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

3
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5
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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

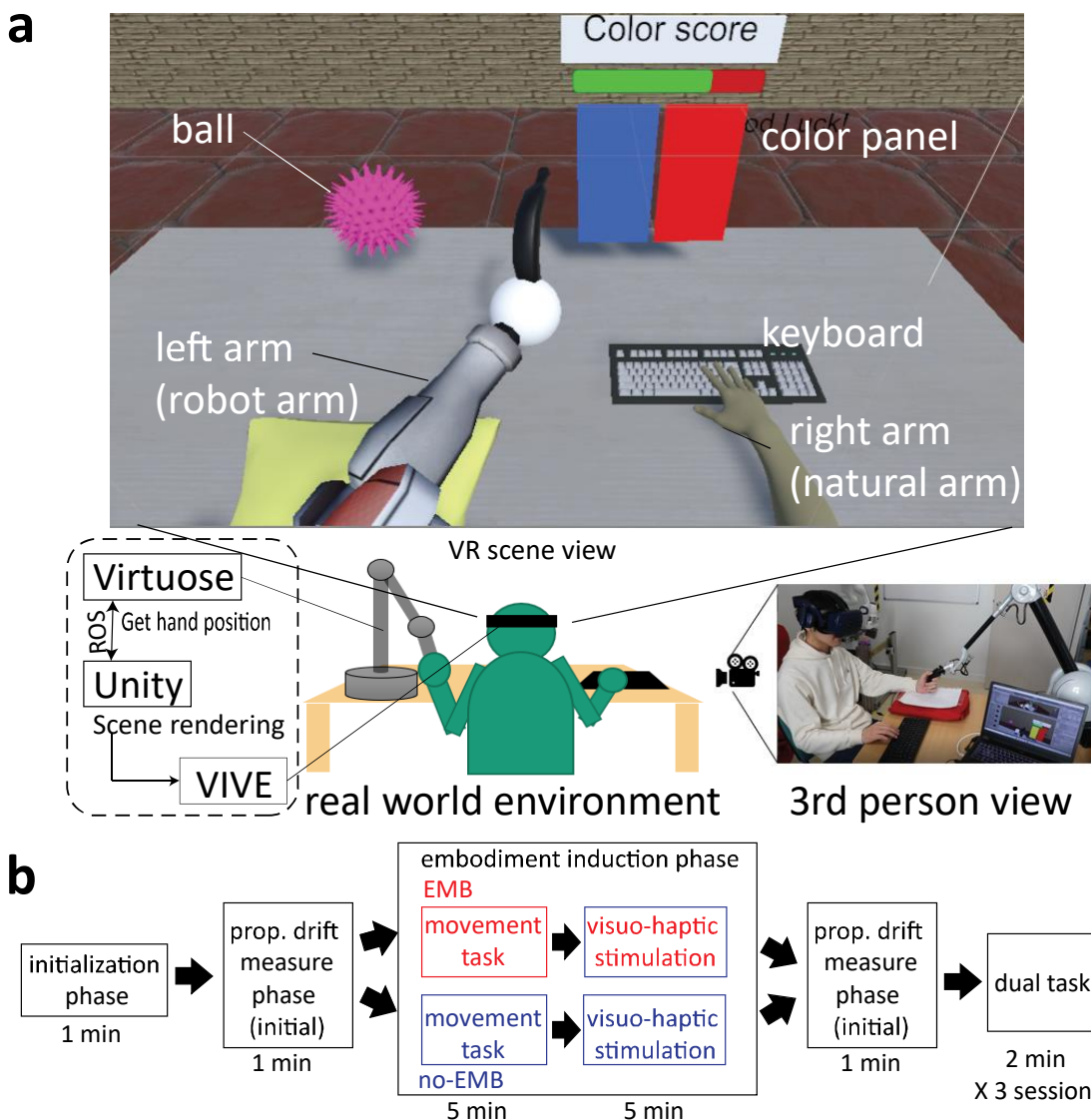
27 We live in a world surrounded by a plethora of inanimate objects, tables, bed and chairs inside a house
28 and trees and buildings outside, as well as animate entities like cars and other humans. Hence, most
29 tasks that involve movement, from walking on the street to moving objects, require us to *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**



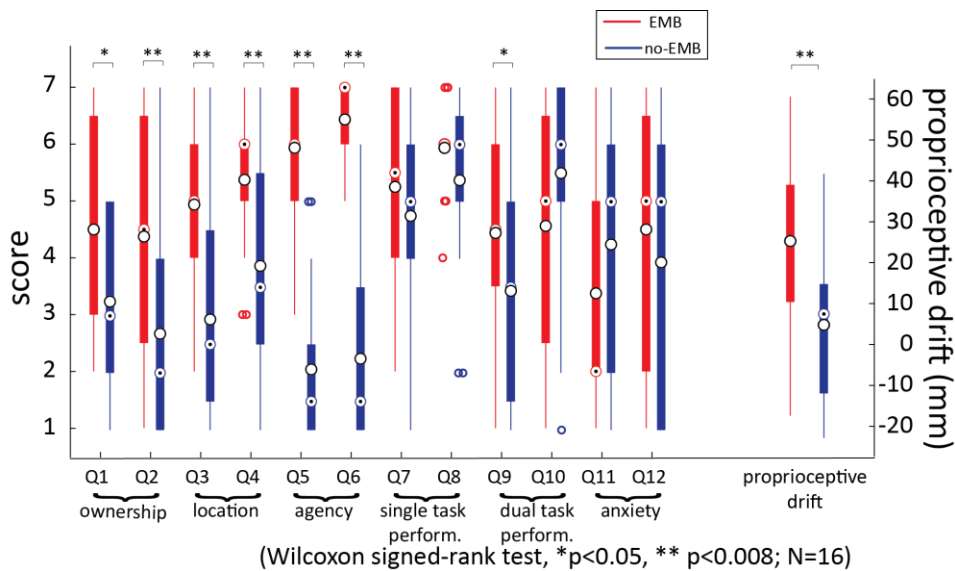
71
 72 **Fig. 1. Setup and paradigm.** (a) The participants performed the experiment in a virtual environment. They
 73 wore a head mounted display and sat on a table with a keyboard under their right hand. They held the
 74 Virtuoso haptic interface in their left hand. In the virtual environment, the 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 5th and 95th 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 ($Z(15)=-2.689$, $p<0.008$, $r_{\text{equivalent}}=0.672$).

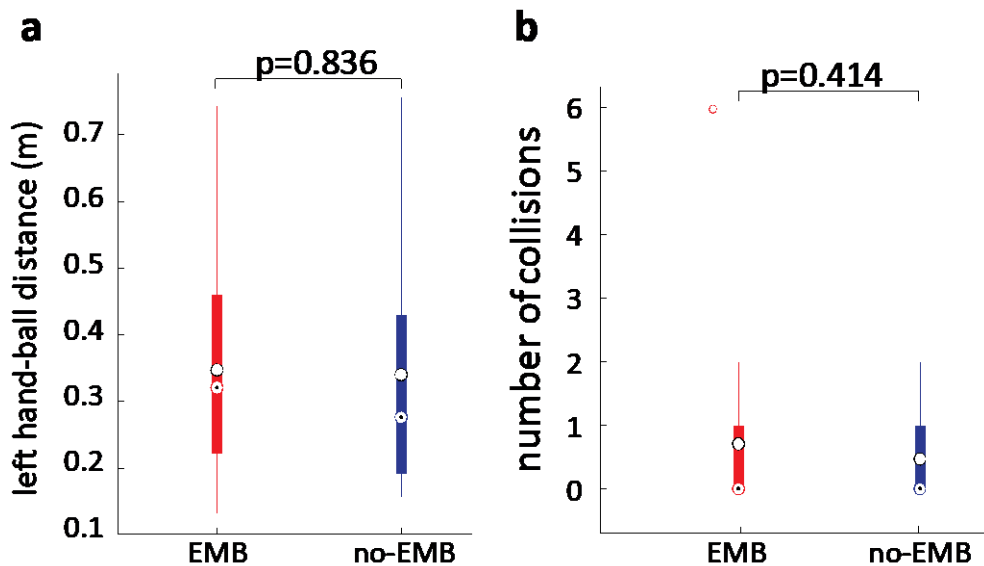
117
118 The initialization and proprioceptive drift measurement was then followed by the same experimental
119 dual task in each condition, which required the participants to perform a main task with their right hand
120 and a secondary collision avoidance task with their left robot hand.

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).

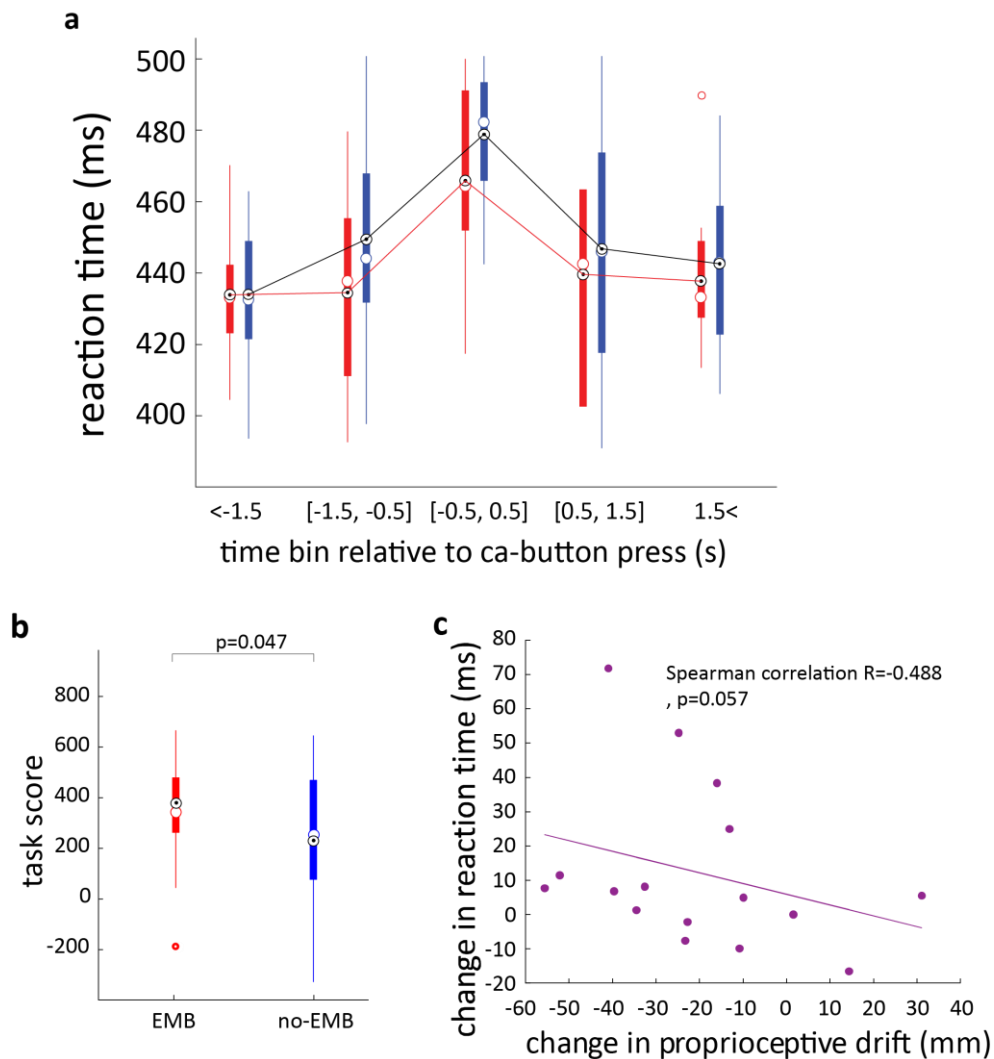
149
150



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 5th and 95th 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

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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

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288
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369 Method

370 Participants

371 17 participants took part in this study (Mean age=26.706, SD=3.477, 12 males). The study and sample size

372 was approved by the local ethics committee at the University of Montpellier, France. All participants gave

373 informed consent for their participation in the study. One participant, who's left hand task performance was

374 an outlier (with ball distance beyond 3 *SD of the mean across participants) was omitted from the study.

375 Overall the participant number of sixteen corresponded to our power analysis in G*Power 3 (Faul, Erdfelder,

376 Lang, & Buchner, 2007), to provide 80% statistical power to achieve a medium effect size ($d = 0.75$) on

377 binary choices using a one-sample t test against a 50% chance level and an alpha of .05.

378

379 Setup and Apparatus

380 We constructed an experimental environment in virtual reality (VR). The VR space was constructed using

381 the Unity engine (<https://unity.com/ja>) at a frame rate of 65 Hz. We used the VIVE VR system

382 (<https://www.vive.com/jp/>) for the VR experience. The participants sat on a chair, in front of a table, and

383 wore a VIVE headset during the experiment and held the handle of VIRTUOSE haptic device

384 (<https://www.haption.com/fr/products-fr/virtuose-3d-fr.html>) in their left hand. They rested their right

385 hand on a keyboard on the table (see Fig. 1(a)).

386 Corresponding to the real environment, in the virtual environment as well, the participants could observe a

387 table in front of them. They observed a keyboard and screen in front of their right hand. A virtual right hand

388 was seen resting on the keyboard (again like in real life). They observed a robot arm, connected to their body,

389 instead of their left hand (see Fig. 1(a) upper panel). The robot arm was oriented to correspond to the left

390 hand configuration of the sitting participant. The robot end effector (hand) was however linearly displaced

391

392

393

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, to 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.

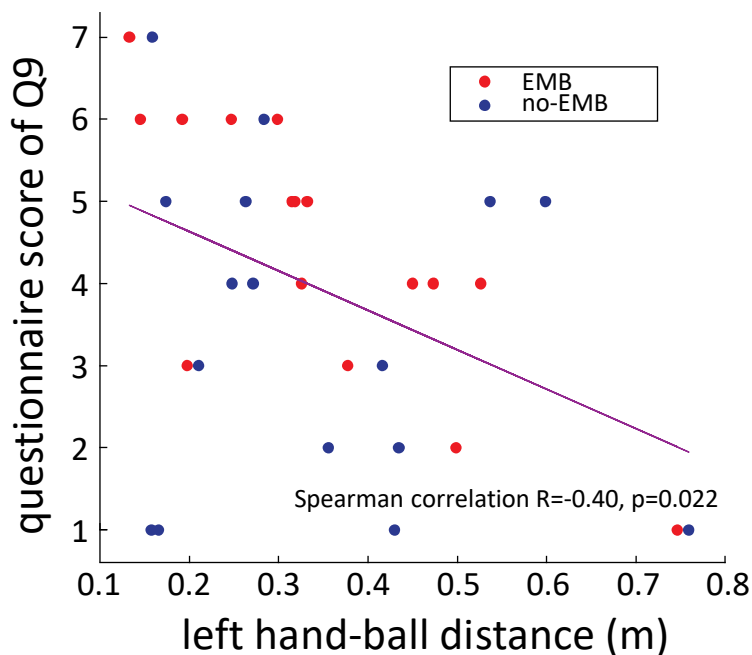
539 540 Data analysis

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)).

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558 Supplementary Figure 1.

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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