The relationship between action, social and multisensory spaces

Laurie Geers, Yann Coello

The relationship between action, social and multisensory spaces

Geers Laurie[1] & Coello Yann[1,*]

[1]CNRS, UMR 9193 - SCALab - Sciences Cognitives et Sciences Affectives, Université de Lille, Lille, France

*Corresponding author:
Coello Yann
SCALab UMR CNRS 9193
University of Lille
Domaine universitaire du Pont de Bois, BP 60149
59653 Villeneuve d'Ascq Cedex, France
Email: yann.coello@univ-lille.fr

Abstract

Several spaces around the body have been described, contributing to interactions with objects (peripersonal) or people (interpersonal and personal). The sensorimotor and multisensory properties of action peripersonal space are assumed to be involved in the regulation of social personal and interpersonal spaces, but experimental evidence is tenuous. Hence, the present study investigated the relationship between multisensory integration and action and social spaces. Participants indicated when an approaching social or non-social stimulus was reachable by hand (reachable space), at a comfortable distance to interact with (interpersonal space), or at a distance beginning to cause discomfort (personal space). They also responded to a tactile stimulation delivered on the trunk during the approach of the visual stimulus (multisensory integration space). Results showed that participants were mostly comfortable with stimuli outside reachable space, and felt uncomfortable with stimuli well inside it. Furthermore, reachable, personal and interpersonal spaces were all positively correlated. Multisensory integration space extended beyond all spaces and correlated only with personal space when facing a social stimulus. Considered together, these data confirm that action peripersonal space contributes to the regulation of the social spaces, and that multisensory integration is not specifically constrained by the spaces underlying motor action and social interactions.

Keywords: PPS - IPS - social interactions - multisensory integration - reachability judgment - comfort distance judgment

1.Introduction

The space immediately surrounding the body is of foremost importance for any living being as it is the space in which physical interactions with the environment take place. During the last decades, countless studies in cognitive neurosciences have fortified the idea that the representation of space is functional, *i.e.,* the space offering information on the possibilities of acting on objects must be processed differently by the brain than the space offering information on the mere presence of objects with no possibilities to act on them. This view has led to the distinction between *peripersonal space* (PPS, *i.e.,* within reach) and *extrapersonal space* (*i.e.,* beyond reach)[1,2], which would be underpinned by different neural networks[3,4]. The concept of PPS originates from single-unit electrophysiological studies in monkeys showing that a number of neurons within the ventral premotor cortex, the parietal cortex and the putamen responded more to objects presented in the near reachable space than objects presented in the far unreachable space[2,5,6]. Thus, PPS has been conceived as an interface between the body and the environment, contributing to the organisation of object-directed motor actions, either in terms of approach when facing incentive objects or in terms of avoidance when facing threatening objects[7,8]. In line with this, neuroimaging studies revealed that the mere observation of an object located in PPS triggered activation in the sensorimotor brain areas, including the reach-related area of the superior parieto-occipital cortex, and the premotor and motor cortical areas[9,10,11,12]. As a consequence, the transient disruption of the left motor cortex using transcranial magnetic stimulation has been shown to produce an alteration of the perception of objects located in PPS[13]. Likewise, corticospinal activity[14] and μ rhythm desynchronization[15,16] increased in the presence of objects in the near (vs. far) space, similar to what has been observed during the preparation and execution of objects-directed motor actions[17,18]. Moreover, modifying the actual reaching-by-hand capabilities (*e.g.,* through tool-use or limb immobilisation), or biasing the spatial consequences of object-directed actions, entailed a congruent increase or decrease of the PPS[19,20,21,22]. Altogether, these

65   results suggest that PPS is an action space, enabling access to motor-related information

66   similar to those implied in the planning and execution of voluntary motor actions[23].

67   As revealed by monkey electrophysiological studies, most PPS neurons are

68   multisensory in that they respond to stimuli in two or three different sensory modalities, with

69   overlapping receptive fields anchored onto the same body region[2,5,6]. In addition, neural and

70   behavioural investigations have consistently shown that stimuli in one sensory modality

71   enhance the processing of stimuli in another modality, especially when those stimuli are

72   perceived as potentially interacting with our body[8]. Importantly, some of these neurons are

73   particularly responsive to a tactile stimulation delivered in co-occurrence with an approaching

74   visual stimulus, provided the two stimuli fall in the neuron's receptive fields[2]. This

75   multisensory integration is of particular relevance for interactions with the environment, which

76   require the position of external stimuli to be combined with information about different body

77   segments[23], as reflected by higher-order activations of somatosensory and associative

78   areas[24]. Such multisensory integration has also been observed in humans, activating a

79   frontoparietal network[25,26,27], in relation to PPS[28]. However, the main line of evidence in

80   humans supporting multisensory integration in relation to PPS comes from behavioural

81   studies showing that the proximity of a visual/auditory stimulus from a certain body region

82   fastens the detection of a tactile stimulation on that body region, and the maximal distance at

83   which such facilitation is observed (as compared to a unisensory control condition) is usually

84   used as a proxy of the PPS extent[29,30,31,32]. The scientific consensus is that the integration of

85   visual/auditory and tactile information would provide an interface between perception and

86   action allowing appropriate (re)actions towards (either threatening or incentive) objects to be

87   generated. The relevance of multisensory integration to action preparation and execution is

88   indeed supported by the studies on the effect of permanent or temporary damage to the

89   monkey's cortex showing a direct relationship between the PPS multisensory network and the

90   accuracy of motor responses[33,34,35,36]. Furthermore, electric stimulation of the PPS

91   multisensory neurons in the monkey premotor and intraparietal cortex elicits a pattern of

4

92   movements that is compatible with defensive arm movements[37], while the PPS multisensory

93   neurons in the parietal and precuneus cortex have been shown to discharge during arm

94   reaching movements towards the part of space corresponding to their visual receptive field[2].

95   PPS represents thus a multisensory and sensorimotor interface mediating the physical

96   interactions between the body and the environment[38].

97   Hence, if PPS consists in a multisensory interface dedicated to physical interactions

98   with the environment, the reachable and multisensory integration spaces are expected to

99   overlap. However, the wealth of studies on behavioural multisensory facilitation in humans

100   has highlighted a high degree of lability of the multisensory integration space, depending

101   notably on the body region targeted by the tactile stimulation[32]. Indeed, when considering

102   similar experimental conditions (*i.e.*, the detection of a tactile stimulus in the presence of a

103   looming auditory stimulus), the extent of the multisensory integration space tended to be

104   shorter when the tactile stimulus was delivered on the hand (around 40 cm), than on the face

105   (around 50 cm) or trunk (around 55 cm). Moreover, it is worth noting that the range of

106   distances leading to multisensory integration varied considerably across studies, even when

107   using the same experimental conditions (from 20 to 66 cm for the hand, from 17 to 86 cm for

108   the head; from 25 to 80 for the trunk[29,30,31,32,39,40,41,42,43,44,45,46,47,48,49,50,51,52]. Hence, multisensory

109   integration does not seem to systematically overlap with the motor action space. In support

110   of this claim, Zanini and colleagues[53] found that the space corresponding to hand-centred

111   visuotactile integration was shorter than the space reachable with the hand, and moved with

112   the hand, while reachable space was insensitive to hand position. They concluded that

113   multisensory and reachable spaces are distinct spatial representations. However, it is worth

114   underlying that the observed dissociation might also arise from the different frames of

115   reference involved in the two tasks. It is indeed known that object-directed action involves a

116   stable trunk-centred frame of reference[54,55]. By contrast, multisensory integration was

117   thoroughly tested using a hand-centred or head-centred frame of reference, requiring, for

118   motor action, to refer to a more global representation of the body constituting the

5

119 egocentre[32,38,56,57]. Accordingly, the "trunk-centred" reachable-by-hand space was not

120 expected to coincide exactly with the "hand-centred" multisensory integration space. In line

121 with this claim, Serino and colleagues[32] considered that "hand- and face-centred PPS are

122 referenced to the trunk-centred PPS, which [is] a more extended representation of the space

123 surrounding the body". Hence, multisensory integration might be compatible with the

124 representation of the space that is reachable with the hand when referring to the same frame

125 of reference, *i.e.,* a trunk-centred frame of reference, which has never been truly tested.

126 Another important aspect of the body-environment interactions concerns the nature of

127 the stimulus under consideration. Studies in social psychology have focused on interactions

128 with conspecifics instead of physical objects, and have typically divided the space around the

129 body in a series of bubbles that serve to maintain proper spacing between individuals. The

130 smallest bubble is the *personal space* (PS), which is defined as the space in which social

131 intrusion is felt to be threatening or uncomfortable.[58]. It is assumed to serve as a margin of

132 safety around the body and is typically assessed with discomfort distance judgments

133 requiring the participants to judge at which distance a confederate makes them

134 uncomfortable[59,60,61,62]. A second and larger bubble is the *interpersonal space* (IPS), which is

135 defined as the space one maintains between oneself and others during social interactions[63].

136 It is typically assessed with comfort distance judgments requiring the participant to place a

137 confederate at the most comfortable distance to interact with[64,65]. Not only do these social

138 spaces refer to the space surrounding the body as PPS, but also share common

139 characteristics with PPS. For instance, PPS is modulated by social factors such as the

140 proximity of confederates and the relation that is held with them[46,66, 67,68]. Furthermore, both

141 PPS and social spaces shrink or enlarge depending on the emotional valence of the facing

142 stimulus[59,66,69]. They are also both influenced by individual characteristics such as anxiety[61].

143 These observations probably explain why several researchers in the last decades have taken

144 a closer look at the relationship between PPS and social spaces. Until now, studies have

145 mainly focused on the link between PPS and PS. For instance, Iachini and colleagues[70,60]

146   reported that both spaces have a similar size (around 50cm) and are similarly affected by the

147   nature, age, and gender of the stimulus. They reported that both PPS and PS reduce with

148   humans as compared to robots and cylinders, with females as compared to males, and with

149   children as compared to adults. It has therefore been proposed that PPS, and more particularly

150   its sensorimotor and multisensory properties, serves as a spatial anchor to calibrate social

151   distances[23,71,72]. In support of this claim, Quesque and colleagues[62] found that extending arm

152   length's representation through tool-us increased PPS with a concomitant effect on PS. Social

153   spaces seem thus rooted in the same sensorimotor representation as PPS[23]. However, the

154   above studies have mainly focused on the relative impact of different factors on the PPS and

155   social spaces, which provides little information about their relationship. Moreover, these

156   studies did not include a measure of IPS and thus failed to provide a comprehensive picture

157   of the extent of the different social spaces and their relationship to PPS. Finally, the

158   involvement of multisensory integration in social spaces has not yet been studied in depth.

159   In this context, the present study investigated the relationship between the different

160   action and social spaces anchored on the body and multisensory integration. Participants had

161   to indicate when an approaching neutral visual stimulus (human, robot or lamp) was reachable

162   with the arm (indexing reachable space, RS), at the most comfortable distance to interact with

163   (indexing interpersonal space, IPS), or started to generate discomfort due to too much

164   proximity (indexing personal space, PS). We also included a visuotactile integration task that

165   required participants to respond as fast as possible to a tactile stimulation delivered on the

166   trunk at various times of the approach of the visual stimulus, while ignoring the latter (indexing

167   multisensory integration space, MIS). We expected RS to overlap and correlate with MIS, as

168   being two representative measures of the trunk-centred PPS. Also, along with the idea that

169   the regulation of social distances is based on PPS representation[23,71,72], we expected RS and

170   MIS to correlate with PS and IPS, although IPS should be larger and PS should be smaller than

171   RS and MIS[60,62,70]. Finally, all spaces should be similarly impacted by the nature of the stimulus,

172 with a preference for the lamp and robot to be kept at a larger distance compared to the
173 human[70].

2. Materials and Methods

2.1 Participants

176   Fifty-three participants from the Université of Lille participated in this study, but one
177 participant was excluded because they missed 20% of the tactile stimulations in the
178 multisensory integration task, and two others were excluded because they showed no
179 multisensory facilitation effect, making it impossible to compute its location in space. The
180 final sample was thus composed of 50 participants (12 males, mean [M] age ± standard
181 deviation [SD] = 22.6 ± 4.0). A sample size analysis performed in G*Power indicated that at
182 least 41 participants were required to detect a small effect (Cohen's f = 0.15) with a high power
183 criterion (0.9) in a 4 x 3 repeated-measure ANOVA. All participants were right-handed and had
184 a normal or corrected-to-normal vision. They all gave written informed consent prior to the
185 experiment. The study was performed in accordance with the ethical standards of the
186 Declaration of Helsinki and was approved by the Research Ethics Board of the University of
187 Lille (CESC Lille, Ref. 2021-515-S95).

2.2 Apparatus & stimuli

189   The virtual stimuli were presented through an HTC Vive Pro head-mounted display in a
190 virtual room measuring 6 x 5 x 3 m, and consisting of a white floor, a grey ceiling and grey
191 walls. The stimuli consisted of a human male avatar aged about 30 years, an anthropomorphic
192 robot and a cylindrical lamp. The man and robot looked straight ahead and showed a neutral
193 facial expression (Figure 1). The height of the stimuli was calibrated so that the eye level of
194 the human and robot were aligned with the eye level of the participant. All stimuli had the
195 same height and width. We verified that the visual stimuli were perceived as neutral by
196 requiring the participants to rate the emotional valence of each stimulus on the Self-

Assessment Manikin (SAM) scale, a 9-points graphic Likert scale ranging from 1 (extremely negative) to 9 (extremely positive)[73]. One sample t-test to 5 (*i.e.,* neutral emotional valence) indicated that the human, $t(49) = 0.47$, $p = .643$, robot, $t(49) = 1.85$, $p = .071$, and lamp, $t(49) = -1.24$, $p = .220$, were similarly judged as neutral.

Figure 1.

2.3 Tasks & procedure

Participants were standing while holding a response button in their right hand, and wearing the head-mounted display. A vibrotactile stimulator (DRV2605 Haptic Driver, Texas Instruments) was fixed to their sternum with an elastic band. They performed the four following tasks in a counterbalanced order:

2.3.1   Reachability Distance Judgment

Participants were required to press the response button as soon as they judged being able to reach the approaching visual stimulus, without actually performing any reaching movement. Each trial started with the appearance of a visual stimulus at 300 cm in front of the participant for a duration of 500 ms, which then approached the participant at a velocity of 0.75m/sec. Whenever the participant pressed the response button, the visual stimulus stopped moving and remained still for 1000 ms before disappearing. The next trial started at a random delay between 800 and 850 ms following the disappearance of the previous stimulus. The task consisted of 18 trials (3 stimuli x 6 repetitions), lasted about 2 minutes, and was used to assess RS.

218 *2.3.2   Comfort Distance Judgment*

219   The same procedure as in the reachability distance judgment task was used, except that

220   participants were required to press the response button as soon as the visual stimulus was

221   judged at the most comfortable distance to interact with it. This task was used to assess IPS.

222   *2.3.3   Discomfort Distance Judgment*

223   *T*he same procedure as in the reachability distance judgment and comfort distance

224   judgment tasks was used, except that participants were required to press the response button

225   whenever the visual stimulus was at a distance that made them feel uncomfortable. This task

226   was used to assess PS.

227   2.3.4   *Multisensory Integration Task*

228   Participants were required to respond as quickly as possible to a tactile stimulation (60

229   ms, 3.6 V, 250 Hz) delivered well above the detection threshold on their sternum while ignoring

230   the visual stimulus facing them. The task included 4 types of trials: bimodal visuotactile,

231   unimodal tactile, bimodal catch and unimodal catch trials. In all types of trials, the visual

232   stimulus appeared at 300 cm in front of the participants for 500 ms. In the bimodal visuotactile

233   trials, the stimulus moved towards the participants at a velocity of 0.75m/sec. A tactile

234   stimulation was delivered at one of the 8 following delays: 1333, 2000, 2267, 2533, 2800, 3067,

235   3333 or 3600 ms after the setting in motion of the visual stimulus. This means that the visual

236   stimulus was respectively at 200, 150, 130, 110, 90, 70, 50 and 30 cm from the participant at

237   the time the tactile stimulation occurred. Hence, the longer the delay, the closer the stimulus

238   from the participants. In the unimodal tactile trials, the tactile stimulation was provided after

239   1333, 2800 or 3600 ms, but the visual stimulus remained still. These trials served as baseline

240   and allowed us to investigate the facilitation effects induced by the spatial proximity of the

241   visual stimulus while controlling that these effects were not merely due to the expectancy of

242   tactile stimulation or attention varying with temporal delay. In the bimodal catch trials, the

10

243   visual stimulus moved toward the participant until being at a distance of 20 cm, but no tactile

244   stimulation was delivered. In the unimodal catch trials, the visual stimulus remained still, but

245   no tactile stimulation was delivered. These catch trials were included to avoid automatic

246   motor responses and make sure that the participants were attentive to the task all along the

247   experiment. Whenever the participant pressed the response button, the visual stimulus

248   stopped moving and remained still for 1000 ms before disappearing. The next trial started at

249   a random delay between 800 and 850 ms following the disappearance of the previous

250   stimulus. The whole task consisted of 414 trials, including 240 visuotactile bimodal (3 stimuli

251   x 8 delays x 10 repetitions), 90 unimodal (3 stimuli x 3 delays x 10 repetitions), 42 bimodal

252   catch (3 stimuli x 14 repetitions) and 42 unimodal catch (3 stimuli x 14 repetitions) presented

253   in a random order. The trials were divided into 6 blocks of about 6 minutes intermingled with

254   5-minutes breaks. This task was used to assess MIS.

255 2.4 Data analyses

256   The data were analysed using *R* (version 4.1.0) and *R Studio* software (version 1.3.1093).

257   We first verified that our multisensory integration task succeeded in showing the typical

258   effects of the tactile stimulation delay on reaction times (RT) in each of the three stimuli used

259   (see Supplemental Materials for procedure and results).

2.4.1 Extent of the different spaces.

261   To determine the individual extent of RS, PS and IPS, we averaged for each participant

262   and each stimulus the distance of the visual stimulus at the time of the response in the

263   reachability judgement task, and in the discomfort and comfort distance judgement tasks,

264   respectively. The extent of MIS was determined by identifying the farthest distance at which

265   the bimodal trials induced facilitation effects as compared to the unimodal trials in the

266   visuotactile integration task (see Supplemental Materials for detailed procedure). We then

267   compared the different spaces in terms of their average extent and their sensitivity to the

268   nature of the visuals stimulus by entering the computed extents in a repeated-measures

269   ANOVA with the Space (RS, MIS, IPS, PS) and type of Stimulus (human, robot, lamp) as within-

270   subject variables. Since the extent of MIS was an ordinal variable and the extent of the

271   different spaces, as well as the residuals of the model, did not follow a normal distribution, we

272   used an Aligned Rank Transform (ART) for nonparametric factorial ANOVAs as described by

273   Wobbrock and colleagues[74]. We planned to conduct pairwise comparisons on the significant

274   effects, but also on the effect of the Stimulus on each task, to investigate whether we replicate

275   the observation of expanded PPS and PS in the presence of a virtual human as compared to

276   a virtual robot and a lamp[70,60] when using stimuli controlled for their (neutral) emotional

277   valence. The paired comparisons were performed using the ART[74] or ART-C[75] alignment

278   procedure, as appropriate to the requested contrast, and with Bonferroni correction.

279   *2.4.2 Relationship between the different spaces.*

280   We then further investigated the relationship between the different spaces with pairwise

281   correlation analyses. We computed the correlation coefficients for each stimulus separately.

282   In particular, we computed Pearson *r* coefficients, except when correlation included MIS, in

283   which case we computed the Spearman *r* correlation coefficient for ordinal variables.

284 *2.4.3 Bayesian analyses*

285   We also conducted the corresponding Bayesian analyses in JASP (with default values)

286 in order to quantify the evidence in favour of an effect (H1) compared to an absence of effect.

287 These analyses provided Bayes Factors (BF_{10}) varying between 0 and ∞, where values below

288 1 provide increasing evidence in favour of the null hypothesis and values above 1 provide

289 increasing evidence for the alternative hypothesis (H1/H0)[76]. A BF above 3 is typically

290 considered sufficient evidence for the alternative hypothesis, while a BF below ⅓ is typically

291 considered sufficient evidence for the null hypothesis[77].

292 3. Results

293 3.1 Extent of the different spaces

294   The ANOVA comparing the extent of the different spaces and the sensitivity to the

295 different visual stimuli showed a significant effect of Space, $F(3,539) = 181.31$, $p < .001$, $\eta_p^2 =$

296 0.502, $BF_{10} = 6.94^{+66}$. The average extent ± standard error [SE] was 127.40 ± 2.98 cm for MIS,

297 116.35 ± 4.05 cm for IPS, 91.36 ± 3.08 cm for RS and 53.47 ± 2.37 cm for PS. Post hoc pairwise

298 comparisons showed that all spaces were significantly different from each other (all *p*-values

299 < .001; Figure 2A). There was no significant effect of the Stimulus, $F(2,539) = 0.62$, $p = .536$,

300 $\eta_p^2 = .002$, $BF_{10} = 0.04$, or Space by Stimulus interaction, $F(6,539) = 0.73$, $p = .626$, $\eta_p^2 = .008$,

301 $BF_{10} = 0.02$. The planned comparisons, however, showed a significant effect of the Stimulus

302 on RS, $F(2, 98) = 13.84$, $p < .001$, $\eta_p^2 = .220$, $BF_{10} = 2018.02$, with participants judging the human

303 as reachable at shorter distances (M ± SE = 86.24 ± 5.04 cm) than the robot (93.16 ± 5.55 cm),

304 $t(98) = -3.43$, $p = .002$, $BF_{10} = 3835.21$, and the lamp (94.66 ± 5.41 cm), $t(98) = -5.17$, $p < .001$,

305 $BF_{10} = 355.93$, while RS for the robot and lamp did not significantly differ from each other, $t(98)$

306 $= -1.74$, $p = .195$, $BF_{10} = 0.205$. The effect of Stimulus was also significant for IPS, $F(2, 98) =$

307 6.88, $p = .002$, $\eta_p^2 = .123$, $BF_{10} = 36.62$. Post-hoc pairwise comparisons further indicated that

308 participants preferred to place the lamp at shorter distances (108.43 ± 6.65 cm) than the robot

309 (121.34 ± 7.34 cm), $t(98)$ = -3.42, p = .003, BF_{10} = 14.78, and the human (119.27 ± 6.98 cm),

310 $t(98)$ = −2.95, p = .011, BF_{10} = 3.02, while the preferred distance for the human and robot did

311 not significantly differ from each other, $t(98)$ = -0.47, p = .884, BF_{10} = 0.271. By contrast, the

312 effect of the Stimulus was marginal (or null, according to Bayesian analyses) on PS, $F(2, 98)$

313 = 3.01, p = .054, η_p^2 = .057, BF_{10} = 0.290, with only the lamp being tolerated closer than the

314 robot, $t(98)$ = -2.45, p = .047, BF_{10} = 0.56. Finally, the effect of Stimulus on multisensory space

315 was not significant, $F(2, 98)$ = 0.28, p = .752, η_p^2 = .005, BF_{10} = 0.089.

316 **Figure 2.**
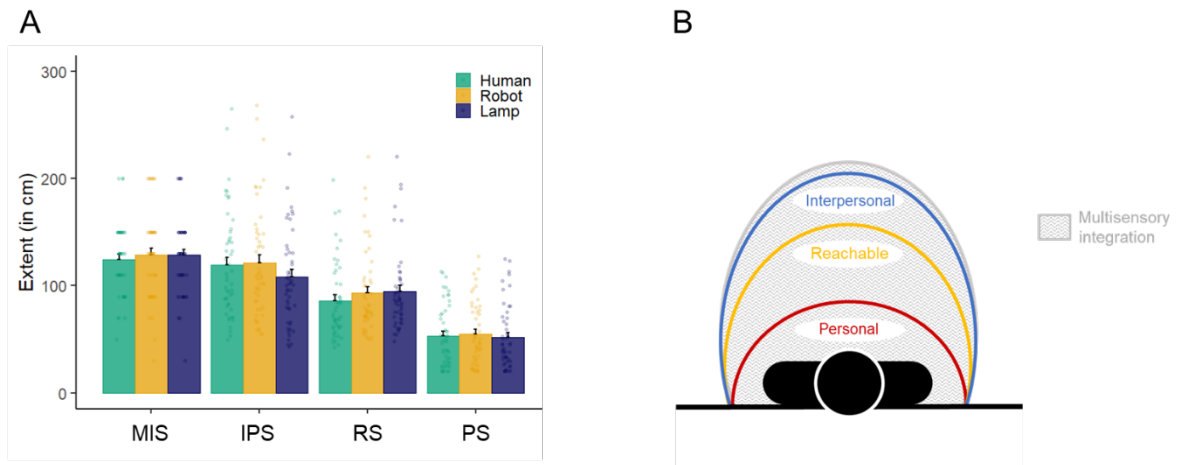
318 ## 3.2 Relationship between the different spaces

319 Regarding the lamp, a significant positive correlation was found between RS and IPS, r

320 = .54, p < .001, BF_{10} = 594.58, between RS and PS, r = .46, p < .001, BF = 42.33, as well as

321 between IPS and PS, r = .64, p < .001, BF_{10} = 31768.77. The correlation between RS and MIS

322 was not significant, r = -.11, p = .443, BF_{10} = 0.28, so as the other correlations including MIS (all

323 p-values > .407, all BF_{10}-values < 0.27; Figure 3). Regarding the robot, we also found a

324 significant positive correlation between RS and IPS, r = .41, p = .003, BF_{10} = 11.23, RS and PS,

325 r = .35, p = .014, BF_{10} = 3.38, as well as between IPS and PS, r = .53, p < .001, BF_{10} = 335.11. In

326 addition, there was a significant negative correlation between PS and MIS, r = -.45, p < .001,

14

327 *BF*$_{10}$ = 63.84. No other correlation was significant (all *p*-values > .938, all *BF*$_{10}$ < 0.31), including

328 the correlation between RS and MIS, *r* = -.10, *p* = .499, *BF*$_{10}$ = 0.23 (Figure 4). Regarding the

329 human, we found the same significant correlations as in the robot: a positive correlation

330 between RS and IPS, *r* = .42, *p* = .003, *BF*$_{10}$ = 13.92, and between RS and PS, *r* = .37, *p* = .007,

331 *BF*$_{10}$ = 5.40, PS and IPS, *r* = .59, *p* < .001, *BF*$_{10}$ = 4169.65, as well as a negative relation between

332 PS and MIS, *r* = -.38, *p* = .006, *BF*$_{10}$ = 8.94. There was no other significant correlation (*p-values*
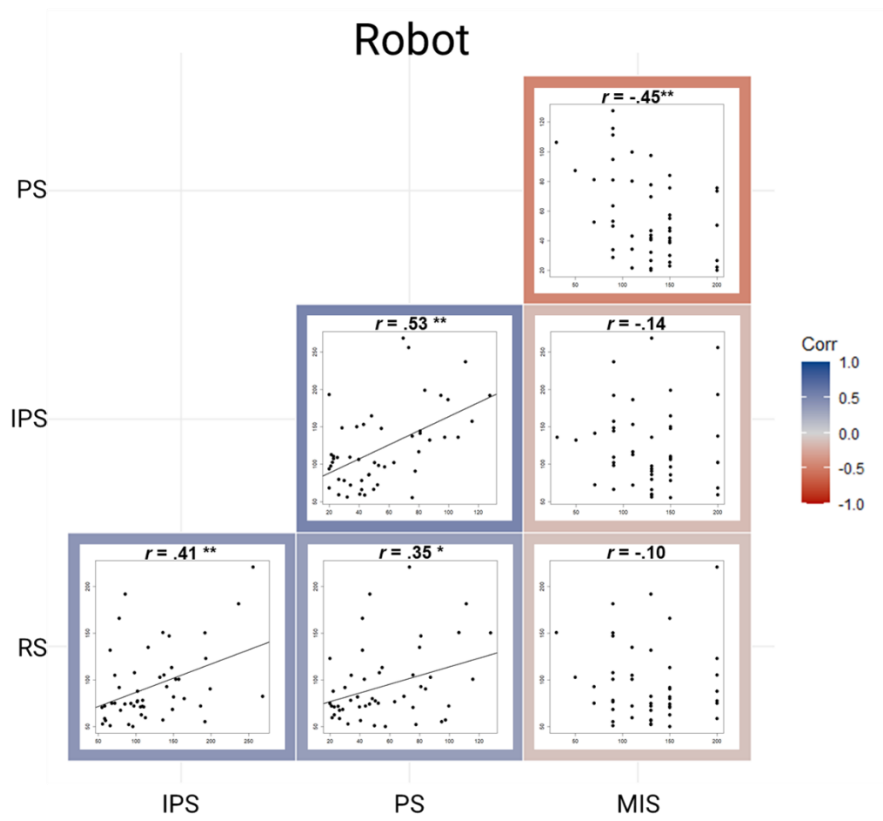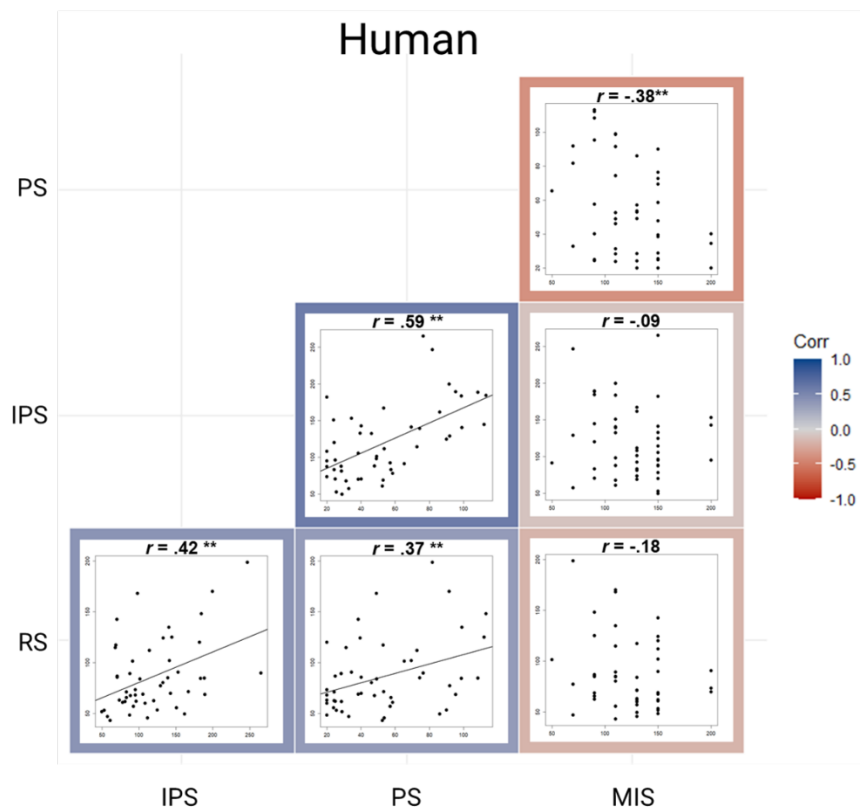
333 >.210, *BF*$_{10}$-values < 0.439; Figure 5).

334 **Figure 3.**
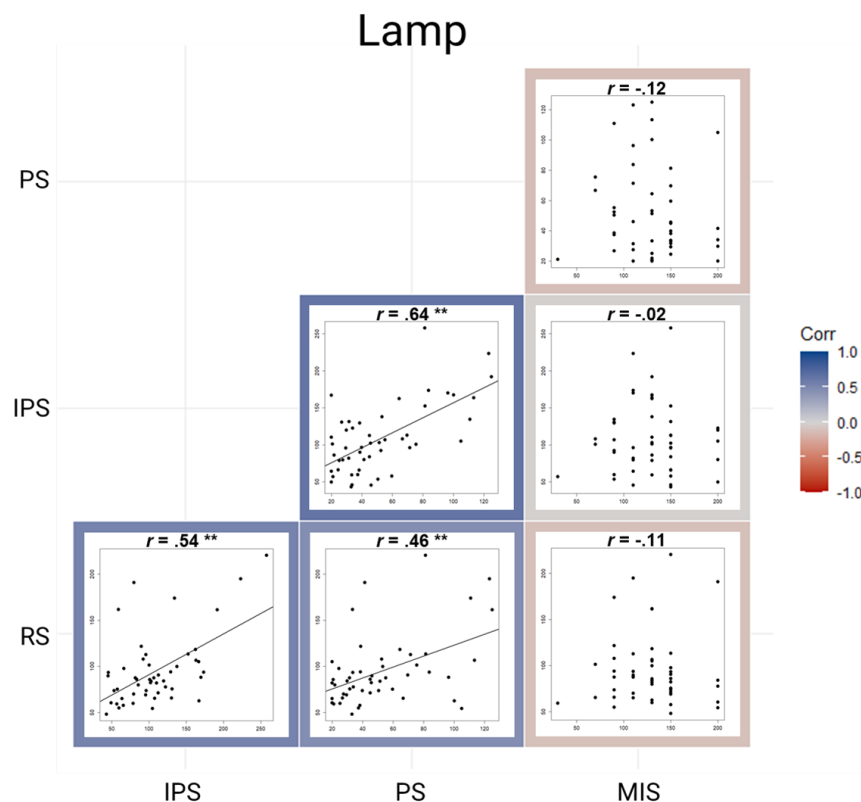
335

Figure 4.

Figure 5.

4. Discussion

The aim of the present study was to assess the relationship between the reachable and multisensory spaces, two representative measures of the trunk-centred PPS, and how the latter related to the social spaces (interpersonal and personal). To do so, we required participants to indicate when an approaching neutral visual stimulus (human, robot or lamp) was reachable with the arm (RS), at the most comfortable distance to interact with (IPS), or too close so that it generated a feeling of discomfort (PS). We also included a visuotactile integration task (MIS) that required participants to respond as fast as possible to tactile stimulation delivered on the trunk at various times of the approach of the visual stimulus. Based on the idea that PPS is an action space characterised by sensorimotor and multisensory properties, we expected the extent of RS and MIS not only to overlap but also to correlate. Moreover, along with the idea that PPS contributes to the regulation of the social

352   spaces, we expected all spaces to correlate and to be similarly impacted by the nature of the

353   stimulus, although PS should have the smallest extent and IPD the largest one.

354   The analyses of the extent of the different spaces showed that MIS was larger (127 cm)

355   than IPS (121 cm), which was, in turn, larger than RS (95 cm) and PS (58 cm, Figure 2B). This

356   indicates that, as expected, both objects and humanoids were preferentially placed outside

357   RS to interact with, and generated discomfort when present well inside it. The extent of RS is

358   known to slightly overestimate arm length[78] (here 73.2 ± 5.6 cm, corresponding for RS to an

359   overestimation of 29%), in particular in virtual environments[79]. Moreover, the relative extents

360   of the reachable and social (PS and IPS) spaces are in line with previous observations showing

361   that IPS extent is typically between 80 and 140 cm[65], while RS and PS extents are typically

362   smaller, i.e., between the range of 50-70 cm[20,70,62]. The data analysis conducted in the present

363   study further showed that the extent of PS is smaller than that of RS. This confirms the

364   previous findings highlighting that one feels progressively uncomfortable whenever RS is

365   violated[80,81]. It is also worth noting that the extent of RS and IPS were both affected by the

366   type of stimulus presented, even though the latter were all rated as neutral. As already

367   shown[60,70], RS was significantly shorter in the presence of a virtual human than in the presence

368   of a lamp or robot (7.7 cm in the present study). This confirms that PPS representation

369   expanded with virtual objects and reduced with virtual humans. Conversely, the extent of IPS

370   was not different between the robot and human, and significantly shorter with the lamp (11.9

371   cm in the present study). This might reflect the fact that interactions with objects require

372   touching them and thus be at shorter distances than people for which interactions might be

373   primarily conceived as a verbal exchange, especially when the situation involves a stranger[63].

374   The lack of difference between the robot and human stimulus might suggest that the

375   anthropomorphic aspect of the robot used in the present study was sufficient to consider

376   social interaction with it. It is indeed expected that human-like stimuli with the same (neutral)

377   emotional valence should be positioned at the same IPS[59,71,80]. A complementary

378   interpretation could be that the human stimulus used in the present study was a male who

379   was shown to trigger larger IPS than a female human stimulus[60,70]. Further experiments would

380   be required to disentangle these different interpretations.

381   The correlational analyses revealed that RS, IPS and PS, although they were

382   characterised by different extents, were positively correlated to each other, whatever the

383   stimulus presented. This means that the participants with a larger RS were also those who

384   had a larger IPS and PS, and conversely, whichever the stimulus presented. These data

385   confirm previous studies that highlighted that the regulation of PS depends in some respect

386   on the representation of PPS[62], although the outcome of the present study extends the

387   contribution of PPS also to IPS. The observed pattern of results, therefore, provides an

388   additional argument for the involvement of PPS in the calibration of social spaces[60,62,70,71], and

389   corroborates brain imaging studies showing that the frontoparietal network involved in the

390   representation of PPS also supports social interactions[82,83]. Overall, these findings comfort

391   the idea that action and social spaces are related but more specifically that the sensorimotor

392   properties of PPS serve as a spatial reference to specify the appropriate social distances, as

393   suggested by the homeostatic theory of social interactions[71]. According to this theory, the

394   appropriate inter-individual distance corresponds to PPS plus an extra margin of safety, that

395   adapts according to the valence or level of threat endowed on conspecifics. This theory,

396   therefore, accounts for the observation that IPS correlates with RS but has a larger extent. In

397   its original form, the theory did not take into account PS and assumed that PPS is a protective

398   buffer zone whose intrusion produces discomfort[80,81] and triggers defensive behaviour[84]. As

399   discussed above, the present study rather underlines that discomfort is experienced when

400   stimuli are well inside RS. PS is therefore a better candidate if we consider the priority space

401   dedicated to the protection of the body, although it seems calibrated from PPS representation.

402   This spatial relationship between PPS and PS would allow for PPS intrusion, at least to some

403   extent, which is often required during interactions both with objects and living beings.

404   The striking result of the present study is however the observation that trunk-centred

405   multisensory integration extended much further away than both reachable and social spaces,

406   which is in contradiction with our initial hypothesis. Indeed, MIS was 11.05 cm larger than IPS,

407   36.04 cm larger than RS and 73.93 cm larger than PS. MIS extent is furthermore much larger

408   in the present study than what was previously observed with auditory stimuli when also using

409   a trunk-centred frame of reference (*i.e.,* around 55 cm, from 25 to 80)[32]. One potential

410   explanation could be that multisensory integration extended more when facing meaningful

411   visual stimuli. A careful inspection of previous studies supports this hypothesis: hand-centred

412   and face-centred multisensory integration were found to be both more extended when facing

413   virtual human characters (up to 127 and 150 cm, respectively)[85,86] than when facing looming

414   pink noise (up to 66 and 75 cm, respectively)[42,49]. However, even when centred on the same

415   trunk-centred frame of reference as the reachability task, MIS did not correspond to RS. This

416   result has two consequences. First, it indicates that multisensory integration is not specifically

417   related to the motor action space. Second, the fact that MIS encompasses both action space

418   and social spaces may suggest that multisensory integration contributes to the overall

419   interactions with objects and people in the environment, without specifically contributing to

420   the specification of the spaces where these interactions occur. These findings contrast with

421   the single-cell recording studies in monkeys showing that the receptive fields of the

422   multisensory neurons are within RS[2]. However, one may hypothesise that the sensory

423   facilitation reported in the behavioural studies and the neural mechanisms highlighted in the

424   single-cell studies do not refer to the exact same multisensory integration process[87]. While

425   the link between the two has been strongly advocated[29], it is apparent that the behavioural

426   multisensory facilitation effect in humans is more flexible than what was reported in single-

427   cell studies. As evidence, multisensory facilitation in behavioural studies has been found to

428   be altered by the valence or meaning of the visual/auditory stimulus[66], individual traits such

429   as anxiety/phobia[45], interoceptive traits[40], bodily changes such as pregnancy[41] or limb

430   immobilisation[88], and even lockdown experience[85]. Moreover, a number of studies indicated

20

431 that the visual/auditory stimulus does not have to target the same body part as the tactile

432 stimulation to trigger multisensory facilitation[87]. This might be because the behavioural

433 effects evidenced arose not only from the multisensory brain areas but also from their

434 interaction with other brain areas such as those involved in body representation[89] and object-

435 directed action control[7]. Another aspect of the behavioural studies on humans is that they

436 implied a task-dependent motor response, while monkeys were generally studied in a passive

437 condition. Thus, despite their pioneering role, single-cell studies might represent only a small

438 window onto the network underpinning multisensory integration in the context of goal-

439 directed motor action and social interaction. This may explain the lack of correlation that we

440 found between MIS and RS, corroborated by the Bayesian analysis, albeit single-cell studies

441 revealed a link between multisensory integration and arm RS[2,5]. From a behavioural

442 perspective, it seems thus that RS refers to a different spatial representation than MIS despite

443 being tested with a typical looming task and using the same spatial frame of reference. PPS,

444 as an action space, must thus be viewed as a sensorimotor interface anchored on the body

445 that involves, but does not depend on, multisensory integration. Moreover, the negative

446 correlation found between MIS and PS, although specific to the humanoid stimuli (human and

447 robot), could suggest that multisensory integration serves mostly a defensive purpose[8].

448 People characterised by a larger MIS were also characterised by a shorter PS, which may

449 reveal an adaptive link between anticipation of physical contact with social stimuli and

450 acceptance of the proximity of these stimuli.

451   Another implication of MIS encompassing all other spaces is that multisensory

452 processes, usually related to the action space, extend also to the social space. This is not that

453 surprising since the need to combine several sensory cues is not restricted to interactions

454 with objects but also applies to social stimuli. For instance, emotions are expressed through

455 facial expressions but also voice such that visual and auditory cues integration is an essential

456 part of emotion reading and more globally of social interactions[90]. Moreover, multisensory

457 integration is assumed to allow the preparation of the body for action, either for the purpose

458   of defensive or approaching behaviour[7,8,70,71]. Physical contact with people, though less

459   frequent than with objects, is also experienced on a daily-base: we shake hands, hug, are

460   tapped on the shoulder to get our attention, or brush against each other in crowded

461   environments, with some of these contacts, for instance when concerning people with bad

462   intentions, being at risk for the body. The functional advantage provided by multisensory

463   integration is thus also relevant for social interactions to anticipate possible contact with

464   others and programme appropriate actions and responses — for example, to avoid harmful

465   contact or shake hands properly with our interlocutor. A consequence of this approach is that

466   multisensory integration must be viewed as a process at hand during interactions with either

467   objects or individuals, which is not specific to the nature of the present stimulus or the type of

468   interaction envisaged, and which thus seems not constitutive of the spaces underlying object-

469   directed actions and social interactions.

470   In conclusion, this first study comparing PPS (RS and MIS) and the social spaces (PS

471   and IPS) showed that only (the action PPS was related to the social spaces. This finding

472   confirms previous studies reporting that RS and PS are related[60,62,70,80], but extends this

473   relationship to IPS. This further underlines the particular role of the sensorimotor aspects of

474   PPS in the regulation of the social spaces, providing new evidence in support of the

475   homeostatic theory of social interactions[71]. Multisensory integration was not restricted to

476   action PPS and social spaces, as it extended beyond all these spaces. This indicates that

477   multisensory integration is involved in interactions with objects and people, in relation to the

478   anticipatory aspects of these interactive behaviours, but does not specifically determine the

479   representation of both action PPS and social spaces. The specific role of multisensory

480   integration in the different interactions with the environment, therefore, remains to be further

481   clarified, paving the way for future research.

5. References

1. Previc, F. H. The neuropsychology of 3-D space. *Psychological Bulletin* **124**, 123–164 (1998).

2. Rizzolatti, G., Scandolara, C., Matelli, M. & Gentilucci, M. Afferent properties of periarcuate neurons in macaque monkeys. II. Visual responses. *Behavioural Brain Research* **2**, 147–163 (1981).

3. di Pellegrino, G. & Làdavas, E. Peripersonal space in the brain. *Neuropsychologia* **66**, 126–133 (2015).

4. Cléry, J., Guipponi, O., Wardak, C. & Ben Hamed, S. Neuronal bases of peripersonal and extrapersonal spaces, their plasticity and their dynamics: Knowns and unknowns. *Neuropsychologia* **70**, 313–326 (2015).

5. Graziano, M. S. A. & Gross, C. G. A bimodal map of space: somatosensory receptive fields in the macaque putamen with corresponding visual receptive fields. *Exp Brain Res* **97**, (1993).

6. Graziano, M. S. A., Yap, G. S. & Gross, C. G. Coding of Visual Space by Premotor Neurons. *Science* **266**, 1054–1057 (1994).

7. Brozzoli, C., Makin, T. R., Cardinali, L., Holmes, N. P. & Farnè, A. Peripersonal Space: A Multisensory Interface for Body–Object Interactions. in *The Neural Bases of Multisensory Processes* (CRC Press/Taylor & Francis, 2012).

8. Graziano, M. S. A. & Cooke, D. F. Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia* **44**, 845–859 (2006).

9. Bartolo, A. *et al.* Contribution of the motor system to the perception of reachable space: an fMRI study. *Eur J Neurosci* **40**, 3807–3817 (2014).

10. Ferri, F. *et al.* Intertrial Variability in the Premotor Cortex Accounts for Individual Differences in Peripersonal Space. *Journal of Neuroscience* **35**, 16328–16339 (2015).

507   11. Grafton, S. T., Fadiga, L., Arbib, M. A. & Rizzolatti, G. Premotor Cortex Activation during

508   Observation and Naming of Familiar Tools. *NeuroImage* **6**, 231–236 (1997).

509   12. Quinlan, D. J. & Culham, J. C. fMRI reveals a preference for near viewing in the human

510   parieto-occipital cortex. *NeuroImage* **36**, 167–187 (2007).

511   13. Coello, Y. *et al.* Perceiving What Is Reachable Depends on Motor Representations:

512   Evidence from a Transcranial Magnetic Stimulation Study. *PLoS ONE* **3**, e2862 (2008).

513   14. Cardellicchio, P., Sinigaglia, C. & Costantini, M. The space of affordances: A TMS study.

514   *Neuropsychologia* **49**, 1369–1372 (2011).

515   15. Proverbio, A. M. Tool perception suppresses 10–12Hz μ rhythm of EEG over the

516   somatosensory area. *Biological Psychology* **91**, 1–7 (2012).

517   16. Wamain, Y., Gabrielli, F. & Coello, Y. EEG μ rhythm in virtual reality reveals that motor

518   coding of visual objects in peripersonal space is task dependent. *Cortex* **74**, 20–30 (2016).

519   17. Bestmann, S. & Duque, J. Transcranial Magnetic Stimulation: Decomposing the Processes

520   Underlying Action Preparation. *Neuroscientist* **22**, 392–405 (2016).

521   18. Pfurtscheller, G. & Neuper, C. Event-related synchronization of mu rhythm in the EEG over

522   the cortical hand area in man. *Neuroscience Letters* **174**, 93–96 (1994).

523   19. Bourgeois, J. & Coello, Y. Effect of visuomotor calibration and uncertainty on the

524   perception of peripersonal space. *Atten Percept Psychophys* **74**, 1268–1283 (2012).

525   20. Bourgeois, J., Farnè, A. & Coello, Y. Costs and benefits of tool-use on the perception of

526   reachable space. *Acta Psychologica* **148**, 91–95 (2014).

527   21. Leclere, N. X., Sarlegna, F. R., Coello, Y. & Bourdin, C. Sensori-motor adaptation to novel

528   limb dynamics influences the representation of peripersonal space. *Neuropsychologia*

529   **131**, 193–204 (2019).

530   22. Toussaint, L., Wamain, Y., Bidet-Ildei, C. & Coello, Y. Short-term upper-limb immobilization

531   alters peripersonal space representation. *Psychological Research* **84**, 907–914 (2020).

532   23. Coello, Y. & Fisher M. *Foundations of embodied cognition. Volume 1: Perceptual and*

533   *emotional embodiment*. (Routledge, Taylor & Francis Group, 2016).

534   24. Guipponi, O., Cléry, J., Odouard, S., Wardak, C. & Ben Hamed, S. Whole brain mapping of
535   visual and tactile convergence in the macaque monkey. *NeuroImage* **117**, 93–102 (2015).

536   25. Bremmer, F. *et al.* Polymodal Motion Processing in Posterior Parietal and Premotor
537   Cortex. *Neuron* **29**, 287–296 (2001).

538   26. Cléry, J. *et al.* The Prediction of Impact of a Looming Stimulus onto the Body Is Subserved
539   by Multisensory Integration Mechanisms. *J. Neurosci.* **37**, 10656–10670 (2017).

540   27. Serino, A., Canzoneri, E. & Avenanti, A. Fronto-parietal Areas Necessary for a Multisensory
541   Representation of Peripersonal Space in Humans: An rTMS Study. *Journal of Cognitive*
542   *Neuroscience* **23**, 2956–2967 (2011).

543   28. Brozzoli, C., Gentile, G., Petkova, V. I. & Ehrsson, H. H. fMRI Adaptation Reveals a Cortical
544   Mechanism for the Coding of Space Near the Hand. *Journal of Neuroscience* **31**, 9023–
545   9031 (2011).

546   29. Canzoneri, E., Magosso, E. & Serino, A. Dynamic Sounds Capture the Boundaries of
547   Peripersonal Space Representation in Humans. *PLoS ONE* **7**, e44306 (2012).

548   30. Canzoneri, E. *et al.* Tool-use reshapes the boundaries of body and peripersonal space
549   representations. *Exp Brain Res* **228**, 25–42 (2013).

550   31. Noel, J.-P., Pfeiffer, C., Blanke, O. & Serino, A. Peripersonal space as the space of the bodily
551   self. *Cognition* **144**, 49–57 (2015).

552   32. Serino, A. *et al.* Body part-centered and full body-centered peripersonal space
553   representations. *Sci Rep* **5**, 18603 (2015).

554   33. Ettlinger, G. & Kalsbeck, J. E. Changes in tactile discrimination and in visual reaching after
555   successive and simultaneous bilateral posterior parietal ablations in the monkey. *Journal*
556   *of Neurology, Neurosurgery & Psychiatry* **25**, 256–268 (1962).

557   34. Faugier-Grimaud, S., Frenois, C. & Stein, D. G. Effects of posterior parietal lesions on
558   visually guided behavior in monkeys. *Neuropsychologia* **16**, 151–168 (1978).

559   35. Gallese, V., Murata, A., Kaseda, M., Niki, N. & Sakata, H. Deficit of hand preshaping after
560   muscimol injection in monkey parietal cortex: *NeuroReport* **5**, 1525–1529 (1994).

561 36. Rizzolatti, G., Matelli, M. & Pavesi, G. Deficits in attention and movement following removal

562   of postarcuate (area 6) and prearcuate (area 8) cortex in macaque monkeys. *Brain* **106**,

563   655–673 (1983).

564 37. Cooke, D. F. & Graziano, M. S. A. Defensive Movements Evoked by Air Puff in Monkeys.

565   *Journal of Neurophysiology* **90**, 3317–3329 (2003).

566 38. Serino, A. Peripersonal space (PPS) as a multisensory interface between the individual

567   and the environment, defining the space of the self. *Neuroscience & Biobehavioral Reviews*

568   **99**, 138–159 (2019).

569 39. Amemiya, T., Ikei, Y. & Kitazaki, M. Remapping Peripersonal Space by Using Foot-Sole

570   Vibrations Without Any Body Movement. *Psychol Sci* **30**, 1522–1532 (2019).

571 40. Ardizzi, M. & Ferri, F. Interoceptive influences on peripersonal space boundary. *Cognition*

572   **177**, 79–86 (2018).

573 41. Cardini, F., Fatemi-Ghomi, N., Gajewska-Knapik, K., Gooch, V. & Aspell, J. E. Enlarged

574   representation of peripersonal space in pregnancy. *Sci Rep* **9**, 8606 (2019).

575 42. Di Cosmo, G. *et al.* Peripersonal space boundary in schizotypy and schizophrenia.

576   *Schizophrenia Research* **197**, 589–590 (2018).

577 43. Ferroni, F. *et al.* Schizotypy and individual differences in peripersonal space plasticity.

578   *Neuropsychologia* **147**, 107579 (2020).

579 44. Galli, G., Noel, J. P., Canzoneri, E., Blanke, O. & Serino, A. The wheelchair as a full-body tool

580   extending the peripersonal space. *Front. Psychol.* **6**, (2015).

581 45. Taffou, M. & Viaud-Delmon, I. Cynophobic Fear Adaptively Extends Peri-Personal Space.

582   *Front. Psychiatry* **5**, (2014).

583 46. Teneggi, C., Canzoneri, E., di Pellegrino, G. & Serino, A. Social Modulation of Peripersonal

584   Space Boundaries. *Current Biology* **23**, 406–411 (2013).

585 47. Hobeika, L., Taffou, M. & Viaud-Delmon, I. Social coding of the multisensory space around

586   us. *R. Soc. open sci.* **6**, 181878 (2019).

587   48. Hobeika, L., Taffou, M., Carpentier, T., Warusfel, O. & Viaud-Delmon, I. Capturing the
588   dynamics of peripersonal space by integrating expectancy effects and sound propagation
589   properties. *Journal of Neuroscience Methods* **332**, 108534 (2020).

590   49. Noel, J.-P., Blanke, O., Magosso, E. & Serino, A. Neural adaptation accounts for the
591   dynamic resizing of peripersonal space: evidence from a psychophysical-computational
592   approach. *Journal of Neurophysiology* **119**, 2307–2333 (2018).

593   50. Maister, L., Cardini, F., Zamariola, G., Serino, A. & Tsakiris, M. Your place or mine: Shared
594   sensory experiences elicit a remapping of peripersonal space. *Neuropsychologia* **70**, 455–
595   461 (2015).

596   51. Noel, J.-P. *et al.* Full body action remapping of peripersonal space: The case of walking.
597   *Neuropsychologia* **70**, 375–384 (2015).

598   52. Pfeiffer, C., Noel, J., Serino, A. & Blanke, O. Vestibular modulation of peripersonal space
599   boundaries. *Eur J Neurosci* **47**, 800–811 (2018).

600   53. Zanini, A. *et al.* Peripersonal and reaching space differ: Evidence from their spatial extent
601   and multisensory facilitation pattern. *Psychon Bull Rev* **28**, 1894–1905 (2021).

602   54. Lacquaniti & Caminiti. Visuo-motor transformations for arm reaching. *European Journal of*
603   *Neuroscience* **10**, 195–203 (1998).

604   55. McIntyre, J., Stratta, F. & Lacquaniti, F. Short-Term Memory for Reaching to Visual Targets:
605   Psychophysical Evidence for Body-Centered Reference Frames. *J. Neurosci.* **18**, 8423–
606   8435 (1998).

607   56. Alsmith, A. J. T. & Longo, M. R. Where exactly am I? Self-location judgements distribute
608   between head and torso. *Consciousness and Cognition* **24**, 70–74 (2014).

609   57. Bertossa, F., Besa, M., Ferrari, R. & Ferri, F. Point Zero: A Phenomenological Inquiry into
610   the Seat of Consciousness. *Percept Mot Skills* **107**, 323–335 (2008).

611   58. Hediger, H. *Studies of the psychology and behavior of captive animals in zoos and circuses.*
612   (Books, Criterion Inc., 1955).

613   59. Cartaud, A., Lenglin, V. & Coello, Y. Contrast effect of emotional context on interpersonal

614   distance with neutral social stimuli. *Cognition* **218**, 104913 (2022).

615   60. Iachini, T., Coello, Y., Frassinetti, F. & Ruggiero, G. Body Space in Social Interactions: A

616   Comparison of Reaching and Comfort Distance in Immersive Virtual Reality. *PLoS ONE* **9**,

617   e111511 (2014).

618   61. Iachini, T., Ruggiero, G., Ruotolo, F., Schiano di Cola, A. & Senese, V. P. The influence of

619   anxiety and personality factors on comfort and reachability space: a correlational study.

620   *Cogn Process* **16**, 255–258 (2015).

621   62. Quesque, F. *et al.* Keeping you at arm's length: modifying peripersonal space influences

622   interpersonal distance. *Psychological Research* **81**, 709–720 (2017).

623   63. Hall, E. T. *The Hidden Dimension*. (NY: Doubleday, 1966).

624   64. Perry, A., Nichiporuk, N. & Knight, R. T. Where does one stand: a biological account of

625   preferred interpersonal distance. *Social Cognitive and Affective Neuroscience* **11**, 317–326

626   (2016).

627   65. Sorokowska, A. *et al.* Preferred Interpersonal Distances: A Global Comparison. *Journal of*

628   *Cross-Cultural Psychology* **48**, 577–592 (2017).

629   66. Pellencin, E., Paladino, M. P., Herbelin, B. & Serino, A. Social perception of others shapes

630   one's own multisensory peripersonal space. *Cortex* **104**, 163–179 (2018).

631   67. Coello, Y., Quesque, F., Gigliotti, M.-F., Ott, L. & Bruyelle, J.-L. Idiosyncratic representation

632   of peripersonal space depends on the success of one's own motor actions, but also the

633   successful actions of others! *PLoS ONE* **13**, e0196874 (2018).

634   68. Gigliotti, M. F., Soares Coelho, P., Coutinho, J. & Coello, Y. Peripersonal space in social

635   context is modulated by action reward, but differently in males and females. *Psychological*

636   *Research* **85**, 181–194 (2021).

637   69. Coello, Y., Bourgeois, J. & Iachini, T. Embodied perception of reachable space: how do we

638   manage threatening objects? *Cogn Process* **13**, 131–135 (2012).

639   70. Iachini, T. *et al.* Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. *Journal of Environmental Psychology* **45**, 154–164 (2016).

641   71. Coello, Y. & Cartaud, A. The Interrelation Between Peripersonal Action Space and Interpersonal Social Space: Psychophysiological Evidence and Clinical Implications. *Front. Hum. Neurosci.* **15**, 636124 (2021).

644   72. Lloyd, D. M. The space between us: A neurophilosophical framework for the investigation of human interpersonal space. *Neuroscience & Biobehavioral Reviews* **33**, 297–304 (2009).

646   73. Bradley, M. M. & Lang, P. J. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry* **25**, 49–59 (1994).

649   74. Wobbrock, J. O., Findlater, L., Gergle, D. & Higgins, J. J. The aligned rank transform for nonparametric factorial analyses using only anova procedures. in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* 143–146 (ACM, 2011).

652   75. Elkin, L. A., Kay, M., Higgins, J. J. & Wobbrock, J. O. An Aligned Rank Transform Procedure for Multifactor Contrast Tests. in *The 34th Annual ACM Symposium on User Interface Software and Technology* 754–768 (ACM, 2021).

655   76. Dienes, Z. Using Bayes to get the most out of non-significant results. *Front. Psychol.* **5**, (2014).

657   77. Jeffreys, H. *The theory of probability*. (1988).

658   78. Fischer, M. H. Estimating reachability: Whole body engagement or postural stability? *Human Movement Science* **19**, 297–318 (2000).

660   79. Xiong, W., Yu, X. & Lee, Y.-C. The Difference in Measuring Reachability Distance between Using Virtual Reality Technology and Manual Measurement. in *2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA)* 390–393 (IEEE, 2020).

663   80. Cartaud, A., Ruggiero, G., Ott, L., Iachini, T. & Coello, Y. Physiological Response to Facial Expressions in Peripersonal Space Determines Interpersonal Distance in a Social Interaction Context. *Front. Psychol.* **9**, 657 (2018).

666   81. Kennedy, D. P., Gläscher, J., Tyszka, J. M. & Adolphs, R. Personal space regulation by the

667   human amygdala. *Nat Neurosci* **12**, 1226–1227 (2009).

668   82. Holt, D. J. *et al.* Neural Correlates of Personal Space Intrusion. *Journal of Neuroscience* **34**,

669   4123–4134 (2014).

670   83. Vieira, J. B., Pierzchajlo, S. R. & Mitchell, D. G. V. Neural correlates of social and non-social

671   personal space intrusions: Role of defensive and peripersonal space systems in

672   interpersonal distance regulation. *Social Neuroscience* **15**, 36–51 (2020).

673   84. Evans, G. W. & Wener, R. E. Crowding and personal space invasion on the train: Please

674   don't make me sit in the middle. *Journal of Environmental Psychology* **27**, 90–94 (2007).

675   85. Serino, S. *et al.* Sharpening of peripersonal space during the COVID-19 pandemic. *Current*

676   *Biology* **31**, R889–R890 (2021).

677   86. Buck, L. E., Park, S. & Bodenheimer, B. Determining Peripersonal Space Boundaries and

678   Their Plasticity in Relation to Object and Agent Characteristics in an Immersive Virtual

679   Environment. in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* 332–

680   342 (IEEE, 2020).

681   87. Beccherle, M., Facchetti, S., Villani, F., Zanini, M. & Scandola, M. Peripersonal Space from

682   a multisensory perspective: the distinct effect of the visual and tactile components of

683   Visuo-Tactile stimuli. *Exp Brain Res* **240**, 1205–1217 (2022).

684   88. Bassolino, M., Finisguerra, A., Canzoneri, E., Serino, A. & Pozzo, T. Dissociating effect of

685   upper limb non-use and overuse on space and body representations. *Neuropsychologia*

686   **70**, 385–392 (2015).

687   89. Grivaz, P., Blanke, O. & Serino, A. Common and distinct brain regions processing

688   multisensory bodily signals for peripersonal space and body ownership. *NeuroImage* **147**,

689   602–618 (2017).

690   90. de Gelder, B. & Vroomen, J. The perception of emotions by ear and by eye. *Cognition &*

691   *Emotion* **14**, 289–311 (2000).

692   # 6. Acknowledgement

696   7. Author Contributions

697   All authors contributed to the design of the study and the writing of the manuscript.

698   L.G., in addition, collected and analysed the data.

699   8. Data Availability Statement

700   All data analysed in this study have been made publicly available on Open Science

701   Framework (OSF) via the following link:

702   https://osf.io/xp9r8/?view_only=ed8daecc5dfa43b8b1a024abdb37bb2f.

703   9. Conflict of Interest

704   The authors declare that the research was conducted in the absence of any commercial

705   or financial relationships that could be construed as a potential conflict of interest.

706   10. Figure Captions

707   **Figure 1.** The virtual environment and stimuli used in the four tasks: a neutral human adult male, an

708   anthropomorphic robot and a cylindrical lamp appearing at 300 cm in front of the participant in an

709   undecorated and unequipped room.

710   **Figure 2.** (A) The extent of the different spaces (MIS, IPS, RS, PS) expressed in centimetres as a function

711   of the stimulus (human, robot, lamp). The bars represent the average extent (error bars represent the

712   SE), while the dots represent the individual performances. (B) Schematic representation of the

713   organisation of the different spaces.

714   **Figure 3.** Correlation matrix plot showing the relation between RS, IPS, PS and MIS when facing the

715   virtual lamp. The *r* refers to the Spearman coefficient when the correlation includes MIS and to the

716   Pearson coefficient when it does not. **p-values < .001, * p-values < .05.

717   **Figure 4.** Correlation matrix plot showing the relation between RS, IPS, PS and MIS when facing the

718   virtual robot. The *r* refers to the Spearman coefficient when the correlation includes MIS and to the

719   Pearson coefficient when it does not. **p-values < .001, * p-values < .05.

720   **Figure 5.** Correlation matrix plot showing the relation between the RS, IPS, PS and MIS when facing the

721   virtual human. The *r* refers to the Spearman coefficient when the correlation includes MIS and to the

722   Pearson coefficient when it does not. **p-values < .001, * p-values < .05.