



**HAL**  
open science

## Embodiment improves attention allotment for the benefit of dual task performance

Yukiko Iwasaki, Benjamin Navarro, Hiroyasu Iwata, Gowrishankar Ganesh

► **To cite this version:**

Yukiko Iwasaki, Benjamin Navarro, Hiroyasu Iwata, Gowrishankar Ganesh. Embodiment improves attention allotment for the benefit of dual task performance. 2021. hal-03341908

**HAL Id: hal-03341908**

**<https://hal.science/hal-03341908>**

Preprint submitted on 13 Sep 2021

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

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

# 1 Embodiment improves attention allotment for the benefit of dual 2 task performance

3  
4 Y. Iwasaki<sup>1\*</sup>, B. Navarro<sup>2</sup>, H. Iwata<sup>1</sup>, G. Ganesh<sup>2\*</sup>

5  
6 <sup>1</sup> Graduate School of Creative Science and Engineering, Waseda University, Shinjuku, Tokyo, 1628480, Japan.

7 <sup>2</sup> CNRS-UM Laboratoire d'Informatique, de Robotique et de Microelectronique de Montpellier (LIRMM),  
8 Montpellier, 34095, France.

9 \*corresponding authors

10 Correspondence: [kamiwaza@ruri.waseda.jp](mailto:kamiwaza@ruri.waseda.jp), [ganesh.gowrishankar@lirmm.fr](mailto:ganesh.gowrishankar@lirmm.fr)

## 11 12 13 Abstract

14 Many everyday tasks, like walking down a street, requires us to dual task to also avoid collisions  
15 of our swinging arms with other pedestrians. The collision avoidance is possible with ease because  
16 humans have an ‘awareness’ of their (embodied) limbs. But how does embodiment and awareness  
17 affect attention distribution, and consequently task performance? Here we examined this  
18 question with a dual task that required participants to perform a cued button-press (main task)  
19 with their right hand, while reacting to possible collisions by a moving object with a left ‘robot’  
20 hand (secondary task). We observed that participants consistently improve main task  
21 performance when they perceived the robot hand to be embodied, compared to when they don’t.  
22 Furthermore, the performance improvement correlated with the embodiment perceived by the  
23 participants. The secondary task performance could be maintained in both cases, suggesting that  
24 embodiment of a limb improves attention allotment for dual task performance with it.  
25

## 26 Introduction

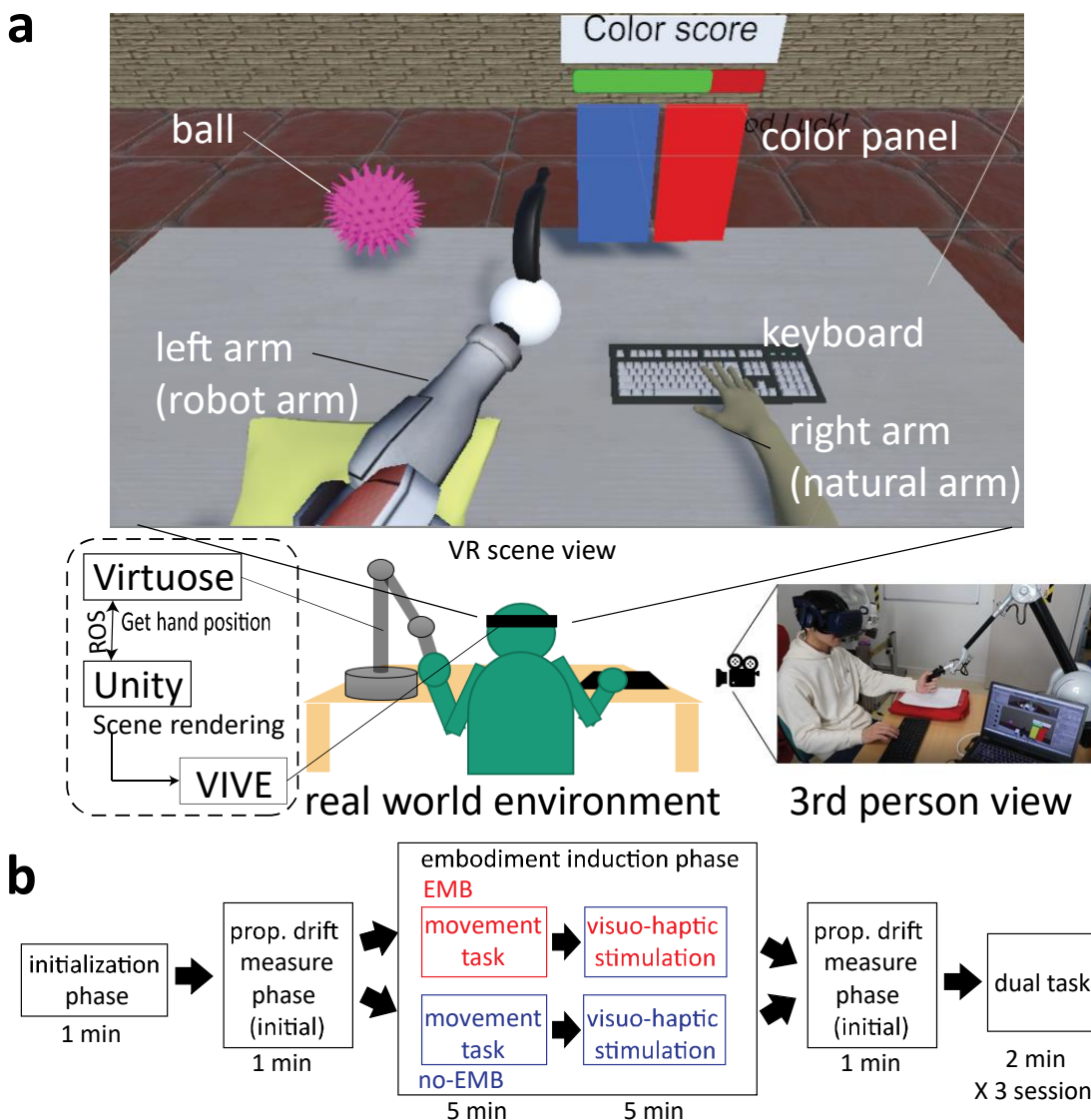
27 We live in a world surrounded by a plethora of inanimate objects, tables, bed and chairs inside a house  
28 and trees and buildings outside, as well as animate entities like cars and other humans. Hence, most  
29 tasks that involve movement, from walking on the street to moving objects, require us to *dual-task*  
30 (Strobach, Wendt, and Janczyk, 2018) to also avoid collisions between these entities and our limbs, and  
31 the objects we carry. For example, imagine you are walking down a supermarket aisle. Even though the  
32 focus of your attention may be on reading the names of the grocery items, you can still also, very  
33 implicitly, avoid colliding with the other shoppers and their shopping cart, with your swinging arm.  
34 Next imagine the same scenario when you are holding a shopping basket in the hand. In both cases, the  
35 grocery search (the main task) and the collision avoidance constitute a dual task that is possible because  
36 the human brain is believed to be ‘aware’ of its body parts and distributes visual attention between the  
37 two tasks.

38 Humans perceive a sense of ‘bodily self-consciousness’ (Bermúdez, Eilan, and Marcel, 1998; Legrand,  
39 2006) or ‘embodiment’ (Arzy, Overney, Landis and Blanke, 2006; Longo, Schüür, Kammers, Tsakiris,  
40 and Haggard, 2008) towards their limbs. Embodiment of a limb is believed to include a sense of  
41 ‘ownership’, a sense of an ability to control, or ‘agency’, and a sense of ‘location’ of the limb (Longo,  
42 Schüür, Kammers, Tsakiris, and Haggard, 2008). Ownership of a limb is known to improve its visual  
43 awareness (Hoort, Reingardt, and Ehrsson, 2017), suggesting that we will be more aware of obstacles  
44 to our swinging arm, than to the swinging basket in our arms, which we do not feel a sense of  
45 embodiment towards. But what does high embodiment and high awareness mean in regard to attention?  
46 does the arm, which is embodied, attract more attention than the basket, or does high awareness mean  
47 that we in fact require less attention for avoiding arm collisions? Consequently, how does the attention  
48 to the arm affect the attention assigned to the main task? Answers to these issues remains unclear.

49 In this study, to answer these issues, we developed a dual task in virtual reality (VR) motivated by the  
50 shopping cart collision example. The task required participants to perform a visually cued button press  
51 task with their right hand (their main task which required high attention) while reacting to possible  
52 collisions by a moving object that sometimes approached their left ‘robot’ hand (the secondary task).  
53 Recent studies have shown that the human self is plastic and that multi-sensory stimulations can induce

54 a sense of embodiment in humans, towards a rubber hand (Botvinick and Cohen, 1998; Ehrsson, 2012;  
 55 Graziano and Botvinick, 2002; Tsakiris, 2010; Makin, Holmes and Ehrsson, 2008) as well as  
 56 functionally similar (Aymerich-Franch and Ganesh, 2016) robot limbs (Aymerich-Franch, Petit,  
 57 Ganesh, and Kheddar, 2016; Aymerich-Franch, Petit, Ganesh, and Kheddar, 2015). Here, we used  
 58 multi-sensory stimulations to modulate the sense of embodiment perceived by the participant towards  
 59 their left robot hand and create two conditions, one in which the robot limb is perceived to be part of  
 60 the body, and another in which it is more like an object held in one's hand (similar to a shopping basket).  
 61 We then investigated how the embodiment (measured using a behavioral measure and reports in  
 62 questionnaires) affects performance of the main task performed by the right hand. We chose to use a  
 63 robotic left arm to avoid preexisting attentional biases associated to the shape of the human arm.  
 64 We hypothesized one of two possible scenarios. First, if increased embodiment of the robot arm attracts  
 65 more attention towards the robot arm, then this will be evident as a decrease in performance in the right  
 66 hand main task. On the other hand, an increase in right hand performance is expected if embodiment of  
 67 the robot arm either enables increased attention towards the main task, or improves the attention  
 68 distribution between the two arms.  
 69

70 **Result**



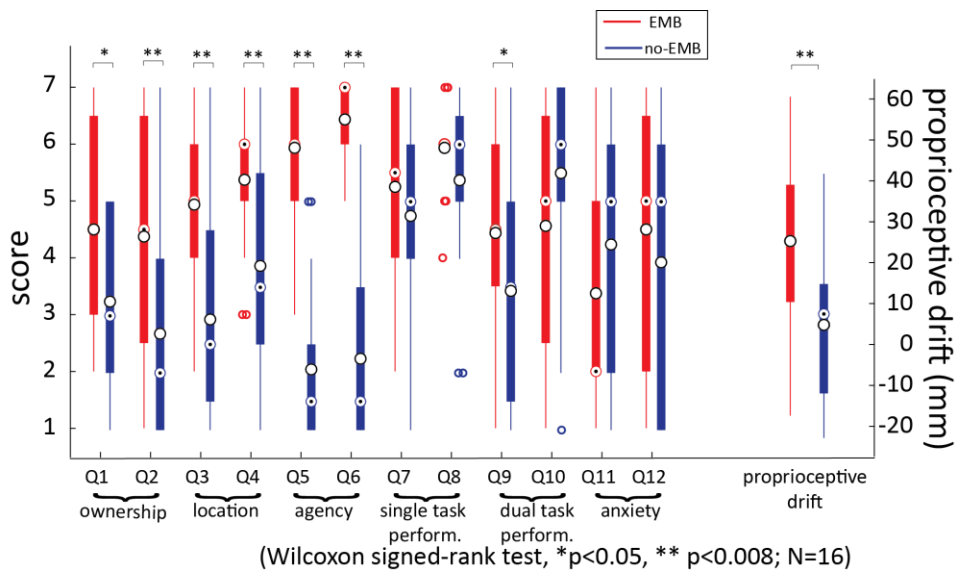
71  
 72 **Fig. 1. Setup and paradigm.** (a) The participants performed the experiment in a virtual environment. They  
 73 wore a head mounted display and sat on a table with a keyboard under their right hand. They held the  
 74 Virtuose haptic interface in their left hand. In the virtual environment, the participants observed a table,  
 75 and a right hand with the keyboard (upper panel). They saw a robot hand instead of their left hand. The

76 robot hand held a black banana shaped object that was the shape of the handle of the haptic interface the  
 77 participants held in their real left hand. The participants were also shown a pink ball which moved near  
 78 the robot hand. (b) The participants worked in two conditions, EMB and no-EMB. Each condition consisted  
 79 of five phases, and lasted 20 minutes in total.

80

81 Our experiment required participants to wear a VR headset and hold a haptic feedback device (Haption  
 82 Virtuoso 3D) in their right hand (Fig. 1(a), lower). They were shown a robot arm in place of their real  
 83 left arm (Fig. 1(a), upper). The robot arm was purposely presented displaced, by 10 cm towards the  
 84 body, from the real arm. This displacement was later utilized to quantify the embodiment (and  
 85 specifically ownership) felt by the participants towards the robot hand using a measure of proprioceptive  
 86 drift (Longo, Schüür, Kammers, Tsakiris and Haggard, 2008; Botvinick and Cohen, 1998; Holmes, Full,  
 87 Koditschek and Guckenheimer, 2006). Any movement of the hand by the human was displayed as the  
 88 movement of the robot inside the VR environment. All participants performed in two conditions (the  
 89 order was balanced across participants). In the robot embodiment (EMB) condition, after the calibration  
 90 and setup in the initialization phase, we induced the feeling of embodiment (see Fig. 1(b)) towards the  
 91 robot arm using standard visuo-haptic stimulation techniques (see methods for details). In the no-  
 92 embodiment (no-EMB) condition, the same stimulations were presented asynchronously to prevent  
 93 embodiment of the robot arm. We utilized a proprioceptive localization task before and after the  
 94 stimulation phase to evaluate the proprioceptive drift as a behavioral measure of the induced  
 95 embodiment. We evaluated the cognitive sense of ownership, agency, location, and task performance  
 96 using a questionnaire at the end of each condition.

97



98

99 **Fig. 2. Embodiment modulation across conditions.** The participants scored twelve questions on a Likert  
 100 scale after the EMB (red plot) and no-EMB (blue plot) conditions. The white circles show the mean and the  
 101 dotted circle show the median scores across participants. The box edges show the 5<sup>th</sup> and 95<sup>th</sup> percentile of  
 102 the data and the whiskers show the data range. The questions included two each on their subjective  
 103 perception of ownership, location, agency of the robot hand, their single and dual task performance, and  
 104 the anxiety during their performance respectively. We considered the average score from their first six  
 105 questions as the measure of embodiment (the embodiment score) perceived towards the robot hand. We  
 106 also measured the proprioceptive drift in each condition.

107

108 Fig. 2 shows the answers to the questionnaire, and the proprioceptive drift observed in the two  
 109 conditions. We observed that the ownership (average score in Q1 and Q2), agency (average of Q3 and  
 110 Q4) as well the sense of location (average of Q5 and Q6) towards the robot arm was consistently higher  
 111 ( $Z(15)=2.516$ ,  $p<0.012$ ,  $r_{\text{equivalent}}=0.629$ ;  $Z(15)=2.927$ ,  $p<0.003$ ,  $r_{\text{equivalent}}=0.732$  and  $Z(15)=3.463$ ,  
 112  $p<0.001$ ,  $r_{\text{equivalent}}=0.868$  respectively) in the EMB condition, in comparison to the no-EMB condition.  
 113 Overall the robot arm embodiment (average of Q1 to Q6) was higher in the EMB condition, in  
 114 comparison to the no-EMB condition ( $Z(15)=-3.337$ ,  $p<0.001$ ,  $r_{\text{equivalent}}=0.834$ ). Correspondingly, the

115 proprioceptive drift was observed to be higher in the EMB condition, compared to the no-EMB  
116 condition ( $Z(15)=-2.689$ ,  $p<0.008$ ,  $r_{\text{equivalent}}=0.672$ ).

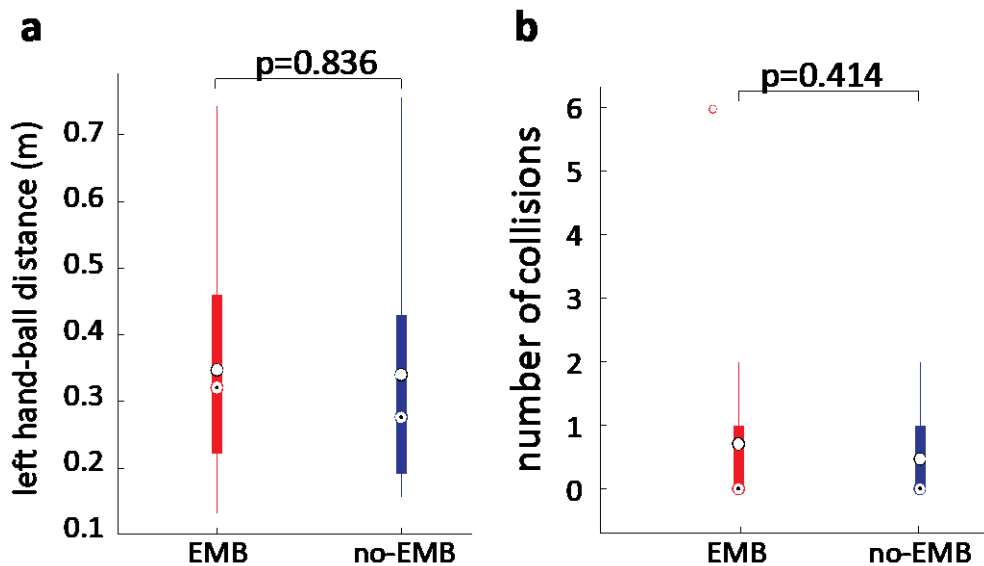
117  
118 The initialization and proprioceptive drift measurement was then followed by the same experimental  
119 dual task in each condition, which required the participants to perform a main task with their right hand  
120 and a secondary collision avoidance task with their left robot hand.

121  
122 As the main task, the participants were presented with a screen in their right visual field inside the VR,  
123 in front of their right hand that rested on a keyboard. The main task required the participants to watch  
124 two rectangular panels on the screen, that changed their colors randomly every 500 ms. The participants  
125 were instructed to “press the space key as soon as the colors of the two rectangles became the same”,  
126 which happened roughly every one to 2 seconds. The participants were informed that the reward points  
127 correlated with reaction speed of their presses, and that they will be penalized for erroneous presses (see  
128 methods for details). We analyzed the ‘reaction time’ of the participants, defined as the time between  
129 when the colour of the rectangles became same, and the key-board press by the participant. This allowed  
130 us to quantify and compare the main task performance (between the EMB and no-EMB conditions) by  
131 the reaction time and task score exhibited by the participants.

132  
133 As the secondary task, the participants were presented with a pseudo-randomly flying ball (speed range:  
134 0.25 - 0.75 m/s) in the left visual field in VR, that sometimes approached the left robot arm of the  
135 participants. The secondary task required participants to press a collision avoidance button (ca-button)  
136 with their left thumb on the handle of the haptic device held in their left hand when they perceived a  
137 danger of collision. The ca-button press resulted in the ball being deflected away from their hand. The  
138 participant were not required to actively move their left hand during the Crucially, the ball approached  
139 the hand between 5 and 8 seconds. Note that the collision avoidance only required the pressing a button  
140 with their left thumb. Thus, in both conditions, the dual task was identical and did not require any hand  
141 or arm movement by the participants.

142  
143 Therefore, apriori, the main task required much higher attention compared to the secondary collision  
144 avoidance task. Collisions resulted in penalization of points. The participants were however rewarded  
145 points if they could press the ca-button after the ball was closer than 30 cm to their hand. Any presses  
146 when the ball was beyond 30 cm earned them no points. This scenario enabled us to quantify the  
147 secondary task performance by the number of left hand collisions, and the distance of the hand and the  
148 ball, when the ca-button was pressed (See methods for more details).

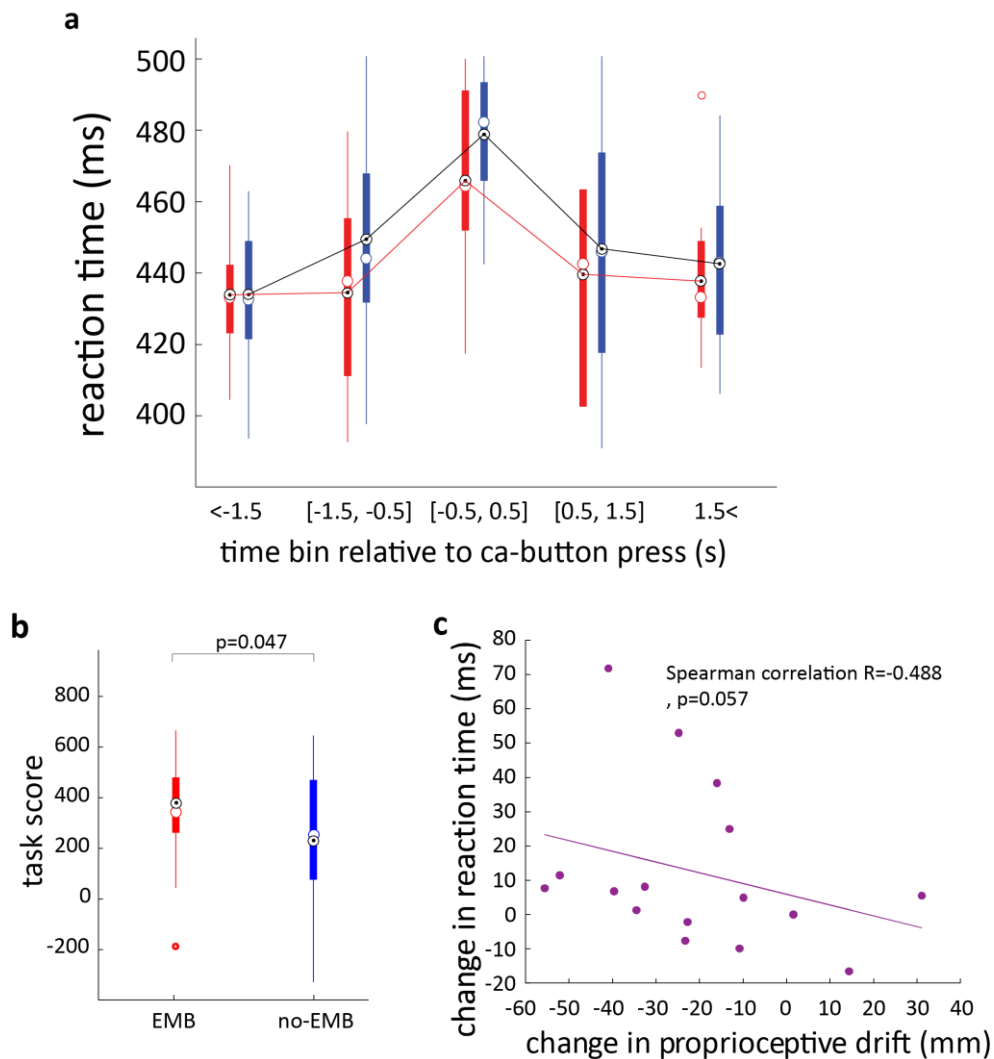
149  
150



151  
152 **Fig 3. Embodiment does not affect Secondary (collision avoidance) task performance.** There were no  
153 significant differences between either the distance of the ball from the left hand (see (a), one sample T-test),

154 or the number of collisions (see (b), one sample Wilcoxon signed rank test) between the EMB (red) and no-  
 155 EMB (blue) data. The white circles show the mean and the dotted circle show the median values across  
 156 participants. The box edges shows the 5<sup>th</sup> and 95<sup>th</sup> percentile of the data and the whiskers show the data  
 157 range.

158  
 159 Here, we are interested to evaluate the attention distribution between the participant's hands during our  
 160 task, and specifically to compare the effect of the secondary collision avoidance in the EMB and no-  
 161 EMB conditions on the performance of the main task. For this, we first started by examining the  
 162 secondary task performance in the two conditions. Fig. 3(a) shows the average distance of the ball from  
 163 the robot's spherical end-effector (hand) at which a participant presses the ca-button. Like mentioned  
 164 before, the ca-button press deflected the ball away from the hand. Thus this distance also represents the  
 165 minimum distance between the ball and the robot hand for that particular trial. The ball distances were  
 166 observed to be  $0.348 \pm 0.161\text{STD}$  cm and  $0.341 \pm 0.177\text{STD}$  cm in the EMB and no-EMB conditions  
 167 respectively (bars in Fig. 3(a)), and were similar between the two conditions ( $T(15)=0.23$ ,  $p>0.83$ , one-  
 168 sample T-test). The participants could largely avoid ball collisions, and the few collisions that occurred  
 169 were also observed to be similar in the two conditions ( $Z(15)=-0.816$ ,  $p>0.414$ , one-sample Wilcoxon  
 170 signed rank test). Overall these results show that the participants could perform the collision avoidance  
 171 equally well, both with an embodied and non-embodied robot arm.  
 172



173  
 174  
 175 **Fig. 4: Embodiment improves main (right hand) task performance.** (a) The reaction times for the right  
 176 hand button press were collected from the EMB (red data) and no-EMB (blue data) conditions into time  
 177 bins aligned to the left hand ca-button presses. A 2-way ANOVA showed a significant main effect of  
 178 conditions ( $F(1,15)=5.28$ ,  $p<0.037$ ), with highest reaction times in the  $[-0.5,0.5]$  second time bin compared

179 **to the other time-bins ( $T(31)=4.89$ ,  $p < 2 \times 10^{-5}$ , post hoc test, Bonferroni corrected). (b) The cumulative task**  
180 **scores were higher across participants in the EMB condition. (c) The change of reaction times in the [-**  
181 **0.5,0.5] second time bin between the EMB and no-EMB conditions correlated with the change in**  
182 **proprioceptive drift between the conditions (Spearman  $r=-0.488$ ,  $p=0.057$ ).**  
183

184 Next, we examined the main task performance by analyzing the average right hand reaction time. We  
185 expected the main task performance to be affected by the left collision avoidance task, but we noted  
186 that the collision avoidance task required ca-button presses only every seven seconds on average,  
187 compared to the right hand key-board press every 1 to 2 seconds. We therefore recognized that the  
188 reaction time may have varied across trials, depending on when the right hand key was pressed relative  
189 to the ca-button press. We therefore evaluate the embodiment effect on the main task using a 2-way  
190 ANOVA considering also the temporal changes in the effect. Specifically, we collected the reaction  
191 times for the right hand button presses into 5 time-bins aligned with the ca-button presses (see Fig.  
192 4(a))- those presented before 1.5 seconds of a ca-button press (marked as [ $<-1500$ ]); those presented  
193 between 1.5 and 0.5 seconds before a ca-button press ( $[-1500,-500]$ ); those presented between -0.5 and  
194 +0.5 seconds of a ca-button press ( $[-500,500]$ ); those presented between 1.5 and 0.5 seconds after a ca-  
195 button press ( $[500, 1500]$ ); and those presented after 1.5 seconds (and before 1.5 sec o the next ca-  
196 button press) of a ca-button press ( $[>1500]$ ).

197  
198 A 2-way ANOVA on the reaction times, across the factors of conditions (EMB and no-EMB) and time  
199 bins showed a significant effect condition ( $F(1,15)=5.28$ ,  $p < 0.037$ ,  $\eta^2=0.02$ ) as well as time-bins ( $F$   
200 ( $4,60$ )= $15.59$ ,  $p < 10^{-8}$ ,  $\eta^2=0.23$ ), with no interaction ( $F(4,60)=0.75$ ,  $p=0.56$ ,  $\eta^2=0.012$ ).

201  
202 Crucially, the clear effect of condition seen from the ANOVA showed that the participants could react  
203 faster with their right hand when they perceived their left robot hand to be embodied (the EMB  
204 condition) compared to when they did not (no-EMB condition). It is interesting to note that this  
205 improvement emerged after just 10 minutes of embodiment induction. Correspondingly, the  
206 performance scores were higher in the EMB condition, compared to the no-EMB condition ( $T(15)=2.16$ ,  
207  $p=0.047$ , one-sample Ttest, Cohen's  $d=0.540$ , Fig. 4(b)).

208  
209 These results show that the embodiment of the robot arm enabled the participants to improve their main  
210 task performance. Across the participants, we also observed a good correlation between the change in  
211 proprioceptive drift, and the change in main task performance (Fig. 4(c), Spearman  $r=-0.488$ ,  $p=0.057$ )  
212 in the  $[-500, 500]$  ms time bin, in which post hoc analysis showed that the reaction times, and hence the  
213 attention load, was highest through the two conditions ( $T(31)=4.89$ ,  $p < 2 \times 10^{-3}$ , Bonferroni corrected,  
214 Cohen's  $d=1.09$ ).

## 216 Discussion

217 In this study we investigated how the sense of embodiment affects the attention assigned to limbs during  
218 a dual task, and consequently how this affects the task performance. We developed an experimental  
219 dual task (Fig. 1) motivated by collision avoidance instances that we experience regularly in daily life.  
220 Our task required participants to perform a task requiring heavy attention, with their right hand, while  
221 avoiding collisions of their left robot hand. We modulated the embodiment perceived towards the robot  
222 hand (Fig. 2), and investigated how this affected the task performance with each hand. We observed  
223 that the embodiment of the left robot hand did not affect the secondary task performance by the left  
224 hand (Fig. 3), but enabled the participants to significantly improve their main task performance with  
225 the right hand (Fig. 4 (a), (b)). Importantly, this improvement could be observed throughout the task  
226 period (Fig. 4(a)). Furthermore, the right hand performance improvement correlated with the change of  
227 embodiment across the participants (Fig. 4(c)). These results have several implications.

228  
229 Primarily, these results suggest that embodiment of the robot hand modifies the attention allotment to  
230 the two hands. We observed that, while the right reaction times exhibited a general increase in the no-  
231 EMB condition (Fig. 4(a)), the reaction time profile did not change between the conditions (see  
232 ANOVA result that shows a main effect of condition but no interaction). This indicates the attention re-

233 allotment did not vary with time, but further studies are required to confirm this issue. However,  
234 crucially, the consistent lower reaction times in the main task indicates that a non-embodied robot arm  
235 (which is more like an object held in one's hand) attracts more attention for the collision avoidance task.  
236 Conversely, higher attention allotment was possible to the right hand when the robot left hand was  
237 embodied. Interestingly, this was possible even when the left hand collision avoidance performance  
238 was maintained, suggesting that our brain is able to better optimize the attention allotment in a dual task  
239 when the involved limbs are perceived to be part of one's body (that is, they are embodied).

240  
241 Moreover, our results highlight attention modulation as a key effect of embodiment. Previous studies  
242 have shown that embodiment of a limb leads to increased physiological responses to perceived dangers  
243 to the limb (Graziano and Botvinick, 2002; Tsakiris, 2010; Guterstam and Ehrsson, 2012; Suzuki, Galli.,  
244 Ikeda, Itakura and Kitazaki, 2015) and increased sensitivity to sensory stimulations (Aymerich-Franch,  
245 Petit, Kheddar, and Ganesh, 2016; Aymerich-Franch, Petit, Ganesh and Kheddar, 2017; Makin, Holmes,  
246 Ehrsson, 2008), compared to when the same limb is not embodied. Embodiment has also been suggested  
247 to improve the control of limbs (Newport, Pearce and Preston, 2009). Tool embodiment, which also  
248 leads to changes in body representation (Cardinali et al., 2009; Sposito, Bolognini, Vallar and Maravita,  
249 2012; Ganesh, Yoshioka, Osu and Ikegami, 2014), though not ownership, has also been suggested to  
250 be a key reason enabling human tool use (Head and Holmes, 1912; Maravita and Iriki, 2004; Jacobs,  
251 Bussel, Combeaud and Roby-Brami, 2009). Mechanisms of attention allotment, due to the embodiment,  
252 may provide a unified explanation for all these previous results.

253  
254 Finally, in regard to real life scenarios, our results suggest that task performance is indeed improved  
255 when the secondary collision avoidance is performed for one's own hand, rather than a hand held object  
256 (like a shopping basket). A hand held object seems to attract more attention for task performance than  
257 one's own hand. Participants also perceived better dual-task performance in the EMB compared to the  
258 no-EMB condition (see Q9 in Fig. 2). Their left hand distance correlated with this report (Spearman  $r=-$   
259  $0.40$ ,  $p=0.022$ , Suppl. Fig. 1). Note that in our experiment the same robot hand attracted less attention  
260 when it was not embodied. This means that the higher attention to a hand held object is not because of  
261 the shape and size of the object, but rather because the object is not perceived as part of the body. This  
262 result is crucial for application of human functional augmentation (Iwasaki and Iwata, 2018; Iwasaki,  
263 Ando and Iwata, 2019; Sasaki, Saraiji, Fernando, Minamizawa and Inami, 2017; Suzuki, Ganesh and  
264 Miyawaki, 2018) as well as teleoperation (Panzirsch, Balachandran, Weber, Ferre, and Artigas, 2018),  
265 and suggests that the embodiment of these robots can enable better multi-task control and performance  
266 by the human user.

267

## 268 Acknowledgement

269 This work was supported by JST ERATO Grant Number JPMJER1701. The authors thank Guillaume  
270 Gourmelen and Adrien Verhulst for their help with the VR and robot setup

271

## 272 Author contribution

273 Conceptualization, Y. I. and G. G.; Methodology, Y. I. and G. G.; Investigation, Y. I. and G. G.; Writing  
274 – Original Draft, Y. I. and G. G.; Writing – Review & Editing, Y. I., B.N., H. I., and G. G.; Funding  
275 Acquisition, H. I, G. G.; Resources, B. N. and G. G.; Supervision, H. I., and G. G.

276

## 277 Declaration of interest

278 Authors declare no financial interests pertaining to this study.

279

## 280 Data availability

281 The datasets generated during and/or analyzed during the current study are available from the  
282 corresponding author on reasonable request.

283



284 **Code availability**

285 This paper does not utilize any custom code or custom mathematical algorithm.

286

287 **References**

288

289 1. Strobach, T., Wendt, M. & Janczyk, M. (2018). Editorial: Multitasking: Executive Functioning in  
290 Dual-Task and Task Switching Situations. *Frontiers in Psychology*.

291 2. Aymerich-Franch, L. & Ganesh, G. (2016). The role of functionality in the body model for self-  
292 attribution. *Neuroscience Research* **104**, 31-37.

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

296 4. Aymerich-Franch, L., Petit, D., Ganesh, G. & Kheddar, A. (2015). Embodiment of a humanoid  
297 robot avatar is preserved during partial and delayed control. 2015 IEEE International Workshop on  
298 Advanced Robotics and its Social Impacts (ARSO), 1-5.

299 5. Aymerich-Franch, L., Petit, D., Kheddar, A. & Ganesh, G. (2016). Forward modelling the rubber  
300 hand: illusion of ownership reorganizes the motor-sensory predictions by the brain. *Royal Society*  
301 *Open Science* **3**, <https://doi.org/10.1098/rsos.160407>

302 6. Aymerich-Franch, L., Petit, D., Ganesh G. & Kheddar, A. (2017). Touch by an embodied humanoid  
303 robot induces haptic sensation from vision alone. *Journal of Computer mediated Communication*,  
304 **22**, 215-230.

305 7. Head, H. & Holmes, G. (1912). Sensory disturbances from cerebral lesions. *Brain* **34**, 102-254.

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

307 9. Jacobs, S., Bussel, B., Combeaud, M. & Roby-Brami, A. (2009). The use of a tool requires its  
308 incorporation into the movement: evidence from stick-pointing in apraxia. *Cortex* **45**, 444-455.

309 10. Cardinali, L. et al. (2009). Tool-use induces morphological updating of the body schema. *Curr. Biol.*  
310 **19**, 1157.

311 11. Sposito, A., Bolognini, N., Vallar, G. & Maravita, A. (2012). Extension of perceived arm length  
312 following tool-use: clues to plasticity of body metrics. *Neurophysiologia* **50**, 2187-2194.

313 12. Ganesh, G., Yoshioka, T., Osu, R. & Ikegami, T. (2014). Immediate tool incorporation processes  
314 determine human motor planning with tools. *Nature Communications*.

315 13. Newport, R., Pearce, R. & Preston, C. (2009). Fake hands in action: Embodiment and control of  
316 supernumerary limbs. *Experimental brain research*, **204**, 385-95.

317 14. Iwasaki, Y. & Iwata, H. (2018). A face vector - the point instruction-type interface for manipulation  
318 of an extended body in dual-task situations. 2018 IEEE International Conference on Cyborg and  
319 Bionic Systems, 662-666.

320 15. Iwasaki, Y., Ando, K. & Iwata, H. (2019). Haptic Feedback System of the Additional Hand Position  
321 for Multiple Task Situations using a Wearable Robot Arm. 2019 IEEE International Conference on  
322 Cyborg and Bionic Systems.

323 16. Sasaki, T., Saraiji, M.Y., Fernando, C.L., Minamizawa, K. & Inami, M. (2017). MetaLimbs:  
324 multiple arms interaction metamorphism. *ACM SIGGRAPH 2017 Emerging Technologies*  
325 (*SIGGRAPH '17*), **16**, 1-2.

326 17. Suzuki, Y., Ganesh, G. & Miyawaki, Y. (2018). Investigation of the change in body representation  
327 due to a sixth finger. 17th Winter workshop on the mechanisms of brain and mind.

328 18. Panzirsch, M., Balachandran, R., Weber, B., Ferre, M., and Artigas, J. Haptic Augmentation for  
329 Teleoperation through Virtual Grasping Points. *IEEE Trans. Haptics*, **11(3)**, 400-416 (2018).

330 19. Fuchs, X., Riemer, M., Diers, M. et al. (2016). Perceptual drifts of real and artificial limbs in the  
331 rubber hand illusion. *Sci Rep* **6**, 24362.

332 20. Benz, H.L., Sieff, T.R., Alborz, M., Kontson, K., Kilpatrick, E., Civillico, E.F. (2016). System to  
333 induce and measure embodiment of an artificial hand with programmable convergent visual and  
334 tactile stimuli. *Conf Proc IEEE Eng. Med. Biol. Soc.* 2016, 4727-4730.

335 21. Aymerich-Franch, L., Petit, D., Ganesh, G., and Kheddar, A. (2017). Non-human Looking Robot  
336 Arms Induce Illusion of Embodiment. *International Journal of Social Robotics*, Springer, *9(4)*, 479-  
337 490

338 22. Longo, M.R., Schüür, F., Kammers, M.P., Tsakiris, M., and Haggard, P. (2008). What is  
339 embodiment? A psychometric approach. *Cognition*, *107(3)*, 978-998.

- 340 23. Bermúdez, J.L., Eilan, N., and Marcel, A. (1998). *The Body and the Self*. MIT Press.  
341 24. Legrand, D. (2006). The Bodily Self: The Sensori-Motor Roots of Pre-Reflective Self-  
342 Consciousness. *Phenom. Cogn. Sci.*, 5, 89-118.  
343 25. Arzy, S., Overney, L.S., Landis, T., Blanke, O. (2006). Neural Mechanisms of Embodiment:  
344 Asomatognosia Due to Premotor Cortex Damage. *Arch Neurol*, 63(7), 1022-1025.  
345 26. Hoort, B., Reingardt, M., and Ehrsson, H.H. (2017). Body ownership promotes visual awareness.  
346 *eLife Science*, 6, e26022.  
347 27. Botvinick, M., and Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, 391-756.  
348 28. Ehrsson H. H. (2012). The concept of body ownership and its relation to multisensory integration.  
349 *The New Handbook of Multisensory Processes*, MIT Press, 775-792.  
350 29. Graziano, M.S.A., Botvinick, M.M. (2002). How the brain represents the body: insights from  
351 neurophysiology and psychology. *Common mechanisms in perception and action: attention and*  
352 *performance XIX*. Oxford: Oxford University Press, 136-157.  
353 30. Tsakiris, M. (2010). My body in the brain: a neurocognitive model of body ownership.  
354 *Neuropsychologia*, 48(3), 703-12.  
355 31. Makin, T.R., Holmes, N.P., Ehrsson, H.H. (2008). On the other hand: dummy hands and  
356 peripersonal space. *Behav. Brain. Res.*, 191(1), 1-10.  
357 32. Holmes, P., Full, R. J., Koditschek, D. E. and Guckenheimer, J. (2006). The dynamics of legged  
358 locomotion: models, analyses and challenges. *SIAM Rev.* 48, 207-304.  
359 33. Guterstam, A., Ehrsson, H. H. (2012). Disowning one's seen real body during an out-of-body  
360 illusion. *Conscious. Cogn.* 21, 1037-1042.  
361 34. Suzuki, Y., Galli, L., Ikeda, A., Itakura, S., and Kitazaki, M. (2015). Measuring empathy for human  
362 and robot hand pain using electroencephalography. *Sci Rep.* 5, 15924.  
363 35. Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A. (2007). G\*Power 3: A flexible statistical power  
364 analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*,  
365 39, 175-191. doi:10.3758/BF03193146  
366  
367  
368

## 369 Method

### 370 371 Participants

372 17 participants took part in this study (Mean age=26.706, SD=3.477, 12 males). The study and sample size  
373 was approved by the local ethics committee at the University of Montpellier, France. All participants gave  
374 informed consent for their participation in the study. One participant, who's left hand task performance was  
375 an outlier (with ball distance beyond 3 \*SD of the mean across participants) was omitted from the study.  
376 Overall the participant number of sixteen corresponded to our power analysis in G\*Power 3 (Faul, Erdfelder,  
377 Lang, & Buchner, 2007), to provide 80% statistical power to achieve a medium effect size ( $d = 0.75$ ) on  
378 binary choices using a one-sample *t* test against a 50% chance level and an alpha of .05.  
379  
380

### 381 Setup and Apparatus

382 We constructed an experimental environment in virtual reality (VR). The VR space was constructed using  
383 the Unity engine (<https://unity.com/ja>) at a frame rate of 65 Hz. We used the VIVE VR system  
384 (<https://www.vive.com/jp/>) for the VR experience. The participants sat on a chair, in front of a table, and  
385 wore a VIVE headset during the experiment and held the handle of VIRTUOSE haptic device  
386 (<https://www.haption.com/fr/products-fr/virtuose-3d-fr.html>) in their left hand. They rested their right  
387 hand on a keyboard on the table (see Fig. 1(a)).  
388

389 Corresponding to the real environment, in the virtual environment as well, the participants could observe a  
390 table in front of them. They observed a keyboard and screen in front of their right hand. A virtual right hand  
391 was seen resting on the keyboard (again like in real life). They observed a robot arm, connected to their body,  
392 instead of their left hand (see Fig. 1(a) upper panel). The robot arm was oriented to correspond to the left  
393 hand configuration of the sitting participant. The robot end effector (hand) was however linearly displaced

394 by 10 cm from the real hand position. This was required to measure the proprioceptive drift (detailed in  
395 section below).  
396

397 When the subject moved the VIRTUOSE handle, the position information was transmitted to Unity via ROS  
398 (<https://www.ros.org/>), and used to move the robotic left arm in the VR environment such that participants  
399 felt as if they were moving their robotic left hand.  
400

## 401 Task and Procedure

402 Fig. 1(b) shows the experimental flow. All participants participated in two conditions- the embodiment  
403 (EMB) condition and no embodiment (no-EMB) conditions. Each condition was divided in six phases- the  
404 initialization phase, proprioceptive drift measure phase (initial), embodiment induction phase,  
405 proprioceptive drift measure phase (final) and the dual task phase. This was followed by the questionnaire  
406 phase they answered twelve questions on a Likert scale. The phases are detailed below.  
407

### 408 (1) Initialization phase

409 The subjects adjusted their real sitting position and posture to a position where his or her arm coincided with  
410 the position of the arms in VR. After that, the screen blacked out for 10 s. When the VR image reappeared,  
411 the robot arm was shifted 10 cm, without their knowledge, towards the participant's body.  
412

### 413 (2) Proprioceptive drift measure phase (initial):

414 Proprioceptive drift, measure the modification in the joint level representation of a body, and is a popular  
415 measure to quantify embodiment, and specifically bodily ownership (Fuchs et al, 2016). In our study the  
416 participant's real left hand was displaced by 10 cm from the robot hand they observed VR (see setup section  
417 above). Given this displacement, after the initialization phase, we checked where the participants perceived  
418 their left hand to be. For this, the first blacked out the participant's vision in the VR. The participants were  
419 asked to release the handle of haptic interface and place the left hand on the table with their palm down. A  
420 flat plate (attached to legs) was then placed as a cover over the left hand. The plate was placed as close as  
421 possible to the hand's top surface without touching the hand. The participants were then asked to hold a pen  
422 in their right hand, and point to the index finger of their left hand by placing the tip of the pen on the cover  
423 plate. This was done 5 times. Each time, after the pointing was performed, the experimenter moved the right  
424 hand of the participant to a random location before they made the pointing movement again. We recorded  
425 the average coordinates of the pointed locations and compared it with the real position of the participant's  
426 index finger along the frontal plane, do define the initial proprioceptive drift.  
427

### 428 (3) Embodiment induction phase 429

430 We utilized movement and visuo-haptic stimulation (with a paintbrush), two standard methods (Benz, Sieff,  
431 Alborz, Kontson Kilpatrick, and Civillico, 2016; Aymerich-Franch, Petit, Ganesh and Kheddar, 2017) to  
432 induce a sense of embodiment in the participants towards the left robot arm and hand. Both the induction  
433 methods were utilized for the embodiment induction in all participants.  
434

435 Movement task: A pink cylinder object appears near the participant's left hand and the participant were asked  
436 to move his or her left arm to try to touch it. In the EMB condition, the movement of the robot arm in the  
437 VR was synchronized with the participant's real hand, and moved exactly like the participant's actual arm.  
438 In the no-EMB condition, the robot arm started moving after the participants hand (delayed by 0.5-1 sec)  
439 and randomly reached an object other than the one reached by the participant. A small force feedback was  
440 provided by the haptic interface when the cylinder was touched, and the cylinder disappeared. The movement  
441 task was performed for 5 min during which the cylinders were presented at random locations at for 7-12  
442 second (chosen randomly), after which it disappeared even if the participant did not manage to touch it.  
443

444 Visuo-haptic stimulation: The participants were asked to rest their hand on the table and look at their left  
445 robot hand in VR. Their real left hand was brushed around the wrist and back of the hand by the experimenter  
446 using a paintbrush connected to a VIVE tracker. The tracker enabled us to synchronize the real brush with a  
447 brush in VR that the participants saw brushing their robot hand (or end-effector) in VR. In the EMB condition,  
448 the real and VR brushes were synchronized so that the participants felt synchronous visuo-haptic stimulation.

449 In the no-EMB condition, the VIVE tracker was detached from the real brush and the experimenter moved  
450 a VIVE tracker and the real brush independently, such that there was no synchrony between the observed  
451 movement and the felt haptic sensation. The visuo-haptic stimulation was performed for 5 min.

452  
453 The movement task was followed by the visuo-haptic stimulation for all participants with a short break of  
454 30 seconds in between.

455  
456 (4) Proprioceptive drift measure phase (final):

457 The final proprioceptive drift measure was calculated exactly like the initial measure. The difference of the  
458 final and initial proprioceptive measures provided us the proprioceptive drift induced after EMB or no-EMB  
459 for each participant.

460  
461 (5) Dual task phase

462 Next, the participants worked in the experiment dual task in this phase. The dual task required to perform a  
463 main task with their right hand, and a secondary collision avoidance task with their left hand.

464 The main task required the participants to watch two rectangular panels presented in the right visual field of  
465 the VR environment, in front of their right hand. The panels changed their colors (red, blue or yellow)  
466 randomly every 500 ms. The participants were instructed to “press the space key as soon as the colors of the  
467 two rectangles became the same”, which happened roughly every one to 2 seconds. A correct press earned  
468 the participants 20 points. On the other hand, the participants were penalized -10 points when they missed  
469 pressing a button when the panel colors were same, or pressed the keyboard when the panel colors did not  
470 match. We recorded the right hand reaction times, and the cumulative scores as measures of the main task  
471 performance by each participant. The cumulative score was calculated excluding the first 5 seconds of the  
472 experiment, in order to exclude possible errors associated with the surprise at the start for the session and  
473 task.

474  
475 The participants were presented with a pink ball (5 cm in diameter) in their left visual field. The ball flew  
476 near the left robot hand of the participants in a pseudo-random trajectory within 1m X0.8m X1.5m in the  
477 virtual environment around the left hand of the participant. The ball approached the robot hand every 5-8  
478 seconds. The ball approached the hand following one of seven manually designed trajectories in each  
479 collision. Each of the trajectory was designed by choosing 6 via points to the participant’s hand position and  
480 back. A trajectory generator provided in the UNITY software was used to develop the trajectory through  
481 these via points given the velocities at the via points (which were set between 0.25 m/s and 0.75 m/s at each  
482 point).

483  
484 As the secondary task the participants were instructed to prevent the ball from hitting their left hand. They  
485 were instructed to press the collision avoidance button (ca-button), under their left thumb on the handle of the  
486 haptic device, whenever they felt that the ball may collide with the left hand. Pressing the ca-button resulted  
487 in the ball being deflected away from their hand. Collisions resulted in a penalization of 5 points.  
488 The participants were however rewarded 1 point if they could press the ca-button after the ball was closer  
489 than 30 cm to their hand. Any presses when the ball was beyond 30 cm earned them no points. This scenario  
490 enabled us to quantify the secondary task performance by the distance of the hand and the ball, when the ca-  
491 button was pressed and the collisions incurred by the participants.

492  
493 The participants were presented with a pseudo-randomly flying ball (speed range: 0.25 - 0.75 m/s) in the left  
494 visual field in VR, that sometimes approached the left robot arm of the participants. As their secondary task,  
495 the participants were required to press a collision avoidance button (ca-button) on the handle of the haptic  
496 device held in their left hand when they perceived a danger of collision. The ca-button press resulted in the  
497 ball being deflected away from their hand. Crucially, the ball approached the hand every 5-8 seconds.  
498 Therefore, a priori, the main task thus required much higher attention compared to the secondary collision  
499 avoidance task. Collisions resulted in heavy penalization of points. The participants were however rewarded  
500 points if they could press the ca-button after the ball was closer than 30 cm to their hand. Any presses when  
501 the ball was beyond 30 cm earned them no points. This scenario enabled us to quantify the secondary task  
502 performance by the distance of the hand and the ball, when the ca-button was pressed (See methods for more  
503 details).

504

505 The dual task phase consisted of three two minute trials. The participants performed the above mentioned  
506 tasks with their two hands in every trial. The dual task was the same in both the EMB and no-EMB condition.  
507 We utilized the data from the first trial, in which we observed significant differences in the in the EMB and  
508 no-EMB behaviors, for our behavioral analysis. The behaviors in the second and third trials were observed  
509 to be same between the two conditions, probably because of the loss of the embodiment (induced in the  
510 embodiment induction phase) perceived towards the robot arm, with time.

511  
512 Finally, in the end of each condition, each participant answered the following 12 questions on a seven-point  
513 Likert scale.

514  
515 From 1 (not at all) to 7 (very strongly), it seems like...

- 516
- 517 1. The robot arm is part of your body
- 518 2. The robot arm is your arm
- 519 3. The robot arm belongs to you
- 520 4. The robot arm is in the location where your arm is
- 521 5. You could push an object with the arm you see
- 522 6. You could move the arm you see
- 523
- 524 7. You could perform the left hand task well
- 525 8. You could perform the right hand task well
- 526 9. You could perform tasks on each arm equally well
- 527 10. The task on the right hand disturbed the task on the left hand
- 528 11. You were anxious about your left hand task
- 529 12. You were anxious about your right hand task

530  
531 The first three questions estimated the ownership perceived towards the left robot hand, by a participant. The  
532 fourth question estimates the perceived location of the robot arm, while questions five and six estimated the  
533 sense of agency perceived towards the left robot hand by a participant. The average score by a participant  
534 across questions one to six was takes as a measure of embodiment perceived towards the robot arm (Longo,  
535 Schüür, Kammers, Tsakiris, and Haggard, 2008).

536  
537 Questions seven to ten estimated the participant's perception of their performance, while questions eleven  
538 and twelve measured the anxiety felt by the participants during the dual task performance.

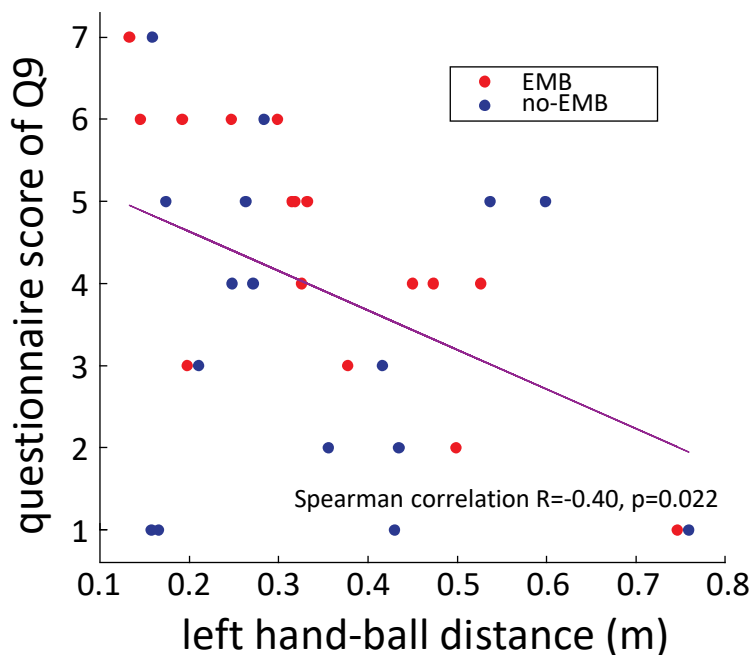
## 539 540 Data analysis

541 All data groups were first checked for normality using the Shapiro Wilk Test. Data groups which were  
542 found to be normal ( $p > 0.05$ ) were treated using parametric tests, namely T-test (Fig. 3(a), Fig. 4(b)) and  
543 ANOVA (Fig. 4(a)). Data groups that were found to be non-normal were compared using the Wilcoxon  
544 Sign Rank test (Fig. 2, Fig. 3(b)) and analyzed using the Spearman correlation (Fig. 4(c)).

545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557

558 Supplementary Figure 1.

559



560

561

562 **Sup. Fig. 1. Correlation between perceived task performance and left hand task performance.**  
563 **Participants were asked to rate the statement “You could perform tasks on each arm equally**  
564 **well“ as Q9. A correlation between their reported scores and the left hand ball distance showed**  
565 **that with an increase of perception of dual task performance, the participants pressed the ca-**  
566 **button when the ball was closer to the left hand.**

567

568