Experiment 1), in order to provide a general measure of multisensory processing in PPS, we computed baseline-corrected RT, by subtracting the fastest RT to the uni-modal tactile trials from mean RTs at each distance for the in visuo-tactile trials. In this way, we measured the modulation of tactile processing due to the distance of the visual stimulus, maintaining the most conservative approach to identify a real multisensory facilitation effect. We first run a complete ANOVA on the results of the two tasks. To this aim, baseline-corrected RTs for each interval time of the tactile stimulation were submitted to a repeated measures ANOVA with the perceived Distance of the cube (D1-D6) and the PPS task (Social vs Non-Social) as within-subjects factors and the Condition (Moral vs Immoral), the Position of the Target (close vs far) and the Order of the PPS task (Social – Non-Social vs Non-Social - Social) as between-subjects factors. The Mauchly's Test of Sphericity revealed a violation of the assumption of sphericity ($\chi^2(14) = 28.83$, $p = .01$); thus, we applied the Huynh-Feldt correction. The expected three way interaction PPS task X Distances X Condition was marginal significant ($F(5.000, 240.000) = 2.016$, $p = .077$, $\eta_p^2 = .04$). Although the interaction did not reach the conventional value of statistical significance ($p < .05$), given that we had some a-priori hypothesis, we decomposed the interaction and run separate analysis for the Social and the Non-Social PPS.

4.5.1 The Social PPS task

Baseline-corrected RTs for each interval time of the tactile stimulation were submitted to a repeated measures ANOVA with the perceived Distances of the cube (D1-D6) as the within-subjects factor and Condition (moral vs. immoral target), Position of the Social target (close vs. far) and the Order of the PPS tasks (Social – Non-social vs Non-social – Social) as between-subjects factors. Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated ($p < .001$). Applying the Huynh-Feldt correction, we found a significant main effect for the Distances of the cube ($F(3.910, 187.687) = 53.082$, $p < .001$, $\eta_p^2 = 0.525$), showing the typical finding in the PPS research that is, RTs were faster at closer distances of the cube from the participant body. Post-hoc comparisons showed that RT ad D1, D2 and D3 were significant faster than those at D4, D5, and D6 (all *ps* < .01 Bonferroni corrected) and that RT at D1 and D2 were significantly faster than the fastest uni-modal tactile trial (single sample t-test, both *ps* < .003, Bonferroni corrected). Most importantly, this effect was qualified by a significant two-way Distances X Condition interaction ($F(3.910, 187.687) = 3.042$, $p = .019$, $\eta_p^2 = .060$), suggesting that the participants multisensory representation of the PPS differed depending on whether they faced the moral or the immoral person.

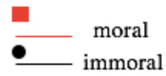
The post hoc comparison confirmed this hypothesis (see Figure 4A). Indeed, when facing the immoral person, tactile responses at D6, D5 and D4 were slower than responses at D3, D2 and D1 (all *ps* < .002, Bonferroni corrected), suggesting that the facilitation effect on tactile processing due to the visual stimulus occurred when this was located between the D3 and the D4 ($p < .002$, Bonferroni corrected). Instead, when facing the moral target, RTs at D6 and D5 were slower than those at all other distances (all *ps* < .05, Bonferroni corrected), whereas RTs at D4 were as fast as at D3 ($p = .78$), suggesting that, in this condition, the facilitation effect of the virtual object on tactile processing occurred when this was located at a father distance from the participants, meaning closer to the moral other person. Indeed, the comparisons among the distances across the two social conditions showed that RTs were similarly fast at every distances (all *ps* > .26) except than at D4, where the responses in the moral condition were faster than those in the immoral one ($p = .03$).

The analysis of the parameters from the sigmoidal function describing the relationship between baseline-correct RT and distance further confirmed the change in the shape of PPS as induced by the social manipulation. In particular, we found that the value of the central point of the curve was significantly higher in the moral than in the immoral condition ($CP_{immoral} = 3.43$, $SD_{immoral} = .70$ and $CP_{moral} = 3.78$, $SD_{moral} = .74$, $t(47) = 1.689$, $p = .049$ (one-tailed)), suggesting that in the former case participants' PPS was extended towards the other perceived more positively. No difference in the slope of the function was found, suggesting the degree of transition between near and far space did not vary between the two social conditions.

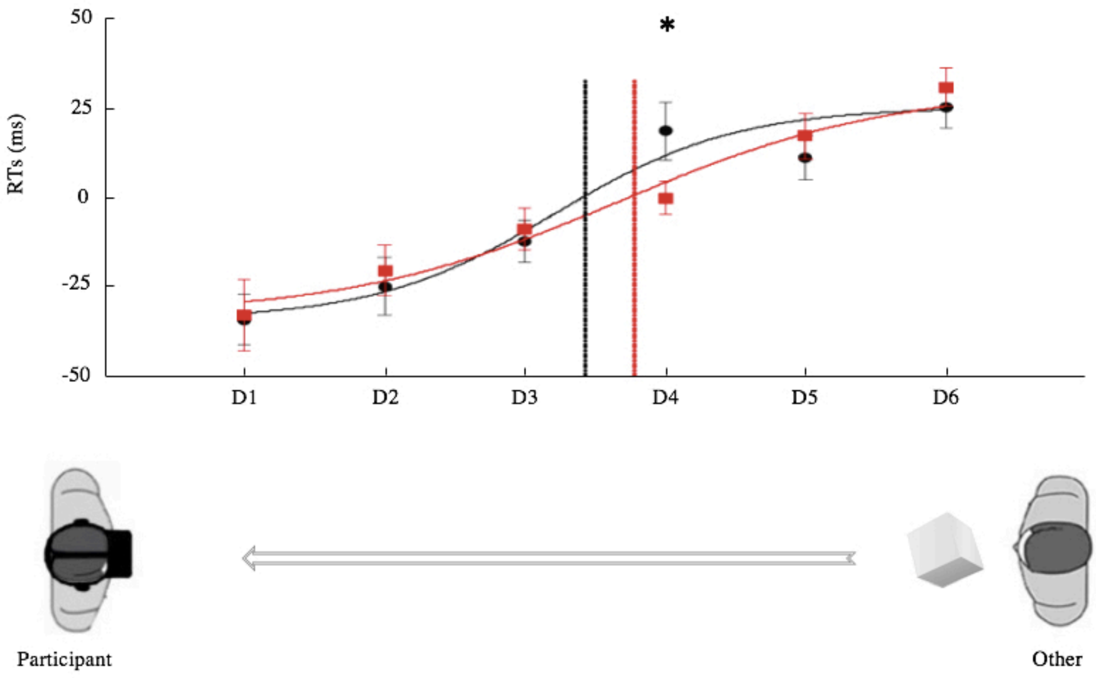
No other interactions from the main ANOVA were significant (all $ps \geq .337$), suggesting that the distance of the social target and the order of the administration of the blocks had no influence on the results.

4.5.2 The Non-Social PPS task

Baseline-corrected RTs for each interval time of the tactile stimulation were submitted to a repeated measures ANOVA with Distances of the cube (D1-D6) as the within-subjects factor and Condition (moral vs. immoral target), Distance of the Non-Social target (close vs. far) and Order of the PPS tasks (Social – Non-social vs. Non-social – Social) as between-subjects factors. The Mauchly's Test of Sphericity revealed a violation of the assumption of sphericity ($\chi^2(14) = 28.83$, $p < .001$); thus, we applied the Huynh-Feldt correction and, as expected, we found again a significant main effect of the Distances of the cube ($F(2.949, 141.574) = 63.733$, $p < .001$, $\eta_p^2 = 0.570$). Post-hoc comparisons showed that RT at D1, D2 and D3 were faster than those at D4, D5 and D6 (all $ps < .01$, Bonferroni corrected) and that RT at D1 and D2 were significantly faster than the fastest uni-modal tactile trial (single sample t-test, both $ps < .003$, Bonferroni corrected). Importantly, for the Non-social PPS task, the two-way interaction Distances X Condition was not significant (F(2.949, 141.574) = .235, p = .869, η_p^2 = .005), so as the Distances X Condition X Order of the PPS task interaction (F(2.949, 141.574) = 1.035, p = .378, η_p^2 = .021), indicating that the social manipulation did not affect the PPS as assessed in non social domain. No other interaction was significant (all $ps \geq$ .306), except for a marginal significant interaction between Distances and the Distance of the Non-Social target (F(2.949, 141.574) = 2.503, p = .063, η_p^2 = .050). The absence of a change in the shape of the PPS for the non-social task was also confirmed by the function analyses, showing no significant difference between the central points in the moral and the immoral conditions ($CP_{immoral}$ = 3.456, $SD_{immoral}$ = .73 and CP_{moral} = 3.50, SD_{moral} = .72, $t(47)$ = .211, p = .417 (one-tailed).



A



B

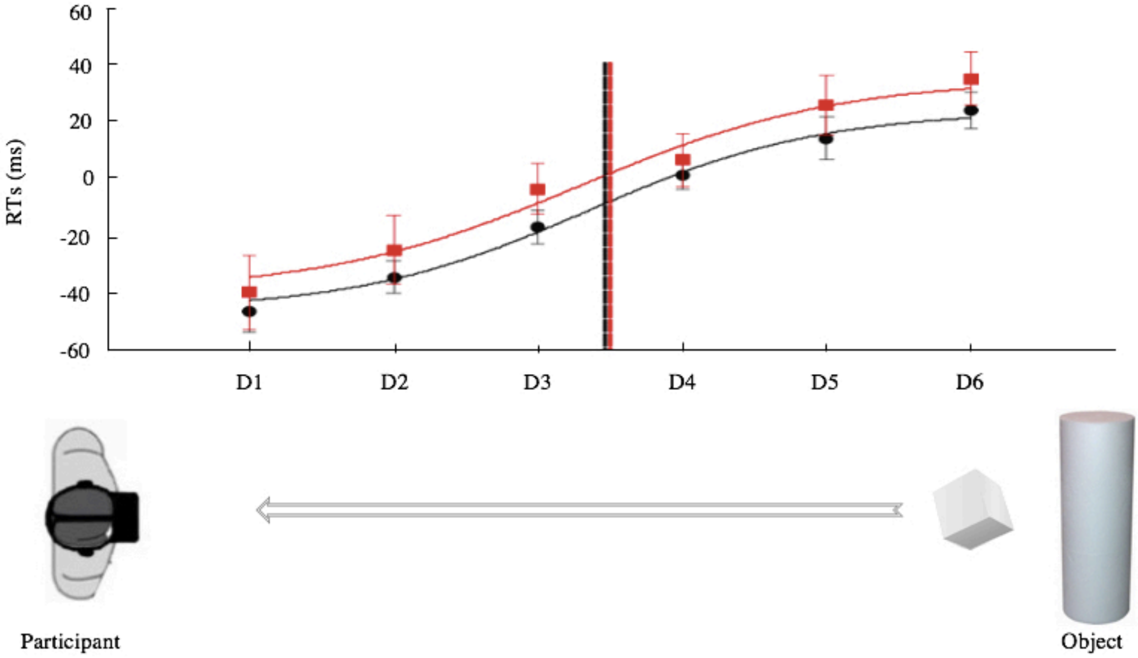


Figure 4. Social modulation of PPS representation.
Panel A. Results from the Social PPS task. The graph shows mean RTs at the different perceived distances of the cube (error bars represent SEM) for the Moral (red) and the Immoral (black) condition, when participants were facing the other person. Data are fitted with a sigmoidal function, and the vertical lines represent the location of the central point of the sigmoidal function for the Immoral (black line) and the immoral (red line) condition. The results show an extension of the PPS boundaries toward the moral, as compared to the immoral, other.
Panel B. Results from the Non-Social PPS task. The graph shows the mean RTs at the different perceived distances of the cube (error bars represent SEM), and the respective sigmoidal function (with central point – vertical line) for the Moral and the Immoral condition, when participants were facing a neutral object.

4.5.3 Social vs Non-Social PPS tasks: additional analyses

In the present experimental design, half of the participants run the Non-Social PPS task before the manipulation and the other half after the manipulation. Thus, the effect of the social impression manipulation on the Non-Social PPS task could be effective only in the second half of the participants, whereas in all participants it could affect the Social PPS task, as this always followed the social impression manipulation. Therefore, in order to exclude that the differential effects on the Social and Non-Social PPS tasks was due to comparatively less statical power for the latter condition, we run further analyses only in those participants where the social manipulation preceded both PPS tasks. These analyses showed that the social manipulation did not affect the Non-Social

PPS task (interaction Condition X Distance: $F(3.098, 71.257) = 0.527$, $p = .671$; Huynh-Feldt corrected), whereas significantly affected the Social PPS task ($F(4.203, 96.661) = 3.15$, $p = .016$; Huynh-Feldt corrected). In the Non-Social PPS task, the RT function was equivalent both for the participants who were facing the "moral other" and for those facing the "immoral other". In contrast, the RT function for the Social PPS task was different depending on the nature of the impression of the other person as induced by the social manipulation; a more extended PPS representation emerged in the moral as compared to the immoral condition. These analyses confirm the main finding of the study, although they were conducted on a reduced number of participants (those who received the social manipulation - that is the impression formation task - at first).

We then run a second set of analyses aimed at exploring the difference between the PPS representation when facing a person (i.e. the social PPS) and an object (i.e. the non-social PPS), independently from the social impression manipulation. Although this was not a goal of the present study, we investigated whether the present results were in line with previous evidence from Teneggi et al. (2013, Study 1), who found that participants' PPS was more extended when facing an anthropomorphic object (i.e. robot) than a person (for other comparisons between the social and non-social PPS, see also Iachini, Coello, Frassinetti, & Ruggiero, 2014). As reported in 4.5, the complete ANOVA did not yield a PPS task X Distance significant interaction, ($F(5.000, 240.000) = 1.625$, $p = .15$, Huynh-Feldt corrected), but three-way a PPS task X Distance X Condition significant interaction ($F(5.000, 240.000) = 2.016$, $p = .077$, $\eta_p^2 = .04$, Huynh-Feldt corrected). This suggests that the difference between the PPS representation in the social and in the non-social context was modulated by the morality manipulation. To better understand the difference between the PPS representation when facing a person or an object, we run an ANOVA with PPS Task, Distance of the cube, Position of the Target and Order of the PPS task, separately for moral and immoral other condition. For the moral other condition, the PPS task X Distance interaction was not significant, ($F(5.000, 120.000) < 1$, Huynh-Feldt corrected), so as any other higher order interaction involving both the PPS task and the Distance factor (all *ps* $\geq$.10). In the immoral condition, a significant PPS task X Distance interaction emerged, ($F(5, 120) = 2.258$, $p = .033$, $\eta_p^2 = .095$). Post-hoc comparisons among the distances across the two PPS tasks showed that the RTs were similarly fast at every distance (all *ps* > .20), except than for the D4, where the responses when the participants were facing the object were faster than when in front of the person ($p = .008$, Bonferroni corrected) (See Figure 5; for the comparisons among the distances within each PPS task, we redirect the reader to 4.5.1, for the social PPS, and 4.5.2, for the Non-Social PPS). This result suggests that PPS was less extent when facing a person rather than an object, a pattern of results consistent with the one found in Teneggi et al. (2013).

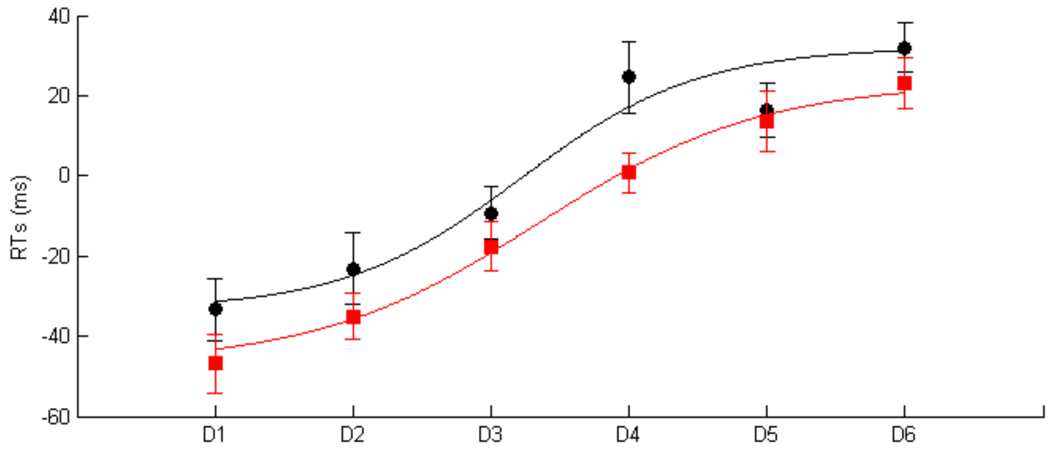


Figure 5 The Social and Non-Social PPS in the Immoral condition
The graph shows mean RTs at the different perceived distances of the cube (error bars represent SEM) for the Social PPS task (black) and the Non-Social PPS task (red) in the Immoral condition.

4.6 The interpersonal distance task.

An average of the button press time for the 6 trials was calculated and used as a proxy of the comfort distance in the stop distance paradigm. As expected, participants stopped the person approaching them at shorter duration of the video, i.e. greater distance, when she was described as immoral rather than moral ($t(54) = 3.744$, $p < .001$).

4.7. Correlational analysis

We investigated the relationship between the different effects induced by the social impression manipulation by a series of correlational analyses, whose results are reported in Table 1. Consistently with literature in social psychology, measures of identification, overall attitude and behavioral intention to interact are highly positively correlated among each other. These measures are also positively and significantly correlated with the interpersonal distance, showing that the more participants identified with the target, the more positive was the attitude and the intention to interact with her, the closer they allowed the target to come to their body. For the central point of the social PPS curve, the correlations with the social measures were all in the same direction.

However,, only the correlation with the self-other overlap ($r(49) = .283$, $p = .049$) and the behavioral intention to interact ($r(49) = .295$, $p = .039$) reached the conventional value for statistical significance: the greater willingness to interact with the other person and the more the self-and the other representations overlapped (i.e. IOS), the greater the extension of the participant' PPS toward the partner was. The interpersonal distance measured as comfort zone and the PPS central point were not correlated between each other.

Table1. Inter-correlations among Experiment 2 Variables.

	M	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13
1. CP	3.60	.73	1												
2. Morality	3.75	2.30	.25	1											
3. Competence	4.71	1.46	.22	.79***	1										
4. Sincerity	4.53	2.01	.04	.63***	.60***	1									
5. Sociability	5.43	1.35	.19	.09	.04	.24	1								
6. Pleasant	3.59	1.74	.21	.91***	.81***	.65***	.14	1							
7. Global Attitude	3.67	59.8	.23	.93***	.75***	.70***	.01	.89***	1						
8. Similarity	3.55	2.07	.20	.85***	.71***	.58***	.06	.84***	.85***	1					
9. IOS	2.59	1.35	.28*	.67***	.57***	.46**	.09	.70***	.70***	.69***	1				
10. Willingness to meet	3.43	1.80	.23	.87***	.78***	.59***	.16	.95***	.86***	.80***	.65***	1			
11. Willingness to interact	3.51	1.84	.30*	.87***	.79***	.59***	.18	.91***	.88***	.87***	.73***	.93***	1		
12. Seating Distance	3.08	1.73	-.26	-.80***	-.61***	-.56***	-.09	-.78***	-.86***	-.78***	-.63***	-.79***	-.85***	1	
13. ID	13.1	2.94	-.01	.46**	.44**	.34*	-.15	.50***	.57***	.42**	.45***	.47**	.48***	.51***	1

* $p < .05$; ** $p < .01$; *** $p < .001$

5. Discussion

In the present study, we investigated whether and how social context shapes the representation of individuals' multisensory PPS. To this aim, in Experiment 1, we developed in augmented reality and validated a new behavioural task to quantify the extent of individuals' PPS representation when facing another person in a realistic context, i.e., the social PPS task. This task, inspired by a well-validated audio-tactile PPS paradigm (e.g., Canzoneri et al, 2012; Teneggi et al., 2013; Ferri et al., 2015; Taffou & Viaud-Delmon, 2014), captures the spatial modulation of multisensory interaction as a proxy of PPS representation (Rizzolatti et al., 1997; Graziano & Cooke, 2006; Ladavas & Serino, 2008; Clery et al., 2015). Here we show that a virtual approaching visual stimulus, presented in a pre-recorded scene whereby the participant was immersed by means of a head-mounted display in presence of another person, speeded up participant's reaction time to a tactile stimulation on her body. This visuo-tactile interaction effect depended on the distance between the virtual stimulus and the body of the participant, as a significant facilitation emerged specifically when the virtual object was closer than a certain distance, which can be measured as proxy of the location of the boundary of individual's PPS (Serino et al., 2015; Ferri et al., 2016; Serino, 2016).

Then in Experiment 2 we used this task to test whether and how participants' PPS representation varies as a function of the social perception of the person they are facing. Relying on a well-established procedure in social psychology, in which participants are asked to form an impression of a stranger on the basis of some pieces of information (in this case whether the person behaved morally or immorally accordingly to a series of answers to a questionnaire), we experimentally manipulated the social perception participants gathered about the other person as a moral or an immoral character. We found that such high-level and social manipulation affected the participants' PPS representation, as assessed by the social visuo-tactile PPS task. The distance at which the virtual stimulus speeded up tactile reaction times was farther in space when participants were facing a moral than an immoral person, suggesting that, in the moral condition, participants' PPS extended towards the other person.

This finding is in line with previous studies (Teneggi et al., 2013; Maister et al., 2015; Heed et al., 2010) showing a social modulation of PPS representation. However, in the present research we extend this evidence by showing that a PPS modulation occurs even in the initial moments of a social encounter, that is when we form a first impression of another person: what we think of the other person placed in the far space is sufficient to influence our PPS representation. Differently from Teneggi et al. (2013) and Maister et al. (2015), our participants had no direct exchanges or experience with the other person, as our manipulation just varied the type of information available to the participants to form an idea about the moral character of the other person. Nevertheless, this was sufficient to modulate the participants' PPS. In addition, we showed that this change in PPS representation was strictly "social". Indeed our morality manipulation selectively affected PPS in a social context, since, no changes in the extent of PPS was found when PPS was probed when participants were facing a neutral object instead of a person. One could however argue that our social manipulation did not have an effect on the non-social PPS, as it never directly preceded this task. Although we cannot exclude this possibility, it should be noted that the morality manipulation still influenced the interpersonal distance measure that was always the last task administered suggesting the the effect of the manipulation lasted for the whole duration of the experimental session.

This finding echoes those from a previous study showing an extension of PPS representation when in presence of a partner of a positive and fair interaction (Teneggi et al., 2013), whereas it differs from another study by Iachini et al. (2015), who found a contraction of the PPS when in presence of a moral as compared to an immoral person. However, in order to quantify the size of participants' PPS, Iachini and colleagues used a reachability task (implemented within a stop-paradigm, i.e. pressing a button when an approaching virtual other was at a hand reaching distance), whereas here we used a visuo-tactile interaction task to fully capture the multisensory nature of the PPS around the body (Serino et al., 2015; Serino et al., 2016). Thus, although these findings appear at a first sight opposite to each other, this incongruence might depend on the nature of the task used, and these results might be actually driven by similar psychological processes. Indeed, both a reduced reachability distance (as in Iachini et al., 2015) and an extended multisensory interaction space towards the other – may reflect a positive attitude and willingness to interact with the person in the far space. This possibility is supported by the similarities between our and Iachini et al. (2015) findings concerning the participants comfort distance, that was shorter toward the moral than the immoral person.

To better understand which social process triggers such PPS extension, we also assessed a series of social outcomes (i.e. attitude, behavioural intention to interact and identification) of perceiving the other as a moral (vs. immoral) person. We know from research in social cognition that social perception is ultimately for action. Differently stated, we form an impression of other person as this guides our behaviour toward that person (Fiske & Taylor, 2013). Consistently with this tenet and with previous studies on morality (Goodwin, 2015 for a review), we found that the more the other person was perceived as moral, the more positive was the attitudes toward her and the greater was the willingness to directly interact with that person. These results also confirm the effectiveness of our social manipulation. Interestingly, the behavioural intention to interact with the person and the identification with her were significantly correlated with location of the boundary of participants social PPS (as captured by the shift in the central point of the sigmoidal function of the social PPS). These results suggest the involvement of two high-level social processes in the PPS regulation. On the one hand, the correlation between the location of the PPS boundary and the behavioural intention to interact is suggestive that similarly to non-social contexts, also in social context, an action-related goal is implicated in regulating the extent of PPS. On the other hand, the correlation with identification is coherent with the idea that a PPS extension is the result of including or remapping the other's PPS into one's own PPS (Teneggi et al., 2013; Maister et al., 2015). This said, these considerations should be taken with cautions as they are based on correlations from a relative small sample of participants. Future studies are needed to replicate these findings and to further understand the functions of PPS plasticity in social contexts.

A final goal of the present research was to explore the relation between the regulation of the multisensory PPS and the personal space, operationalized as the preferred comfortable interpersonal distance between the participants and the other person. These two conceptualizations of the space around the body have been sometimes treated as overlapping notions (e.g., Kennedy. Gläscher, Tyszka, & Adolphs, 2009; de Vignemont & Iannetti, 2015; Iachini et al., 2015, 2016). Research has only recently started to empirically investigate the relation between these two spatial representations providing contrasting evidence on whether they share common code (Iachini et al., 2015, 2016) or are independent from each other (Patanè, Iachini, Farnè, & Frassinetti, 2016). In the present research we found that participants accepted a closer interpersonal distance when facing a moral than an immoral person. This result is consistent with previous studies manipulating morality (Iachini et al., 2015) and coherent with work in social psychology suggesting that interpersonal distance reduces toward a person we like (e.g. Fasoli et al., 2016; Novelli, Drury, & Reicher, 2010; Word, Zanna, & Cooper, 1974). The fact that the PPS and the ID were similarly affected by our social manipulation and correlated with similar social outcomes (e.g. the behavioural intention to interact) suggests that these two space regulations might respond to some similar processes at least in this specific context under investigation (i.e. person morality). However, this does not imply that they serve exactly the same functions in the social context. For instance, a closer interpersonal distance might be functional to signal the other the desire to interact, with some affective connotation. Differently an extension of the PPS might reflect the motor component preparation of physically interacting with the other person.

As a final contribution, the present study also describes a new task to measure PPS in social context. The social PPS task has been created by means of a new virtual reality technology, namely the Reality Substitution Machine (RealiSM), which merged together pre-recorded scenes and virtual elements in predetermined way. This allowed us to modify the environment in a fully controlled way, adding a movie of another person in space, while over-imposing virtual experimental stimuli, in a fully synchronized way. The implementation of multisensory interaction tasks in virtual reality represents a powerful tool for researchers interested in studying the social role of PPS, as it allows to capture the boundaries of the PPS in a validated and fully controlled experimental set-up, yet maintaining the complexity and the richness of real social events.

To sum up, here we show that social perception, that is the ability to form an impression of other people, influences not only the psychological relations with that person but also the multisensory representation of the space between oneself and the other. These results add new evidence to the role of PPS representation as an interface not only for individual-objects interaction, as previously concevied, but also for individual-individual interactions and more generally on the relation between social cognition and body processing.

REFERENCES

Avenanti, A., Annela, L., & Serino, A. (2012). Suppression of premotor cortex disrupts motor coding of peripersonal space. *Neuroimage, 63(1),* 281-288. doi:10.1016/j.neuroimage.2012.06.063.

Aquino, K., & Reed, A. (2002). The self importance of moral identity. *Journal of Personality and Social Psychology, 83(6),* 1423-1440. doi: 10.1037/0022-3514.83.6.1423

Aron, A., Aron, E. N., & Smollan, D. (1992). Inclusion of Other in the Self Scale and the structure of interpersonal closeness. *Journal of personality and social psychology*, *63*(4), 596-612. http://dx.doi.org/10.1037/0022-3514.63.4.596

Bassolino, M., Finisguerra, A., Canzoneri, E., Serino, A., & Pozzo, T. (2015). Dissociating effect of upper limb non-use and overuse on space and body representations. *Neuropsychologia, 70,* 385-92. doi: 10.1016/j.neuropsychologia.2014.11.028

Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, Neural, and Computational Principles of Bodily Self-Consciousness. *Neuron, 88,* 145-66. doi: 10.1016/j.neuron.2015.09.029

Brambilla, M., Rusconi, P., Sacchi, S., & Cherubini, P. (2011). Looking for honesty: The primary role of morality (vs. sociability and competence) in information gathering. *European Journal of Social Psychology, 41(2),* 135-143. DOI: 10.1002/ejsp.744

Brambilla, M., Sacchi, S., Pagliaro, S., & Ellemers, N. (2013). Morality and intergroup relations: Threats to safety and group image predict the desire to interact with outgroup and ingroup members. *Journal of Experimental Social Psychology, 49(5),* 811-821. http://dx.doi.org/10.1016/j.jesp.2013.04.005

Brambilla, M., Sacchi, S., Rusconi, P., Cherubini, P., & Yzerbyt, V. Y. (2012). You want to give a good impression? Be honest! Moral traits dominate group impression formation. *British Journal of Social Psychology, 51(1),* 149-166. doi: 10.1111/j.2044-8309.2010.02011.x.

Bremmer, F., Duhamel, J. R., Ben Hamed, S., & Graf, W. (2002). Heading encoding in the macaque ventral intraparietal area (VIP). *European Journal of Neuroscience, 16*, 1554–1568.

Brozzoli, C., Cardinali, L., Pavani, F., & Farnè, A. (2010). Action-specific remapping of peripersonal space. *Neuropsychologia, 48(3),* 796-802. DOI: 10.1016/j.neuropsychologia.2009.10.009

Brozzoli, C., Gentile, G., Bergouignan, L., & Ehrsson, H. H. (2013). A shared representation of the space near oneself and others in the human premotor cortex. *Current Biology, 23(18),* 1764-8. doi: 10.1016/j.cub.2013.07.004.

Brozzoli, C., Ehrsson, H. H., Farnè, A. (2014). Multisensory representation of the space near the hand: from perception to action and interindividual interactions. *Neuroscientist, 20(2),* 122-135. doi: 10.1177/1073858413511153.

Canzoneri, E., Magosso, E., & Serino, A. (2012). Dynamic sounds capture the boundaries of peripersonal space representation in humans. *PLoS ONE 7,* e44306. http://dx.doi.org/10.1371/journal.pone.0044306

Canzoneri, E., Marzolla, M., Amoresano, A., Verni, G., & Serino, A. (2013). Amputation and prosthesis implantation shape body and peripersonal space representations. *Scientific Reports, 3(2844)*. doi:10.1038/srep02844

Cléry, J., Guipponi, O., Wardak, C., & Hamed, S. B. (2015). Neuronal bases of peripersonal and extrapersonal spaces, their plasticity and their dynamics: Knowns and unknowns. *Neuropsychologia, 70,* 313-326. doi: 10.1016/j.neuropsychologia.2014.10.022.

Cooke, D. F., & Graziano, M. S. (2004). Sensorimotor integration in the precentral gyrus: polysensory neurons and defensive movements. *Journal of Neurophysiology, 91,* 1648-1660. DOI: 10.1152/jn.00955.2003

di Pellegrino, G., & Ladavas, E. (2014). Peripersonal space in the brain. *Neuropsychologia, 66C,* 126-133. http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.011

di Pellegrino, G., Làdavas, E., & Farnè, A. (1997). Seeing where your hands are. *Nature, 388(6644),* 730. DOI: 10.1038/41921

de Vignemont, F., Iannetti, G. D. (2015). How many peripersonal space? *Neuropsychologia, 70,* 327-334. http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.018

Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1998). Ventral Intraparietal area of the macaque: Congruent visual and somatic response properties. *Journal of Neurophysiology, 79,* 126–136.

Fasoli, F., Paladino, M. P., Carnaghi, A., Jetten, J., Bastian, B., & Bain, P. (2016). Not "just words": Exposure to homophobic epithets leads to dehumanizing and physical distancing from gay men. *European Journal of Social Psychology, 46,* 237-248. DOI: 10.1002/ejsp.2148

Ferri, F., Costantini, M., Tajadura-Jiménez, A., Väljamäe, A., & Vastano, R. (2015). Emotion-inducing approaching sounds shape the boundaries of multisensory peripersonal space. *Neuropsychologia 70,* 468 - 475. doi: 10.1016/j.neuropsychologia.2015.03.001

Fiske, S. T., & Taylor, S. E. (2013). *Social cognition: From brains to culture* (2/e). London: Sage.

Gächter, S., Starmer, C., & Tufano, F. (2015). Measuring the closeness of relationships: a comprehensive evaluation of the'Inclusion of the Other in the Self'scale. *PloS one*, *10*(6), e0129478. http://dx.doi.org/10.1371/journal.pone.0129478

Goodwin, G. P. (2015). Moral character in person perception. *Current Directions in Psychological Science, 24(1),* 38-44.

Goodwin, G. P., Piazza, J., & Rozin, P. (2014). Moral character predominates in person perception and evaluation. *Journal of Personality and Social Psychology, 106(1),* 148-168. doi: 10.1037/a0034726.

Graziano, M. S., & Cooke, D. F. (2006). Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia, 44(13),* 845-859. doi:10.1016/j.neuropsychologia.2005.09.009

Graziano, M. S., Yap, G. S., & Gross, C. G. (1994). Coding of visual space by pre-motor neurons. *Science, 266,* 1054 -1057. DOI: 10.1126/science.7973661

Graziano, M. S., Taylor, C. S., & Cooke, D. F. (2002). The cortical control of movement revisited. *Neuron, 36(3),* 349-362.

Hall, E. T. (1966). The Hidden Dimension. New York: Doubleday.

Hayduk, L.A., (1983). Personal space: where we now stand. *Psychological Bulletin, 94(2),* 293–335.

Heed, T., Habets, B., Sebanz, N., & Knoblich, G. (2010). Others' actions reduce cross-modal integration in peripersonal space. *Current Biology, 20(15),* 1345–1349. http://dx.doi.org/10.1016/j.cub.2010.05.068

Iachini, T., Coello, Y., Frassinetti, F., & Ruggiero, G. (2014). Body Space in Social Interactions: A Comparison of Reaching and Comfort Distance in Immersive Virtual Reality. *PLoS ONE*, *9*(11), e111511. http://doi.org/10.1371/journal.pone.0111511

Iachini, T., Coello, Y., Frassinetti, F., Senese, V. P., Galante, F., & Ruggiero, G. (2016). Peripersonal and interpersonal space in virtual and real environments: effects of gender and age. *Journal of Environmental Psychology, 45,* 154-164. http://dx.doi.org/10.1016/j.jenvp.2016.01.004

Iachini, T., Pagliaro, S., & Ruggiero, G. (2015). Near or far? It depends on my impression: moral information and spatial behavior in virtual reality. *Acta Psychologica 161,* 131-136. doi: 10.1016/j.actpsy.2015.09.003.

Kennedy. D. P., Gläscher, J., Tyszka, J. M., & Adolphs, R. (2009). Personal space regulation by the human amygdala. *Nature Neuroscience, 12,* 1226–1227. doi: 10.1038/nn.2381.

Ladavas, E. (2002). Functional and dynamic properties of visual peripersonal space in humans. *Trends in Cognitive Sciences,* 6, 17-22. DOI: http://dx.doi.org/10.1016/S1364-6613(00)01814-3

Ladavas, E., & Farnè, A. (2004). Visuo-tactile representation of near-the-body space. *Journal of Physiology-Paris., 98(1-3),* 161-170. http://dx.doi.org/10.1016/j.jphysparis.2004.03.007

Ladavas, E., & Serino, A. (2008). Action-dependent plasticity in peripersonal space representations. *Cognitive Neuropsychology, 5,* 1099-113. DOI: 10.1080/02643290802359113

Maister, L., Cardini, F., Zamariola, G., Serino, A., & Tsakiris, M. (2015). Your place or mine: shared sensory experiences elicit a remapping of peripersonal space. *Neuropsychologia, 70,* 455-461. doi: 10.1016/j.neuropsychologia.2014.10.027

Makin, T. R., Holmes, N. P., Brozzoli, C., Rossetti, Y., & Farne, A. (2009). Coding of visual space during motor preparation: approaching objects rapidly modulate corti-cospinal excitability in hand-centered coordinates. *The Journal of Neuroscience, 29(38),* 11841–11851. doi: 10.1523/JNEUROSCI.2955-09.2009

Makin, T. R., Holmes, N. P., Brozzoli, C., & Farnè, A. (2012). Keeping the world at hand: Rapid visuomotor processing for hand–object interactions. *Experimental Brain Research, 219,* 421-428. doi: 10.1007/s00221-012-3089-5.

Maravita, A. & Iriki, A. (2004). Tools for the body (schema). *Trends Cognitive Science 8,* 79-86.

Maravita, A., Spence, C., & Driver, J. (2003). Multisensory integration and the body schema: close to hand and within reach. *Current Biology, 13(13)*, 531-539.

Maravita, A., Spence, C., Kennet, S., & Driver, J. (2002). Tool-use changes multimodal spatial interactions between vision and touch in normal humans. *Cognition, 83,* 25-34.

Mazzurega, M., Pavani, F., Paladino, M. P., & Schubert, T. W. (2011). Self-other bodily merging in the context of synchronous but arbitrary-related multisensory inputs. *Experimental Brain Research, 213,* 213-221. doi: 10.1007/s00221-011-2744-6.

Mehrabian, A., & Diamond, S. (1971). Seating arrangement and conversation. *Sociometry, 34(2),* 281-289.

Noel, J. P., Grivaz, P., Marmaroli, P., Lissek, H., Blanke, O., & Serino, A. (2015a). Full body action remapping of peripersonal space: the case of walking. *Neuropsychologia, 70,* 375-84. doi: 10.1016/j.neuropsychologia.2014.08.030

Noel, J. P., Pfeiffer, C., Blanke, O., & Serino, A. (2015b). Peripersonal space as the space of the bodily self. *Cognition, 144,* 49-57. doi: 10.1016/j.cognition.2015.07.012

Novelli, D., Drury, J., & Reicher, S. (2010). Come together: two studies concerning the impact of group relations on personal space. *British Journal of Psychology, 49(2),* 223-236. DOI: 10.1348/014466609X449377

Paladino, M. P., Mazzurega, M., Pavani, F., & Schubert, T. W. (2010). Synchronous multisensory stimulation blurs self-other boundaries. *Psychological Science, 21,* 1202–1207. doi: 10.1177/0956797610379234.

Patanè, I., Iachini, T., Farnè, A., & Frassinetti, F. (2016). Disentangling action from social space: tool-use differently shapes the space around us. *PloS ONE, 11(5),* e01542472016. http://dx.doi.org/10.1371/journal.pone.0154247

Rizzolatti, G., Scandolara, C., Matelli, M., & Gentilucci, M. (1981). Afferent properties of periarcuate neurons in macaque monkeys. II. Visual responses. *Behavioural Brain Research, 2(2)*, 147–163.
http://dx.doi.org/10.1016/0166-4328(81)90053-X

Schubert, T., & Otten, S. (2002). Overlap of self, ingroup, and outgroup: Pictorial measures of self-categorization. *Self & Identity, 1(4),* 535-576. http://dx.doi.org/10.1080/152988602760328012

Serino, A., Annella, L., & Avenanti, A. (2009) Motor Properties of Peripersonal Space in Humans. *PLoS ONE 4(8),* e6582. http://dx.doi.org/10.1371/journal.pone.0006582

Serino, A. (2016). Variability in Multisensory Responses Predicts the Self-Space. *Trends in Cognitive Sciences, 20(3),* 169-170. DOI: http://dx.doi.org/10.1016/j.tics.2016.01.005

Serino, A., Canzoneri, E., Marzolla, M., Pellegrino, G. d., & Magosso, E. (2015). Extending peripersonal space representation without tool-use: Evidence from a combined behavioral-computational approach. *Frontiers in Behavioral Neuroscience 9*.

Sforza, A., Bufalari, I., Haggard, P., Aglioti, S. M. (2010). My face in yours: Visuo-tactile facial stimulation influences sense of identity. *Social Neuroscience, 5,* 148–162. doi: 10.1080/17470910903205503.

Sommer, R. (1959). Studies in personal space. *Sociometry 22,* 247-260. DOI: 10.2307/2785668

Taffou, M., Viaud-Delmon, I. (2014). Cynophobic Fear Adaptively Extends Peri-Personal Space. *Frontiers in Psychiatry, 5,* 122. http://dx.doi.org/10.3389/fpsyt.2014.00122

Teneggi, C., Canzoneri, E., di Pellegrino, G., & Serino, A. (2013). Social modulation of peripersonal space boundaries. *Current Biology, 23,* 406–411. doi: 10.1016/j.cub.2013.01.043

Tsakiris, M. (2008). Looking for myself: current multisensory input alters self-face recognition. *PLoS ONE* 3:e4040. http://dx.doi.org/10.1371/journal.pone.0004040

Word, C. O., Zanna, M. P., & Cooper, J., (1974). The nonverbal mediation of self-fulfilling prophecies in interracial interaction. *Journal of Experimental Social Psychology*, *10*, 109–120.

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Authors' contribution

Elisa Pellencin, Maria Paola Paladino, and Andrea Serino developed the study concept, designed the studies and contributed to the preparation of the experimental material. Bruno Herbelin contributed to the implementation of the experimental paradigm in the virtual reality. Elisa Pellencin supervised the data collection and analyzed the data. Elisa Pellencin, Maria Paola Paladino, and Andrea Serino interpreted the data and drafted the theoretical introduction and the general discussion. Elisa Pellencin drafted the method and the results section. All the authors edited and contributed to the critical revisions of the manuscript and read and approved the final version for submission.