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Peripersonal Space Perception Is Similar When We Interact With Other Humans or With Humanoid Robots

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Abstract

The peripersonal space is a multisensory interface between the body and the environment, which can be modulated by the presence of objects or other agents. However, how the presence of artificial agents affects the representation of peripersonal space is still poorly understood. We conducted four experiments in which participants had to judge objects' reachability for themselves or for another agent. In Experiment 1, participants performed the reachability task alone. In Experiment 2, participants interacted with another human partner. Experiment 2b was a control condition to test task's physical properties. In Experiment 3, participants performed the task with the humanoid robot iCub, programmed to exhibit motor and social behaviours. The results showed that the extent of the peripersonal space was influenced by the presence of another agent, as participants narrowed their own peripersonal space in a social context, compared to performing the task alone. Furthermore, they perceived their own peripersonal space as larger, compared to the peripersonal space of another human agent (Experiment 2) or humanoid robot (Experiment 3). This suggests that the motor repertoire of a human and a humanoid embodied artificial agent is similarly perceived. The present evidence may open new avenues for space perception in social interactions.

Keywords

peripersonal space, reachable space, human-robot interaction

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Introduction

A large body of neuroscientific evidence has shown that the brain develops a variety of representations of the space surrounding the body, depending on previous experience and on the possibilities to act (Fogassi et al., 1996; Graziano et al., 1994; Rizzolatti, 1981; Rizzolatti et al., 1997). In cognitive psychology, these various representations are commonly referred to as the peripersonal space, that is, the reachable space surrounding the body, in which we can directly interact with objects, and the extrapersonal space, that is, the space beyond our reach (Di Pellegrino & Làdavas, 2015; Holmes & Spence, 2004; Rizzolatti et al., 1997). The representation of the peripersonal space has been extensively investigated (Canzoneri et al., 2012; Costantini, Ambrosini, et al., 2011; Làdavas & Serino, 2008), and it is widely accepted that it is flexible, and it can be shaped by contextual information. Indeed, several

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studies have shown that the extent of the peripersonal space can be modulated by the presence of tools (Canzoneri et al., 2013; Cardinali et al., 2011, 2012; Maravita et al., 2002; Quesque et al., 2017), the rewarding value of objects within (Bertonatti et al., 2021; Gigliotti et al., 2021), the ownership of the objects (Patanè et al., 2021) and the goal of intended actions (Brozzoli et al., 2010; Senna et al., 2019). This evidence suggests that the function of the peripersonal space is to mediate between perceptual and motor processes, guiding the regulation of goal-directed behaviour (Brozzoli et al., 2011; Cléry et al., 2015; de Vignemont & Iannetti, 2015; Di Pellegrino & Làdavas, 2015; Rizzolatti et al., 2014).

Since the seminal electrophysiological evidence on monkeys by Rizzolatti et al. (1981), a broad range of evidence has shown that the presence of objects or visual stimuli placed close to the body activate neurons in brain areas recruited for voluntary actions, that is, the premotor cortex (Caggiano et al., 2009; Rizzolatti et al., 1981), the parietal cortex (Colby et al., 1993; Gallivan et al., 2009) the putamen (Graziano & Gross, 1993) and the intraparietal areas (Colby & Duhamel, 1996). These activations have been reported only when stimuli were presented within the boundary of the peripersonal space but not when they were placed far from it, suggesting that objects' spatial position is encoded in motor terms to facilitate actions (Graziano & Cooke, 2006; Rizzolatti et al., 1997). Supporting this account, the involvement of action-related brain areas has been also described when participants have to perceptually determine the reachable area in the so-called *reachability judgement task*, further suggesting that the perception of the peripersonal space serves as a guide for the action system (Bartolo, Coello, et al., 2014; Gallivan et al., 2009).

The reachability judgement task has been largely employed to investigate the peripersonal space representation. In this task, participants have to establish whether an object or a visual stimulus, usually displayed on an horizontal surface at different locations on the sagittal axis, is within their reach. It has been shown that this task does not only involve a perceptual evaluation of objects' properties but also an estimation of the possibility of the body to act upon them, which requires the recruitment of motor processes (Bartolo, Carlier, et al., 2014; Coello et al., 2008; Grade et al., 2012; Wamain et al., 2016). Indeed, several studies demonstrated that judging whether an object is within our reach, elicits the activation of motor brain areas. Coello et al. (2008) found that reachability judgments were delayed when transcranial magnetic stimulation was applied on the motor cortex. Bartolo, Carlier, et al. (2014) showed that the perception of what is reachable is impaired in stroke patients with brain lesions of the motor cortex. Wamain et al. (2016) reported neural activity over the motor cortex when participants had to judge the reachability of an object placed in the peripersonal space, which was not observed when they had to categorise the object. Further support for the involvement of perceptual and motor processes in the reachability judgement task comes from behavioural evidence showing that body's and movement's constraints might alter the perception of reachable distance. Iachini et al. (2014) asked participants to perform a reachability judgement task in virtual reality with the arm free or blocked. They showed that objects were detected faster in the peripersonal space compared to the extrapersonal but only when participants could freely move the arms, compared to the condition in which they were blocked. Toussaint et al. (2020) found that, after 24 hr of immobilisation, the extent of the peripersonal space shrunk.

In the context of peripersonal space representation, it is important to note that our space is inhabited not only by objects, but also by other moving agents, who might also act in our space. In order to accomplish our intended goals, it is therefore important to take into account others' actions and their possible consequences in our space. A large number of different accounts proposed that to understand and predict others' behaviour, the brain simulates actions performed by others. That is, actions are mapped onto the observer's motor repertoire. In other words, actions performed by others are coded in similar perceptual and motor terms as our own (Decety & Grèzes, 2006; Gallese, 2007; Gallese et al., 2004; Heyes, 2010; Ramnani & Miall, 2004; Rizzolatti & Craighero, 2004; Rizzolatti et al., 2001). These simulative processes allow us to understand and predict others' behaviours and might occur to a different extent dependent on whether or not the observed action violates biological constraints of the body (Candidi et al., 2008), belongs to the motor repertoire of the observer (Buccino et al., 2004) or is performed by an agent perceived as intentional (Liepelt et al, 2010). Similarly, motor simulative processes seem to occur also when estimating the reachable space of other agents. Indeed, studies showed that response times are similar when objects are placed in our own, or in the peripersonal space of a virtual avatar, suggesting that the other' peripersonal space is mapped onto our own space representation (Cardellicchio et al., 2013; Fini et al., 2014; Costantini, Committeri & Sinigaglia, 2011). Consistently, several findings showed how the motor repertoire and the actual ability of performing actions modulate the perception of our own and the others' peripersonal space. For example, Fini et al. (2015) showed that the space judged as near is larger when participants have to judge objects' reachability in relation to a human avatar, compared to static objects and to a wooden dummy, suggesting that reachability judgements are shaped by agents' motor capabilities. Furthermore, Iachini and Ruggiero (2021) demonstrated that participants were slower when judging the reachability of an object from a virtual avatar with the arm blocked compared to when their arms were free, indicating that movement's constraints are taken into account when judging others' peripersonal space.

In the context of research investigating how our motor system encodes others' space and actions, a critical challenge is posed by the introduction of new kinds of agents in our environments. Indeed, the rapid development of technologies means that robots are increasingly present in workspaces, education, and clinical settings, changing our lifestyle and social dynamics. A broad range of investigations has indeed focused on how we perceive robots and their actions, examining whether similar motor simulative processes might also occur when we observe artificial agents' behaviours. However, the findings of this literature are not all aligned. Several studies suggest that motor simulation mechanisms might occur during the observation of action performed either by humans or robots, displayed in a video or images (Hofree et al., 2015; Oztop et al., 2004; Wykowska et al., 2014). Hofree et al. (2015) reported similar muscle activation when observing both human and artificial agents' movements. Oztop et al. (2004) found that the motor interference effect, consisting in an increased movement's variance when an observed action is not compatible with the action executed by the observer, occurs for observed actions performed either by a human or a robot. Furthermore, brain imaging evidence has shown that the brain motor areas involved in the so-called 'action observation network' (cfr. Cross et al., 2009; Grafton et al., 1996; Rizzolatti & Sinigaglia, 2010) are similarly active when participants observed humans' or robots' movements (Cross et al., 2012). In contrast, some other studies show mixed results. For example, Kupferberg et al. (2012) reported that the motor interference effect occurred during action observation but only when the joint configuration of a robot arm resembled that of a human. Similarly, Press et al. (2005) showed that response–compatibility effect occurred only when the robot's hand was similar to a human hand. Furthermore, Liepelt et al. (2010) showed that motor facilitation did not occur when participants observed communicative gestures performed by artificial agents, compared to human agents. As argued by the authors, this would suggest that the attribution of motor intentions plays a critical role for motor simulative processes to occur (Liepelt et al., 2008, 2010).

Although previous literature has provided important evidence on how we perceive human and robot actions, to date, there is a gap in understanding how the presence of embodied robots influences our perception of space. The previous studies focusing on how the presence of other agents modulates the perception of the peripersonal space have mainly employed virtual reality, or, in the case of action observation, videos of actions performed with single effectors. Although very promising, virtual reality paradigms are limited by lack of physical presence and being embedded in a virtual (not actual) environment, which may affect the understanding of processes underlying space perception in social contexts. Indeed, it has been shown that the lack of physical presence might alter object's perception (Grabarczyk & Pokropski, 2016; Ogawa et al., 2018), physiological signals (Meehan et al., 2005) as well as the sense of body ownership (Tieri et al., 2015) or body shape (Kilteni et al., 2012).

Therefore, across four[1] experiments, employing a reachability judgement task, we aimed to investigate how the physical presence of natural and artificial agents (humans and robots) displaying motor and social behaviours might impact the perception of the participant's own and others' peripersonal space. We asked participants to estimate the reachability of a moving object displayed as a moving image on a horizontal screen. In Experiment 1, participants performed the task alone. This served as a baseline with which the effects of the presence of other agents could be compared. In Experiment 2, we asked dyads of human participants to estimate the reachability of a moving object for themselves or for a human partner. To check if the effect was not due to the simple perception of an object moving towards or away from the observer, we conducted a control experiment (Experiment 2b) in which participants were alone and judged when the object crossed the hemispace of the monitor. In Experiment 3, we aimed at examining whether the peripersonal space perception was affected by the presence of a humanoid robot with motor and social characteristics, and whether this perception was comparable to the presence of a human partner. Therefore, in Experiment 3, participants performed the same reachability judgement task as in Experiment 2 with the humanoid robot iCub (Metta et al., 2010), programmed to exhibit both verbal and motor behaviours.

Experiment 1

In Experiment 1, participants performed a reachability judgement task and had to decide whether an object (displayed as a moving image on a screen) was reachable.

Methods

Participants. Thirty-six healthy participants (21 females and 15 males; age range = 19–45; mean age = 25.47 years; $SD = \pm$ 6.39 years; 2 left handed) took part in the experiment. Sample size was determined by research on relevant literature (see Patané et al., 2021). All participants had normal or corrected-to-normal visual acuity. All the participants were reimbursed for their participation. The study was conducted at the Istituto Italiano di Tecnologia, IIT, Genova, and it was approved by the local ethical committee (Comitato Etico Regione Liguria).

Materials and Procedure. Stimuli consisted of six coloured pictures (1280 × 720 px) selected from the BOSS database (Brodeur et al., 2010). The images of objects were processed with Gimp 2.0 to remove the background and were rated by an independent group of 43 participants through an online questionnaire. In this questionnaire, participants were asked to rate each object, presented at two different orientations (i.e. the graspable part of the object to the left or the right), on a five-point Likert scale (1932) according to the object's familiarity, visual complexity, and typicality (belonging to the category of artefacts or natural objects). Paired sample *t*-tests revealed no significant differences across ratings of left and right oriented objects for familiarity, visual complexity or typicality ($p > .05$).

Participants sat on the side of a horizontal 49" touch screen table (Touchwindow Multi-Touch Display, 1099.4 × 634.0 × 36.8 mm). They were asked to sit at a constant distance from the edge of the table (20 cm between the torso and the edge of the table). The experiment was performed using Psychopy (version 2020.1.3) and ran on a laptop connected to the screen. Responses were provided through a black button fixed on the border of the horizontal screen (in the middle of the border, 34 cm from the edges) and connected to the laptop where the experiment was run. A trial started with a fixation cross appearing for 1,500 ms in the centre of the screen (at a position 0 for the *x* and *y* axes, vertical visual angle 63°). Images of objects (displayed with a size of 3650 × 3650 px) appeared in the centre of the horizontal screen (position 0 for *x* and *y* axis on the screen, vertical visual angle 63°) and started to move perpendicularly towards the participant with a speed of 10 cm/s on the y axis. The orientation of the handle of the object (left or right) was counterbalanced within trials. Participants were instructed to press the button and to 'stop' the object when they thought they could reach the object. Responses were provided either with the left or the right hand, and the response side was counterbalanced within participants. Participants performed 10 practice trials and then 192 experimental trials (96 per partner) divided into 4 experimental blocks (48 trials per block). Prior to the experiment, the participants' height, arm length (length from shoulder to the extremity of the medium finger), and maximum reachable space (i.e. maximal reachable distance on the screen with the right finger) were measured in centimetres. Our dependent variable of interest was participants' reaction times (RT) in the reachability judgement task. Importantly, the shorter the RT (the faster participants responded 'reachable'), the larger the representation of the peripersonal space.

Although not the primary aim of the study, which focuses on how the presence of other social agents (humans and robots) affects the peripersonal space perception, in the present work, we examined the potential role of individual motor and physical characteristics, such as the arm length and the height of participants recruited across experiments. Furthermore, to better understand whether the perception of the peripersonal space is modulated by the social context, we analysed the reaction times of participants performing the reachability judgment task across four experimental blocks in each experiment. On the one hand, the inclusion of the block variable in the analysis allows the evaluation of potential effects of practice, which, if present, should emerge when participants perform the task alone (Experiment 1). On the other hand, the inclusion of the block variable allows the comparison of a potential familiarisation effect emerging when interacting with another human partner or with the humanoid robot iCub, in line with prior research suggesting that the peripersonal space representation can be modulated by social interaction and exposure (Cardellicchio et al., 2013; Costantini, Committeri & Sinigaglia, 2011).

Table 1. Descriptive Statistics of RTs Depending on Block in Experiment 1.

Block	Mean ± *SD*
Block 1	1.528 ± 0.351
Block 2	1.555 ± 0.355
Block 3	1.528 ± 0.368
Block 4	1.535 ± 0.372

Transparency and Openness. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. The anonymised data, codes and material of the present study are available upon request from the corresponding author (M.M.). Data were analysed using R, version 2023.03.0 (R Core Team, 2020). The study was not pre-registered.

Results

Practice trials and trials above or below two standard deviations from the overall mean of each participant's reaction times were excluded from the analyses. The remaining trials were averaged in each of the four experimental blocks. Data were analysed using six paired sample *t*-tests contrasting participant's reaction times across four blocks. The *t*-tests did not reveal any significant difference across the four experimental blocks ($p > .05$). Table 1 summarises the participants' reaction times averaged depending on Block in Experiment 1. An additional exploratory analysis on the effect of Congruence in Experiment 1 is reported in the Supplemental Materials. A Pearson correlation coefficient was calculated to assess the linear relationship between reaction times of the reachability judgement task and the participants' height, arm length, and the maximum reachable space. There was a positive correlation between the Self reachable space and the height ($r(35) = .430$, $p = .004$) and the arm length ($r(35) = .442$, $p = .003$) of participants, suggesting that participants had a good representation of their reachable space.

Experiment 1 was performed in order to provide a baseline to establish the extent of the participant's own perceived peripersonal space in the absence of other agents.

These data will then be compared to the conditions in which other agents are present in Experiments 2 and 3.

Experiment 2

The aim of Experiment 2 was to investigate the difference in the perception of the reachable space for the self and other human agents. Participants performed a reachability judgement task in dyads and had to decide whether an object (displayed as an image on a screen) was reachable for themselves or their partner. The conditions of this experiment were nested and counterbalanced with the conditions of another study, focused on the reachability judgement of neutral and dangerous objects, which is outside the focus of the present work. These data are not of interest to the aim of the present study; therefore, they are not included in the analyses.

Methods

Participants. Thirty-six healthy participants (20 females and 16 males; age range = 19–32; mean age = 25.17 years; $SD = \pm$ 3.24 years; 5 left-handed) took part in the experiment. All participants had normal or corrected-to-normal visual acuity. All the participants were reimbursed for their participation. The study was conducted at the Istituto Italiano di Tecnologia, IIT, Genova, and it was approved by the local ethical committee (Comitato Etico Regione Liguria).

Materials and Procedure. Stimuli and apparatus were identical to Experiment 1, with the exception that participants performed the task in dyads. Participants of each couple sat at the opposite side of the horizontal 49" touch screen table facing each other. They were asked to sit at a constant distance from the edge of the table (20 cm between the torso and the edge of the table). A trial started with a blue triangle appearing for 1,500 ms in the centre of the screen (at a position 0 for the x and y axes, vertical visual angle 63°). The triangle could point towards one of the two participants randomly, indicating the participant in turn for each trial. Images of objects (displayed with a size of 3650 × 3650 px) appeared in the centre of the horizontal screen (position 0 for x and y axis on the screen, vertical visual angle 63°) and started to move perpendicularly towards one of the participants with a speed of 10 cm/s on the y axis. The orientation of the handle of the object (left or right) was counterbalanced within trials. An illustration of the task is provided in the top panel of Figure 1. Participants were instructed to press the button and to 'stop' the object when they thought that the object was reachable for themselves or the other agent, depending on the direction of the movement (see Iachini et al., 2014). Responses were provided either with the left or the right hand, and the response side was counterbalanced within participants. Participants performed 20 practice trials (10 for each partner) and then a total of 192 trials (96 per partner) divided into 4 experimental blocks (48 trials per block). Prior to the experiment, the participants' height, arm length (length from shoulder to the extremity of the medium finger), and maximum reachable space (i.e. maximal reachable distance on the screen with the right finger) were measured in centimetres.

Practice trials and trials above or below two standard deviations from the overall mean of each participant's reaction times were excluded from the analyses. Data were analysed using a 2 (Agent: Self vs. Other) × 4 (Block Number) repeated-measures ANOVA. The Greenhouse–Geisser correction was applied whenever the sphericity assumption was violated, and post hoc paired sample t-tests were adjusted for multiple comparisons using the Bonferroni correction. All the remaining results regarding other factors for all the experiments are reported in the Supplemental Materials.

Results

The ANOVA revealed a main effect of Block [$F(1, 35) = 20.657$, $p < .001$, $\eta_p^2 = .071$] as participants were faster in the first block compared to the other experimental blocks (Block 1 vs. Block 2: $t(35) = 4.631$, $p < .001$; Block 1 vs. Block 3: $t(35) = 6.149$, $p < .001$; Block 1 vs. Block 3: $t(35) = 7.329$, $p < .001$). Interestingly, the ANOVA revealed a main effect of Agent [$F(1, 35) = 9.148$, $p = .004$, $\eta_p^2 = .022$], as participants were faster when judging the reachability of the Self reachable space compared to the Other reachable space, that is, the Self reachable space was perceived as larger compared to the Other reachable space (bottom left panel of Figure 1). A two-way interaction between Agent and Block [$F(3, 35) = 5.726$, $p < .001$, $\eta_p^2 = .002$] indicated that the perception of the Self and the Other reachable space changed across the blocks of the experimental session. Post hoc paired sample t-test showed that the Self reachable space was perceived as larger compared to the Other reachable space in the first ($t(35) = 3.716$, $p = .016$) and in the second block ($t(35) = 3.613$, $p = .022$), whereas in the third and in the fourth block, the two spaces were not statistically different from each other ($p > .05$). This is shown in the bottom right panel of Figure 1. Additionally, a Pearson correlation coefficient was calculated to assess the linear relationship between reaction times of the reachability judgement task for each agent (Self, Other) and the participants' height, arm length, and the maximum reachable space. The correlations did not indicate any significant relationship ($p > .05$).

Discussion

The results of Experiment 2 showed that participants perceived their own and their partner's peripersonal space differently. Specifically, participants perceived their own reachable space as larger, compared to the space attributed

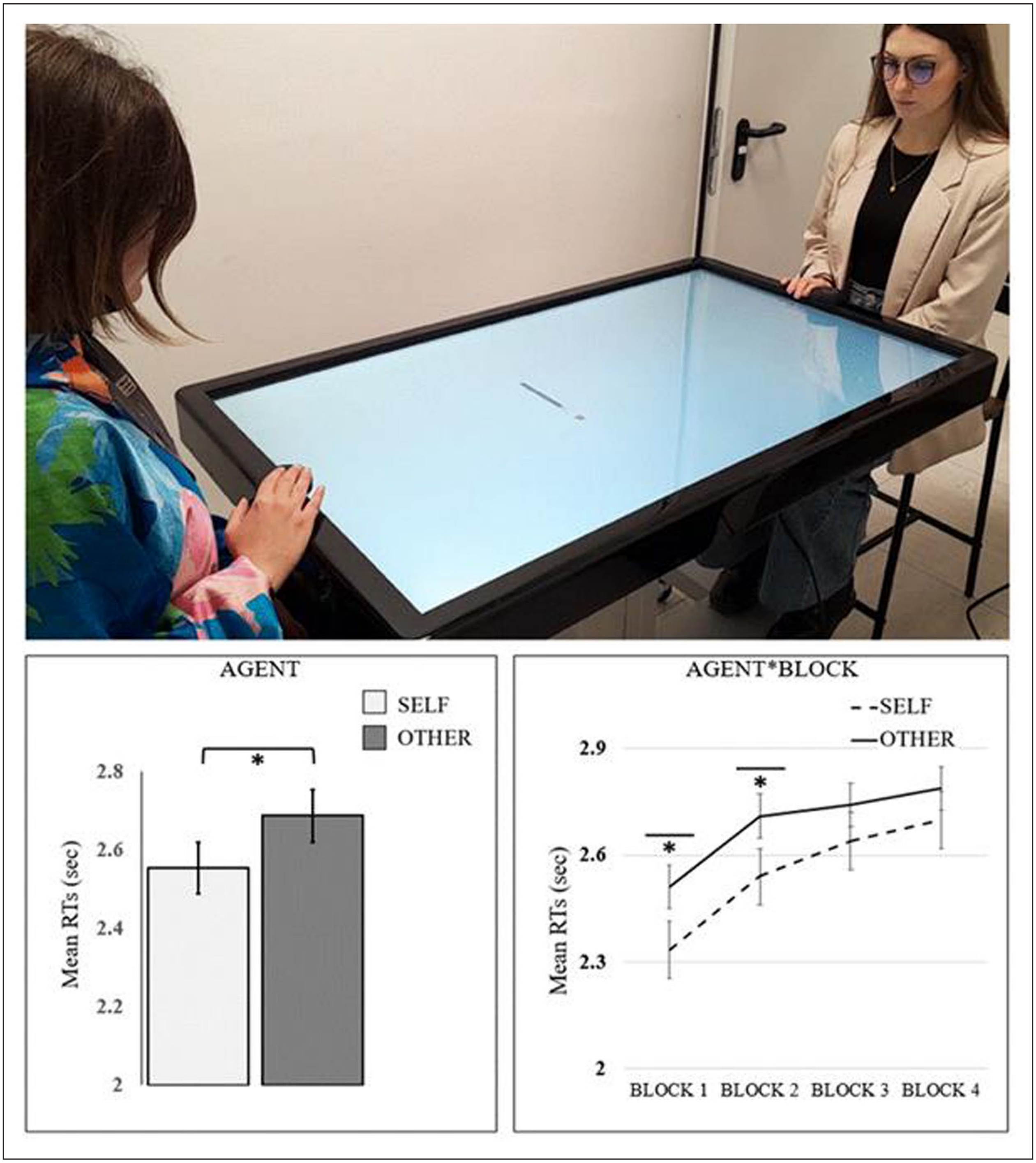

Figure 1. *Top:* Illustration of the task of Experiment 1. *Bottom left:* Bar graph illustrating the main effect of the Agent, as participants were slower when judging the other reachable space compared to the Self reachable space. *Bottom right:* Line graph displaying a significant two-way interaction between Block and Agent. Post hoc paired sample *t*-test indicated that participants were slower when judging the other reachable space compared to the Self reachable space in the first and the second block. Significant comparisons are flagged with an asterisk.

to the other agent. Furthermore, the pattern of results suggests that this difference might change as a function of the time spent in the interaction, as the reachable space attributed to the self and the other agent was different in the first half of the experiment but became not significantly different in the second half of the experimental session.

The findings of Experiment 2 are consistent with previous evidence showing that the presence of other agents modulates our perception of the peripersonal space (Bogdanova et al., 2021; Coello & Iachini, 2020; de Vignemont & Iannetti, 2015). However, we acknowledge that these results might also originate from the mere direction of the object's movement, where objects moving away or towards the participants might influence the perception of the reachable space attributed to the self and to the other agent. Indeed, previous studies have shown that the position of an object with respect to an agent might modulate the perception of object properties. For example, the effect of object affordances is stronger in the near compared to the far space (Costantini, Ambrosini, et al., 2011) and when objects move toward rather than away from participants (Anelli et al., 2013). In order to address this alternative interpretation of our results, we conducted a control experiment (Experiment 2b).

Experiment 2b

Experiment 2 showed that the perception of one's reachable space is different from the space attributed to another agent. Specifically, participants attributed more space to themselves compared to their partners (they were faster in judging the point in space which they thought would be reachable by them, relative to the analogous point for the partner). The data also showed that this perception might vary depending on the familiarisation with the other agent. However, we acknowledge that these results might also originate from the mere direction of the object's movement, where objects moving away or toward the participants might influence the perception of the reachable space attributed to the self and the other agent. Indeed, previous studies have shown that the position of an object with respect to an agent might modulate the perception of object properties and that the spatial processing of visual stimuli moving toward the reachable space differently modulates the activity of motor-related brain areas (Di Pellegrino & Làdavas, 2015; Makin et al., 2009). For example, the effect of object affordances is stronger in the near compared to the far space (Costantini, Ambrosini, et al., 2011) and when objects move toward rather than away from participants (Anelli et al., 2013). This suggests that the perception of the reachable space can be modulated by the movement of a stimulus towards or away from one's action space (Di Pellegrino & Làdavas, 2015). Therefore, the results observed in Experiment 2 could be influenced not only by the presence of another agent but also by the direction in which the object's image moved with respect to the participants (i.e. towards vs. away from the participants) regardless of the social context. To address this alternative interpretation of our results, we conducted a control experiment (Experiment 2b), in which participants performed the task alone and judged when the object crossed the hemispace of the screen. By removing the social component, this experiment allowed us to determine whether the differences observed in Experiment 2 were driven by the presence of another agent or simply by the movement of the object itself.

Methods

Participants. Fifteen healthy participants (7 females and 8 males; age range = 19–42; mean age = 25.86 years; $SD = \pm$ 6.19 years; 5 left-handed) took part in the experiment. All participants had normal or corrected-to-normal visual acuity. All the participants were reimbursed for their participation. The study was conducted at the Istituto Italiano di Tecnologia, IIT, Genova, and it was approved by the local ethical committee (Comitato Etico Regione Liguria).

Materials and Procedure. The stimuli and the apparatus of the Control Experiment were the same as in Experiments 1 and 2. Participants were asked to estimate when an object, displayed as an image on a horizontal screen, reached half of the hemispace of the screen. Responses were provided through a black button fixed on the border of the horizontal screen (in the middle of the border, 34 cm from the edges) and connected to the laptop where the experiment was run. A trial started with a fixation cross appearing for 1,500 ms in the centre of the screen (at a position 0 for the x and y axes, vertical visual angle 63°). Images of objects (displayed with a size of 3650×3650 px) could appear in three possible positions on the screen, and they could start to move towards or away from the participant. The images could appear either in the centre of the screen (position 0 for x and y axis on the screen, vertical visual angle 63°) and started to move perpendicularly towards (condition '*Middle Towards*') or away (condition '*Middle Away*') the participants; or they could appear at the opposite edge of the screen (position 0 for x and -1 y axis on the screen, vertical visual angle 63°) and started to move towards the centre (condition '*Far Towards*'); or they could appear at the edge of the screen where the participant was sitting (position 0 for x and 1 y axis on the screen, vertical visual angle 63°) and they could start to move away the participant (condition '*Close Away*'). Figure 2 shows a representation of the task. Images moved at a constant speed (speed of 10 cm/s on the y axis). The orientation of the handle of the object (left or right) was counterbalanced within trials. Participants were asked to press the button and to 'stop' the object when they thought the object reached half of each hemispace of the screen, depending on the direction of the movement. Responses were provided either with the left or the right hand, and the response side was counterbalanced across participants. Participants performed 20 practice trials (5 for each movement) and then a total of 288 trials divided into 4 experimental blocks (72 trials per block).

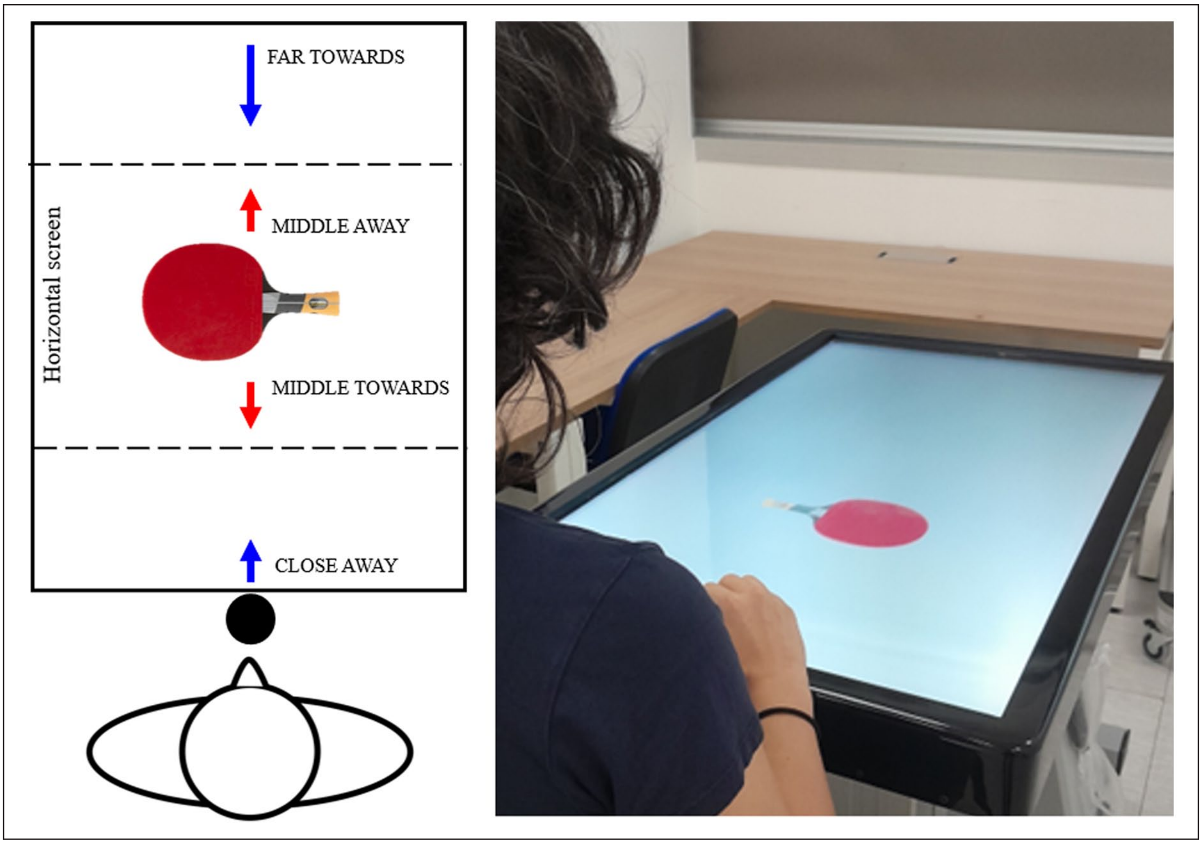

Figure 2. *Left:* Schematic illustration of the task of Experiment 2b. Arrows indicate the direction of the movement of the objects (Close Away, Middle Towards, Middle Away and Far Towards). *Right:* Illustration of a participant performing the task.

Results

To match the number of trials included in Experiment 1, 48 trials were randomly selected from each block for each participant and analysed. Practice trials and trials above or below two standard deviations from the overall mean of each participant's reaction times were excluded from the analyses. The remaining averaged trials were analysed using a 4 (Block) × 4 (Movement: Middle Towards, Middle Away, Far Towards, Close Away) repeated-measures ANOVA. The Greenhouse–Geisser correction was applied whenever the sphericity assumption was violated, and post hoc paired sample *t*-tests were adjusted for multiple comparisons using the Bonferroni correction.

The ANOVA showed a main effect of Movement [$F(14, 1.8) = 6.501$, $p = .006$, $\eta_p^2 = .317$], and post-hoc paired sample *t*-tests showed that participants were faster when the object appeared on the opposite side of the table and started to move towards them (condition Far Towards) compared to the other movements (Far Towards vs. Close Away: $t(14) = 3.201$, $p = .010$; Far Towards vs. Middle Towards: $t(14) = 3.905$, $p = .002$; Far Towards vs. Middle Away: $t(14) = 3.572$, $p = .005$). Importantly, post hoc paired sample *t*-tests did not reveal statistical differences when the object appeared close or in middle, either when it started to move towards or away ($p > .05$) – the two conditions that most closely resembled the reachability judgement of Experiments 1 and 2. The main effect of the Block or the two-way interaction between Block and Movement was not statistically significant ($p > .05$) as shown by the ANOVA. Table 2 shows the participants' reaction times averaged across Block and Movement.

Discussion

The control experiment showed that the movement of the object did not affect the perception of space, as the judgement of the hemispace was similar when the object appeared in the middle of the screen and started to move either away or towards the participant. These results showed that the findings of Experiment 2 are not related to the movement of the objects and suggest that the effects are due to the judgement of reachability and the presence of other agents.

Experiment 3

The results of Experiment 2 and the respective Control Experiment (Experiment 2b) showed that perception of the

Table 2. Descriptive Statistics of RTs Depending on Block and Movement in Experiment 2b.

Block	Movement	Mean ± *SD*
1	Close Away	2.228 ± 0.119
	Far Towards	2.143 ± 0.135
	Middle Away	2.209 ± 0.137
	Middle Towards	2.239 ± 0.168
2	Close Away	2.202 ± 0.251
	Far Towards	2.138 ± 0.267
	Middle Away	2.221 ± 0.261
	Middle Towards	2.205 ± 0.261
3	Close Away	2.223 ± 0.119
	Far Towards	2.170 ± 0.153
	Middle Away	2.242 ± 0.149
	Middle Towards	2.214 ± 0.111
4	Close Away	2.241 ± 0.147
	Far Towards	2.177 ± 0.156
	Middle Away	2.271 ± 0.126
	Middle Towards	2.234 ± 0.123

reachable space is different for oneself, compared to perception of reachable space of others. More specifically, the data indicated that participants perceived their own peripersonal space as larger, compared to the others' peripersonal space. We were then interested in whether similar mechanisms would also emerge in the interaction with an artificial agent exhibiting both social presence and motor repertoire allowing for potential object manipulation. We conducted Experiment 3 in which participants had to interact with the humanoid robot iCub, programmed to act as a social agent with a motor repertoire allowing for both button presses and potential object manipulation (a potential for reaching and grasping objects).

Methods

Participants. Thirty-six healthy participants (22 females and 14 males; age range = 18–44; mean age = 24.66 years; *SD* = ± 4.7 years; 3 left-handed) took part in Experiment 3. All participants had normal or corrected-to-normal visual acuity. All the participants were reimbursed for their participation. The study was conducted at the Istituto Italiano di Tecnologia, IIT, Genova, and it was approved by the local ethical committee (Comitato Etico Regione Liguria).

Materials and Procedure. The stimuli and the apparatus of Experiment 3 were the same as Experiment 2. The difference consisted of using the iCub humanoid robot, instead of involving another human. Participants were asked to sit in front of iCub, placed as the participants at 20 cm from the horizontal screen (distance between the torso and the edge of the screen). The procedure was identical to Experiment 2. The robot behaviours were implemented to make the iCub similar to the human partner, that is, the left and right arms of the robots were programmed to press the black button fixed on the border of the touch screen. The response times of the button presses made by iCub for each trial were randomly selected within two a priori defined ranges, corresponding to the range of reaction times of participants of Experiment 2 for each Agent (Self: 1928-3436 ms) and the Other (1695-3337 ms). Additionally, the robot also had social features: it was programmed to introduce itself at the beginning of the experiment, explaining the task and highlighting its capability of moving arms by saying: 'Objects will appear on this screen, and they can move towards you or me. Your task is to press the button and stop them when you think you, or I, can reach and grab them with our hand. I will do the experiment with you, with the same rules, and an arrow will indicate whose turn it is. Researchers at IIT have developed new programs and now I can move my arms just like you'. The left panel of Figure 3 illustrates the task. The response side of both iCub and the participants was counterbalanced across dyads. Participants performed 20 practice trials (10 for each agent) and then a total of 192 trials (96 per agent) divided into 4 experimental blocks (48 trials per block). Prior to the experiment, the participants' height, arm length (length from shoulder to the extremity of the medium finger), and the maximum reachable space (i.e. maximal reachable distance on the screen with the right finger) were measured in centimetres.

Our dependent variable of interest was participants' RT in the reachability judgement task. Importantly, the shorter the RT (the faster participants responded 'reachable'), the larger the representation of the peripersonal space.

Analysis. The preprocessing and statistical analysis were identical as in Experiment 1.

Results

The 2 × 4 repeated-measures ANOVA with the factors Agent (self vs. iCub), Block (Block 1–4) revealed a main effect of Agent [$F(1, 35) = 18.968$, $p < .001$, $\eta_p^2 = .434$], as participants were faster when judging the reachability of the Self reachable space compared to the iCub reachable space, that is, the Self reachable space was perceived as larger compared to iCub reachable space (see the right panel of Figure 3). Differently from Experiment 2, the ANOVA did not reveal any main effect of the factor Block ($p > .5$) or a significant interaction between Block and Agent factors [$F(2) = 1.214$, $p = .308$, $\eta_p^2 = 5.559$]. Additionally, correlation coefficients between reaction times of the reachability judgement task for each agent (Self, Other) and the participant's height, arm length and the maximum reachable space did not indicate any significant relationship ($p > .05$).

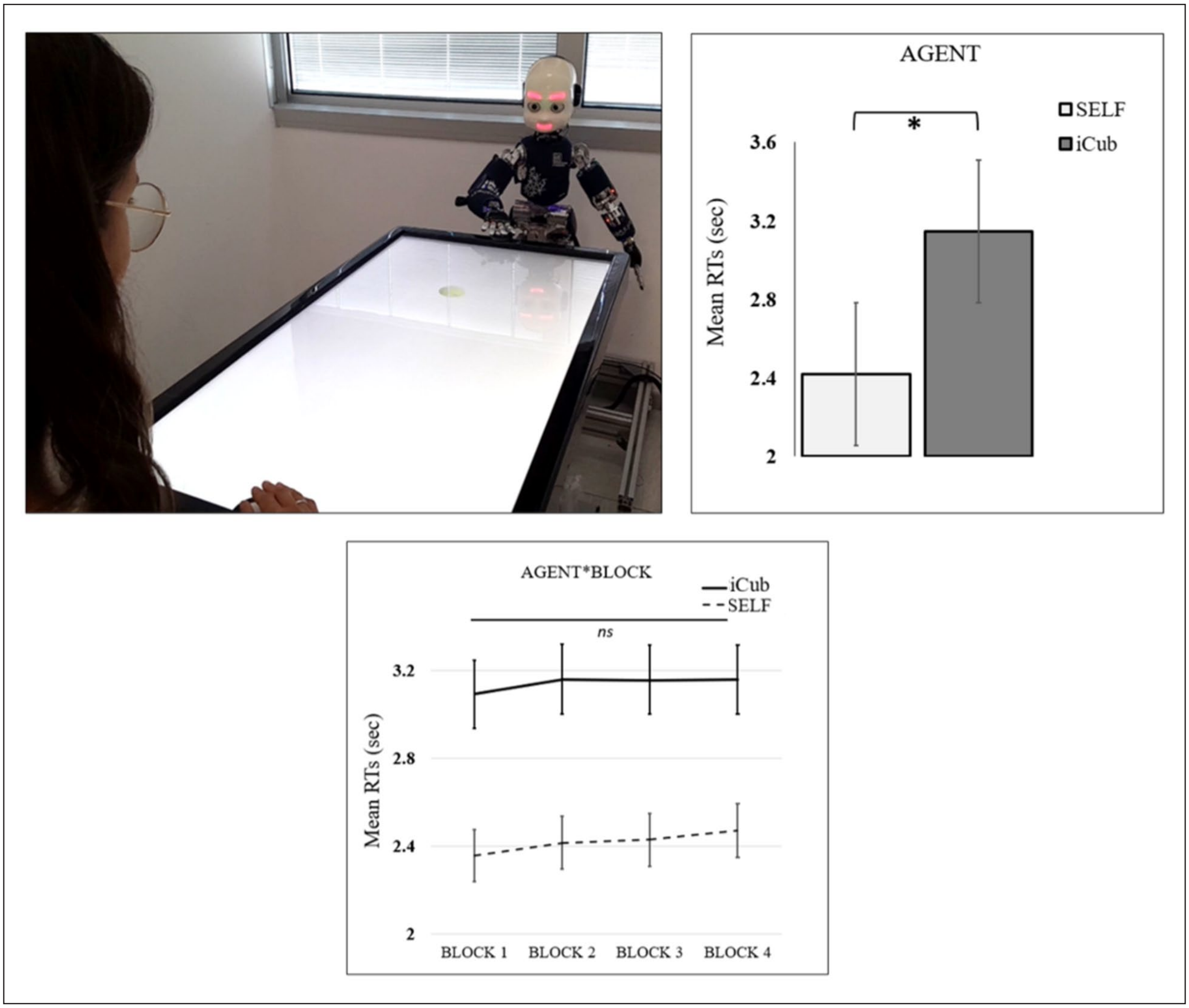

Figure 3. *Left:* Illustration of the task of Experiment 3. *Right:* Bar graph illustrating the main effect of the Agent, as participants were slower when judging iCub's reachable space compared to the Self reachable space. *Bottom:* Bar graph illustrating the non-significant interaction between Block and Agent.

Discussion

The results of Experiment 3 showed a similar pattern to the results of Experiment 2: participants perceived their own reachable space as larger, compared to the space attributed to iCub. This evidence further supports the idea that participants likely attributed similar motor repertoire to humans and humanoid artificial agents, able to perform the ability to manipulate objects. Importantly, our results suggest that, differently from human–human interactions, interacting with a humanoid artificial agent does not lead to familiarisation, as the difference was not modulated across blocks of the experimental session. This effect might be due to the enhanced sense of threat induced by artificial agents, which might be perceived as less familiar and ambiguous partners (Castro-González et al., 2016; Iachini et al., 2014).

In order to better understand the modulation of peripersonal space by social context, we further compared only the Self condition across Experiments 1, 2, and 3.

Comparison between Experiment 1, 2, and 3

Experiments 2 and 3 showed that the extent of the perceived peripersonal space was different for one's own peripersonal space, compared either to the space attributed to another human or to a humanoid robot able to move and to socially interact like a human being. To further examine how the presence of other agents (natural or artificial) affects the perception of one's peripersonal space, we directly compared the Self condition of Experiments 1, 2, and 3.

Figure 4. The bar graph illustrates the main effect of the Experiment, for the self-reachable space. Post-hoc paired sample *t*-tests indicated that participants extended their self-reachable space when alone compared to when they interacted with human agents and with iCub. There was no significant difference between human partners and iCub. Significant comparisons are flagged with the asterisk.

Our dependent variable of interest was participants' RT in the reachability judgement task. Importantly, the shorter the RT (the faster participants responded 'reachable'), the larger the representation of the peripersonal space.

Results

Only trials of the Self condition were used for the comparison between Experiments 1, 2, and 3. Data were analysed using a mixed ANOVA with repeated-measures factors Block (Blocks 1–4) and as between-subjects factor Experiment. The Greenhouse–Geisser correction was applied whenever the sphericity assumption was violated, and post hoc paired sample *t*-tests were adjusted for multiple comparisons using the Bonferroni correction.

The ANOVA revealed a main effect of Experiment [$F(2) = 63.624$, $p < .001$, $\eta_p^2 = .546$, see Figure 4] as participants' perception of reachable space appeared to be smaller when they performed the task either in presence of a human partner ($t(105) = 10.396$, $p < .001$) or with iCub ($t(105) = 8.990$, $p < .001$) compared to when alone. Importantly, there was no significant difference in the perception of the self-reachable space between the conditions of when the task was performed in the presence of a human partner or iCub ($p = .163$). The ANOVA did not show any significant effect of Block ($p > .05$) or interaction between Block and Experiments ($p > .05$).

The main finding of the comparison between the self-reachability judgement trials of Experiments 1, 2, and 3 is that the presence of others alters the peripersonal space compared to when alone. However, the most important finding of the comparison between Experiments 1, 2, and 3 is that the peripersonal space perception is similar when interacting with human partners and with humanoid robots that are shown as able to move and to socially interact. This suggests that robots are recognised as agents to the same extent as other humans, especially when they are perceived as able to interact socially and to produce human-like behaviours.

The enlargement of the participant's own peripersonal space when alone compared to when in the presence of other agents is in line with previous literature showing a common overestimation bias of the actual, possible reachability (Fischer, 2000; Mark et al., 1997). According to this effect, individuals tend to perceive objects that are not within their actual possibility of reach as reachable, indicating that actual motor experience and conscious representations of the world do not necessarily match (Ambrosini et al., 2012). Therefore, it is possible that this bias might play a role when alone; whereas in the presence of other agents, participants take into account the action space of the partner, therefore restricting their own.

General Discussion

The present study aimed to investigate whether the presence of other humans and embodied humanoid robots similarly modulates the peripersonal space representation. To this aim, we employed the reachability judgement task, which is thought to involve the simulation of a reaching action towards a manipulable object whose spatial position is coded in motor terms (Bartolo, Coello, et al., 2014; Coello et al., 2008). In Experiment 1, we asked participants to judge the reachability of a moving object displayed as an image on a horizontal screen, as a baseline to evaluate the extent of participant's perceived peripersonal space. In order to examine whether the peripersonal space is similarly affected by the presence of other humans and artificial agents, in Experiments 2 and 3, participants performed the task with a human (Experiment 2) or an artificial humanoid robot (Experiment 3). Experiment 2b was run as a control experiment to test whether the observed effects are not due to the physical characteristics of the task. In Experiment 2, dyads of human participants were asked to judge the reachability of an object both for themselves and for the partner. In Experiment 3, we replaced the human participants of Experiment 2 with the robot iCub, presented to participants as capable of manual movements and of exhibiting social behaviours. The results of Experiment 2 showed that participants perceived their own reachable space as larger compared to their partners. Interestingly, this pattern was similarly observed in Experiment 3, as participants attributed more space to themselves compared to the space attributed to iCub. Consistently, the comparison across experiments (self-condition only) showed that the presence of other agents – either natural (humans) or artificial (robots) – modulates perception of one's own peripersonal space, compared to when alone. This suggests that robots are perceived as agents endowed with a motor repertoire similar to human agents.

The findings of Experiment 2 showed that participants perceived as different their own peripersonal space compared to the space attributed to another human partner. This is consistent with previous studies showing how the presence of other acting bodies induces a 'remapping' of the peripersonal space (Fini et al., 2014; Saccone et al., 2018). For example, Fini et al. (2014) reported that, compared to the presence of an object, the mere presence of another 'body' in the visual scene enlarged the space perceived as 'near'. Saccone et al. (2018) showed that when participants were alone, objects elicited the congruence effect, that is, faster reaction times when the side of the response matched the orientation of the object, both for objects placed in the peripersonal and in the extrapersonal space. Instead, when participants performed the task in the presence of a confederate, the congruence effect appeared only for objects located in the peripersonal space, indicating that participants took into consideration the action space of another agent. The present results further suggest that the peripersonal space plasticity is influenced by the social context (Bogdanova et al., 2021; Coello & Iachini, 2020; Graziano & Cooke, 2006).

Importantly, the findings of Experiment 3 similarly showed that participants perceived their own peripersonal space as larger, compared to the space attributed to iCub. This suggests that participants' own peripersonal space was affected by the presence of another agent, regardless of whether the other agent was a human or a robot perceived as able to move and behave like a human partner. These results are in line with evidence showing that robot's movements can trigger the simulation of a motor representation during action observation comparable to human actions (Hofree et al., 2015; Oberman et al., 2007; Oztop et al., 2004; Wykowska et al., 2014), and they are perceived similarly to humans in joint action paradigms (Bunlon et al., 2018). The present study extends previous findings, showing that the actual presence of humanoid robots able to move and socially interact affects a representation of one's peripersonal space similarly to the way the presence of another human affects perception of one's own peripersonal space. This might indicate that participants take into account the actual motor repertoire of iCub and that the space surrounding its reachable area is coded in similar motor terms as that of other humans.

The comparison between the data of Experiments 1, 2, and 3 further suggests that human and artificial agents are similarly perceived and that the social context modulates our space perception. As indicated by the analysis, participants' own reachable space was perceived as smaller when in the presence of another human or of a human-like artificial agent, relative to when they were alone. It is worth noting that in Experiment 1, we observed a positive correlation between the participants arm length and their perceived reachable space, in line with the view that the representation of the peripersonal space reflects one's capabilities to act on objects placed within this space (Costantini, Ambrosini, et al., 2011). However, this finding was not systematically observed in Experiments 2 and 3, in which participants performed the reachability judgment task for both themselves and for another social agent. Although this result appears in contrast with the findings of Experiment 1, previous literature has consistently reported a mismatch between one's actual capability to reach for an object and the reachability estimation. (Fischer, 2000; Mark et al., 1997). This indicates that actual motor experience and motor representations do not necessarily match (Ambrosini et al., 2012). In line with this account, Ambrosini et al. (2012) showed that actual reachable space and perceived reachable space are dissociable. They found that participants were faster with both function and manipulation verbs when objects were presented in the actual compared to the perceived reaching space. This finding suggests that the direct, actual experience of world, is not necessarily reflected in conscious estimations or mental representation (Ambrosini et al., 2012). Therefore, our results would support a dissociation between actual physical constraints and mental representation when participants are in the presence of another agent. Indeed, the significant positive correlation between arm length and perceived reachable space found only when participants performed the task alone, but not in presence of another agent, suggests that the social dimension might play a critical role in the processing of peripersonal space representation. This is furthermore in line with prior research showing that individuals adjust their own space representations based on the presence and perceived capabilities of others (Teneggi et al., 2013; Iachini et al., 2014; see also Di Pellegrino & Làdavas, 2015). For example, Teneggi et al. (2013) showed that the extent of the peripersonal space perception was reduced in the presence of other human individuals compared to objects. This would suggest that in the presence of others, we encode in our representation of the surrounding space their action possibilities (Fini et al., 2015; Iachini & Ruggiero, 2021). Consistently, our findings indicated that participants took in consideration the action space of the other agent and reduced their own action space, compared to when alone, presumably in order to 'grant' more space to the other partners who also have the capability to act in the environment. Importantly, the data indicate no significant differences between the perceived peripersonal space when participants interacted with a human partner or with the robot iCub. This finding is strongly suggestive of an attribution of action possibilities and of a 'motor' agency to artificial agents, which might have been triggered by the embodiment iCub, which furthermore displayed motor and social behaviour. In conjunction with the anthropomorphic appearance and the physical action performed by iCub, we cannot exclude that also the presence of verbal behaviour might have played a role in the attribution of a human-like motor repertoire and agency to the robot.

Taken together, the pattern of results of our study is not straightforward. On the one hand, participants' perception of their own peripersonal space was larger, compared to that of their interaction partner (human or robot). On the other hand, however, when comparing the perception of one's own peripersonal space across experiments, the results showed that largest own peripersonal space was perceived when performing the task alone, relative to social contexts. One speculative interpretation of this pattern of results is that two mechanisms might be at stake, underlying the observed phenomena. One mechanism would be responsible for reducing one's own peripersonal space in the presence of others (when compared to being alone), in order to account for others' action possibilities, and in order to 'provide' others with space in which the others can exercise their action capabilities, as explained above. The second mechanism would make one's own peripersonal space appear larger, when compared to the perception of peripersonal space of others. This could be presumably explained by the willingness to cooperate with others in social contexts. Indeed, it has been reported that the boundaries of the reachable space enlarge after the experience of cooperation with other agents compared to non-cooperative interactions (Dell'Anna et al., 2021; Pellencin et al., 2018; Teneggi et al., 2013), when participants interact with human avatars presented as a moral character rather than immoral ones (Pellencin et al., 2018) and after cooperative tool use tasks (Patané et al., 2017). Accordingly, our results suggest that a positive social attitude toward the partner might have modulated the representation of the peripersonal space. Indeed, as observed in Experiment 2, in the second half of the experimental blocks the reachable distance attributed to the self and to the other agent became similar. This pattern resembles the effect found by Teneggi et al. (2013) who showed that after a cooperative interaction in which participants received a fair payoff, the self and the other reachable space merged. Accordingly, our findings could indicate that after a period of familiarisation, participants processed spatial locations more efficiently and adjusted the extent of action space of their own and of the other, as a consequence of a positive attitude developed toward the partner. Interestingly, differently from Experiment 2, no effect of the experimental blocks was found in Experiment 1 or 3. The absence of this finding when the participants judged their reachable space alone (Experiment 1) suggests that the task itself did not induce faster reaction times across the session due to a general practice effect. More importantly, this pattern was not observed when interacting with an artificial agent. Indeed, in Experiment 2, the difference between the space attributed to the self and to iCub did not change across the experimental session. The dissociation between human–human and human–robot interaction provides the strongest evidence that peripersonal space perception is socially modulated. Whereas interacting with a human partner led to a progressive alignment of self and other reachable spaces across experimental blocks, interacting with an artificial agent robot did not elicit such modulation. This could indicate that participants were not susceptible to any familiarisation with robots, which might represent an ambiguous (and presumably less trustworthy) partner compared to a human agent.

When considering those two mechanisms together, it appears that they actually might both be facilitating social interactions and cooperation: when we encounter others, we reduce our own peripersonal space (compared to being alone) in order to account for others' own action capacities. Simultaneously, we perceive our own peripersonal space as larger than that of the others', which encourages cooperation[2] and, for example, joint manipulation activities. This speculative interpretation of our results, postulating two mechanisms (consistent with each other) needs to be further tested in future research.

An interesting alternative explanation for the present findings, though speculative, relates to the audience effect (Triplett, 1898), a well-documented phenomenon whereby individuals modify their behaviour when they are observed, or believe they are being observed, by others. A large body of research has indeed demonstrated that physical performance (Wann & Hackathorn, 2019), gaze behaviour (Laidlaw et al., 2011), emotional facial expressions (Phaf & Rotteveel, 2024) and prosocial behaviour (Cañigueral & Hamilton, 2019) when people are being watched, or believe to being watched, by someone else (see Hamilton & Lind, 2016). While multiple theories have been proposed to account for this effect across different contexts, it is generally attributed to the motivation to present a favourable image of the self to other individuals (cfr. Hamilton & Lind, 2016). In the present study, it is possible that the progressive adjustment of the space attributed to the self and other agent observed in Experiment 2, arose from participants' awareness of being watched – and potentially judged – by their partner. This tendency may have driven individuals to modify their spatial judgments to convey a positive impression or a prosocial disposition. Conversely, this effect did not emerge in interactions with the humanoid robot iCub, as shown by the absence of changes in the estimation of the reachable space for the self and for iCub across the experimental session. The lack of this modulation suggests that participants were not concerned with being observed or judged by an artificial agent.

It is important to acknowledge that the present study primarily examined how individuals' perception of peripersonal space is influenced by interactions with human versus humanoid agents. Consequently, several methodological limitations should be outlined. First, the study did not systematically assess the impact of participants' physical characteristics on the estimation of reachable space. Given the potential relevance of these factors for understanding peripersonal space representation in social contexts, future research should consider their influence. Second, to specifically investigate the estimation of reachable space, a between-subjects design was employed to minimise potential influences of beliefs or attitudes arising from prior interactions with either a human partner or the robot iCub. Future studies may explore this aspect further by incorporating a familiarisation phase or adopting a within-subjects design to better understand the representation of peripersonal space in human-human versus human-robot interactions. Third, the study did not systematically examine the influence of the audience effect or individual differences in susceptibility to social evaluation, both of which warrant further investigation in future research. Finally, it should be noted that the differences in reaction times across Experiments 1, 2, and 3 may also be influenced by differences in task structure. Whereas Experiment 1 consisted exclusively of Go trials, requiring participants to attend to a single cue, Experiments 2 and 3 employed a Go/No-Go paradigm, which required participants to process two cues and thus imposed greater cognitive load. This methodological difference may have contributed to the longer reaction times in Experiments 2 and 3 and could partly account for the lack of differences between human and robot conditions. Future studies could more directly address this potential confound by including a Solo condition with a Go/No-Go design, matching the structure of Experiments 2 and 3.

In conclusion, the present work provides evidence that the interaction with other humans or embodied artificial agents influences the perception of our own peripersonal space. Furthermore, the data suggest that we process similarly the reachable space of humans and robots that exhibit human-like motor and social behaviours. These similarities might indicate that artificial agents might be perceived as intentional agents, and their motor repertoire might activate motor simulative processes in humans. Additionally, we propose that the perception of the peripersonal space is remapped by social mechanisms, which might be at play when in the presence of other agents.

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Supplementary Material

Supplementary Material is available at: qjep.sagepub.com

Notes

1. The original design included five experiments. Experiment 5 aimed to further investigate whether the absence of motor repertoire but the presence of social behaviour (operationalised as verbal behaviour) in humanoid robots modulates the perception of the peripersonal space. However, due to a confounding variable (inconsistent information given by the humanoid robot via verbal communication), Experiment 5 is not included in this paper. For the reasons of transparency, we report the experiment in the Supplementary Materials section.
2. In literature, an alternative explanation has been offered to explain the phenomenon of larger perceived peripersonal space for oneself compared to others. This explanation refers to the defensive mechanisms. According to the account supporting the role of a defensive mechanism, the peripersonal space might represent both a space for action and a protective boundary (Graziano & Cooke, 2006; Bogdanova et al., 2021; Coello & Iachini, 2020). Consistently, several brain imaging evidence have shown that brain areas recruited for the peripersonal space representation and for defensive responses overlap (Holt et al., 2014; Viera, Pierzchajlo and Mitchell, 2020; Zanini et al., 2021). For example, Viera et al. (2020) reported that areas typically involved in the peripersonal space representation, namely premotor and parietal areas, are similarly activated when the peripersonal space is approached by threatening social stimuli, compared to non-social ones. Gianelli et al. (2013) showed that participants respond faster to objects when sitting near unfamiliar partners compared to familiar ones. Additionally, studies employing virtual avatars have shown that participants enlarged their peripersonal space when responding to negative emotional stimuli (Ruggiero et al., 2017, 2021), when interacting with males' compared to females' characters (Iachini et al., 2016) and when interacting with immoral rather than moral virtual confederates (Iachini, Pagliaro & Ruggiero, 2015). This evidence

would suggest that the expansion of the peripersonal space might signal a defensive mechanism from external threats or invaders. However, given the results of the comparison of representation of one's own peripersonal space across experiments of the present study (including the solo condition), this interpretation is less consistent with our results, as it would be rather implausible that the defence mechanisms would be activated to the highest extent (making the perceived peripersonal space largest) when one performs the task alone.

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