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Sensorimotor conflicts alter metacognitive and action monitoring

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1 **Abstract (123)**

2 While sensorimotor signals are known to modulate perception, little is known about their influence on
3 higher-level cognitive processes. Here, we applied sensorimotor conflicts while participants performed
4 a perceptual task followed by confidence judgments. Results showed that sensorimotor conflicts
5 altered metacognitive monitoring by decreasing metacognitive performance. In a second experiment,
6 we replicated this finding and extended our results by showing that sensorimotor conflicts also altered
7 action monitoring, as measured implicitly through intentional binding. In a third experiment, we
8 replicated the same effects on intentional binding with sensorimotor conflicts related to the hand rather
9 than to the trunk. However, effects of hand sensorimotor conflicts on metacognitive monitoring were
10 not significant. Taken together, our results suggest that metacognitive and action monitoring may
11 involve endogenous, embodied processes involving sensorimotor signals which are informative
12 regarding the state of the decider.

13 **Introduction**

14 The self is a multifaceted construct that minimally entails an organism's ability to distinguish its
15 constituents from the surrounding environment. It is defined at different levels of complexity (Rochat,
16 2003), ranging from fundamental biological mechanisms (e.g., homeostasis, immunological
17 tolerance), to bodily representations (e.g., peripersonal space), to more abstract cognitive functions
18 such as self-recognition or autobiographical memory. At the cognitive level, the sense of self includes
19 metacognitive monitoring, defined as the capacity to monitor and control one's own mental states
20 (Koriat, 2006; Fleming & Frith 2012), and to compute the likelihood of being correct given sensory
21 evidence during perceptual tasks (Pouget, Drugowitsch, & Kepecs, 2016). The cognitive self also
22 includes the capacity to monitor and control one's own actions, notably to predict the sensory
23 consequences of a motor command (Blakemore and Frith, 2003; Haggard, 2017). The present study
24 aims at assessing the possibility that cognitive functions such as metacognitive and action monitoring
25 may rely on bodily signals, and more specifically on sensorimotor processes. In support of this view,
26 action-related signals were shown to modulate metacognition: confidence relates to sub-threshold
27 motor activity (Gadjos et al., 2018) and alpha desynchronization over the sensorimotor cortex (Faivre
28 et al., 2018), and is disrupted when transcranial magnetic stimulation pulses are applied to the
29 premotor cortex before or after a visual task disrupt subsequent confidence judgements (Fleming et al.,
30 2015). Plus, metacognitive performance is better for committed vs. observed decisions, suggesting that
31 committing to a decision through a motor action informs confidence (Pereira et al., 2018). Together,
32 these studies suggest that interoceptive and action-related signals from the body may play a role for
33 metacognition (see Filevich et al., 2019 for a critical discussion of these effects).

34 Here, we sought to investigate the role of sensorimotor processes on high-level cognitive functions by
35 measuring the quality of metacognitive monitoring in healthy subjects while their bodily
36 representation was systematically manipulated through the application of sensorimotor conflicts.
37 Participants were asked to perform tapping movements with a robotic device situated in front of them,
38 while another robot connected to the front device applied corresponding tactile stimuli on their back
39 (synchronous condition). In the asynchronous condition, a constant temporal delay between the
40 movement of the participant and the tactile stimulation delivered by the back robot was introduced,
41 which has the effect of increasing prediction errors regarding the sensory consequences of a motor
42 command. Such manipulations are also known to induce alterations of bodily self-consciousness such
43 as changes in self-location (Blanke et al., 2014). Assuming that the mechanisms enabling
44 metacognitive and action monitoring relate to those enabling bodily self-consciousness, we expected
45 alterations of self-location induced by sensorimotor conflicts to induce impairments of metacognitive
46 and action monitoring. In Experiment 1, we quantified the capacity of participants to monitor their
47 performance on an auditory temporal order judgment task while actuating the robot synchronously or
48 asynchronously. Experiment 2 aimed at replicating the results found in Experiment 1 with a new

49 group of participants, and further quantified their capacity to monitor action consequences during the
50 synchronous vs. asynchronous condition. Finally, Experiment 3 aimed at determining whether effects
51 on metacognitive and action monitoring were specific to sensorimotor conflicts impacting full-body
52 representations (Blanke et al., 2014), or whether they could also be induced by similar conflicts
53 impacting limb-representations only. Together, these three experiments show that metacognitive
54 monitoring is altered by sensorimotor conflicts centered on the trunk impacting full-body
55 representations, while action monitoring is altered by sensorimotor conflicts impacting both full-body
56 and limb representations. This indicates that bodily-representations may serve as a scaffold for
57 complex cognitive functions including metacognitive and action monitoring.

58

59 **Method**

60 The experimental paradigm and analysis scripts are available together with anonymized data on the
61 open science framework (<https://osf.io/386az/>).

62

63 **Participants**

64 A total of 54 different participants were recruited: 18 in Experiment 1 (10 females, mean age 22.7
65 years, SD 4.5 years), 18 in Experiment 2 (12 females, mean age 23.7 years, SD 4.2 years) and 18 in
66 Experiment 3 (12 females, mean age 24.1 years, SD 4.2 years). Two participants had to be excluded
67 due to a technical issue during data recording (one in Experiment 1 and one in Experiment 2) as they
68 could not perform the temporal order judgment task). All participants were right-handed, had normal
69 hearing and no psychiatric or neurological history, and participated in exchange for a monetary
70 compensation (20 CHF per hour). They were naive to the purpose of the study and gave informed
71 consent, in accordance with institutional guidelines and the Declaration of Helsinki. The study was
72 approved by the cantonal ethics committee in Geneva. The sample size in Experiment 1 was
73 predefined based on a pilot study, and was kept constant in Experiment 2 and 3.

74 **Apparatus and stimuli**

75 Robotic System: we used a system composed of a commercial haptic interface (Phantom Omni,
76 SensAble Technologies), coupled with a three degree-of-freedom robot in the back (see Fig. 1 and
77 Hara et al., 2011; Blanke et al., 2014 for details). Participants were standing and controlling the front
78 robot situated directly in front of them with their right index finger (excepted in the baseline condition
79 of Experiment 1 in which it was controlled by the experimenter). The back robot was placed directly
80 behind their back and reproduced with virtually no delay the movements produced with the front robot
81 in the synchronous condition, and with 500 ms delay in the asynchronous condition. Participants were
82 asked to perform tapping movements in every direction to touch their back on a 200 mm x 250 mm

83 surface. In Experiment 3, the same setup was used except that the back robot was adjusted to point in
84 the vertical axis so to touch the participants hand instead of their back. Participants could again
85 perform any tapping movements they wanted as long as the robot touched the back of their hand.

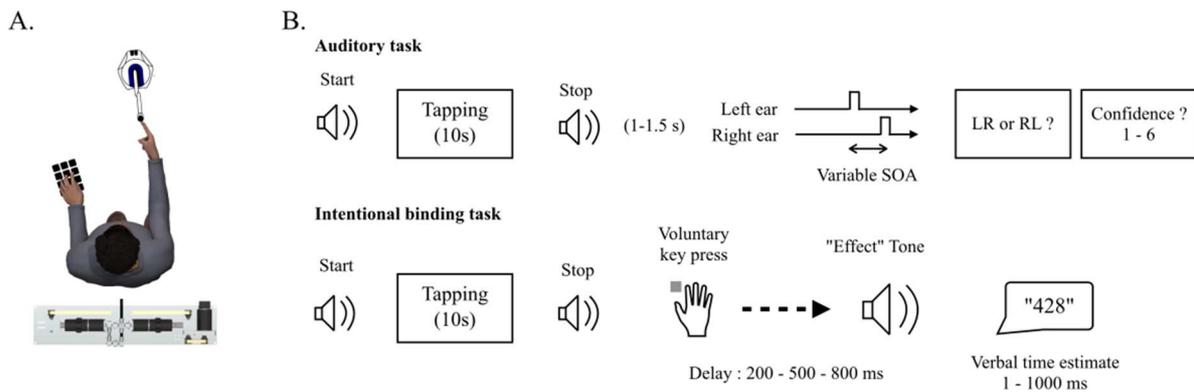
86 Auditory stimuli: all experimental sounds were sinusoidal pure tones, with 1 ms rise/fall time and
87 44100 Hz sampling rate, generated using MATLAB (MathWorks, Natick, MA) with the
88 Psychophysics toolbox (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, Pelli 2007). Auditory stimuli
89 used for the temporal order judgement task were 600 Hz pitch pairs of sounds, played for 10 ms via
90 headphones either to the left and then to the right ear (Left–Right or LR) or to the right and then to the
91 left ear (Right–Left or RL), with a variable stimulus onset asynchrony (SOA) that was adjusted
92 throughout the experiment using an adaptive one-up two-down staircase procedure (Levitt, 1971). The
93 initial SOA was set to 80 ms, and varied in 5 ms steps between 5 ms and 150 ms. Cue sounds (400 Hz
94 pitch, 100 ms duration,) served as indicators of the beginning and the end of each trial. White noise
95 was played in both ears during the whole experiment to isolate the participant from external noises.
96 The sound pressure level was adjusted before the experiment individually at a comfortable level with
97 the auditory stimuli volume always four times higher than the white noise volume.

98 **Procedure**

99 Experiment 1.

100 Prior to the experiment, participants were told about the general experimental procedure, and were
101 instructed in the use of the robot. After filling in a questionnaire for demographic data, participants
102 were equipped with headphones and blindfolded. While standing, they were asked to insert their right
103 index finger into the front device and perform tapping movements, which lead the back robot to
104 deliver tactile pokes on their back. They were allowed to move the front device in any direction along
105 the vertical and horizontal axes, which resulted in pokes applied to different parts of their back. The
106 main task was as follows: each trial started with a cue sound indicating to start the tapping movements
107 with the right index finger. After 10 s of tapping, a second cue sound was played, indicating to stop
108 moving. Following a random interval between 1000 and 1500 ms duration, participants were presented
109 with two successive sounds and were asked to indicate by means of keypress with the left hand
110 whether they perceived an LR or RL pair (temporal order judgment, Bernasconi et al., 2010). This first
111 response defined performance for the first order task, for which no feedback was provided.
112 Subsequently, as a second-order task, participants were asked to report the confidence they had in their
113 response by pressing a key with their left hand between 1 (very unsure) to 6 (very sure). A random
114 inter-trial interval between 1000 and 1500 ms was enforced. The experiment contained three main
115 conditions grouped in blocks. In the synchronous condition, the back device responded to the front
116 robot actuated by the participants with virtually no temporal delay (Hara et al., 2011). In the
117 asynchronous condition, a delay of 500 ms was set between the front and the back devices, so that

118 participants felt a poke on their back 500 ms after moving the front device. The asynchronous
 119 condition resulted in a spatiotemporal sensorimotor conflict between the right hand actuating the front
 120 robot and the back receiving tactile feedback. Such condition is known to induce global changes in
 121 bodily self-consciousness, notably in terms of self-location (Blanke et al., 2014). In the baseline
 122 condition, participants passively received tactile feedback while the front robot was actuated by the
 123 experimenter. While actuating the front robot in the synchronous and asynchronous conditions,
 124 participants received a somatosensory force feedback on their right index finger each time the back
 125 robot touched their back, so to mimic the effect of physical resistance. The experiment was divided in
 126 blocks of 30 consecutive trials of the same condition, with a total of 9 blocks (3 in succession per
 127 condition) counterbalanced across participants. A training phase of 12 trials was enforced before
 128 starting the experiment. At the end of the first block of each condition, participants were asked to fill
 129 in a questionnaire composed of 10 Likert scale items: 1) I felt as if I had no body. 2) I felt as if I was
 130 touching my body. 3) I felt as if I was touching someone else's body. 4) I felt as if I was in front of my
 131 body. 5) I felt as if I was behind my body. 6) I felt as if I had more than one body. 7) I felt as if
 132 someone else was touching my body. 8) I felt as if I was touched by a robot. 9) I felt as if someone
 133 was standing behind my body. 10) I felt as if someone was standing in front my body. The experiment
 134 lasted 120 minutes and ended with an individual debriefing. No part of the study procedures or
 135 analyses was pre-registered prior to the research being conducted.



136
 137 Figure 1: A. Experimental setup: Participants were standing and controlling the front robot situated
 138 directly in front of them with their right index finger. The back robot was placed directly behind their
 139 back and reproduced with virtually no delay the movements produced with the front robot in the
 140 synchronous condition, and with 500 ms delay in the asynchronous condition. B. Experimental
 141 procedure: After actuating the front robot and receiving synchronous or asynchronous tactile feedback
 142 for 10 s, participants were asked to perform one of two tasks. In the auditory task (upper row)
 143 participants had to indicate whether they heard a sequence of two sounds starting in the left and ending
 144 in the right ear or vice versa (i.e., temporal order judgment task). They were then asked to report how
 145 confident they were in their response. Both responses were given using the left hand. In the intentional
 146 binding task (lower row) participants were asked to press a key with the left hand, and report verbally
 147 the delay with which a subsequent effect tone was played.

148

149 Experiment 2

150 Experiment 2 was divided into two sessions. The first session followed the exact same procedure as
151 Experiment 1 (i.e., first and second-order tasks), except that it contained no baseline condition, and
152 therefore lasted 80 min instead of 120 min. The second session relied on the classical intentional
153 binding task (Haggard, Clark & Kalogeras, 2002; Wenke & Haggard, 2009), in which participants
154 were asked to press a key with their left hand whenever they felt the urge to do so. The keypress
155 triggered a target tone (600 Hz pitch, 200 ms duration) after a temporal delay of 200 ms, 500 ms or
156 800 ms. Participants were told that the target tone could occur after a random delay between 1 ms and
157 1000 ms following key press, and were asked to report verbally their best estimate for this delay. After
158 reporting their estimate, they had to press a key to start the next trial. Participants were actuating the
159 front robot with their right hand for the entire trial duration. Session 2 contained a synchronous and
160 asynchronous condition like session 1. Participants completed two blocks of 30 trials per condition,
161 corresponding to 10 repetitions for each temporal delay. The order of conditions was counterbalanced
162 across participants, and remained identical within participant for sessions 1 and 2. The order of
163 temporal delays was randomized across trials. A training phase of 12 trials was enforced before
164 starting session 2. It ended with an individual debriefing and its total duration was about 70 min. A
165 break of 30 min was allowed between session 1 and 2. At the end of session 2, participants were asked
166 to actuate the robot for 1 minute (Synchronous and Asynchronous in the same order as in session 1
167 and 2), and then filled in the same questionnaires as in Experiment 1 (see below). This was performed
168 at the very end of the experiment to avoid demand characteristics effects (Orne, 1962).

169 Experiment 3

170 Experiment 3 was identical to Experiment 2, except that participants were seated and that the stroking
171 was applied on the back of their left hand instead of on their back.

172

173 **Questionnaire**

174 Participants were asked to rate specific aspects of the subjective experience they had in the different
175 experimental conditions. The questions were based on a previous study (Blanke et al., 2014, see
176 supplementary data) and investigated in particular the subjective feeling of touching oneself (“I felt as
177 if I was touching my body”; self-touch) or of touching somebody else’s body (“I felt as if I was
178 touching someone else’s body”; other-touch). Other questions investigated the subjective sensation of
179 corporeal displacement (i.e. “I felt as if I was in front of my body”) and the feeling of a presence (i.e.
180 “I felt as if someone was standing behind my body.”). Other items served as control questions for
181 suggestibility (i.e. “I felt as if I had no body”). Ratings were reported on a Likert scale from 0 (Not at
182 all) to 6 (Very strong) and transformed into Z-scores prior to statistical analysis.

183

184 **Data analysis**

185 We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria,
186 whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all
187 measures in the study. Reaction times for temporal order judgments longer than 3 s and shorter than
188 300 ms were discarded (corresponding to 6.2 % of total trials in Experiment 1, 6.4 % in Experiment 2,
189 and 11.4 % in Experiment 3). Reaction times for confidence judgements longer than 6 s and shorter
190 than 300 ms were discarded (corresponding to 3.0 % of total trials in Experiment 1, 2.0 % in
191 Experiment 2, and 4.7 % in Experiment 3).

192 Metacognitive performance was analysed with two different approaches. First, we performed mixed
193 effects logistic regressions between accuracy and confidence, and considered the regression slope as
194 an indicator of metacognitive performance (that is, the capacity for a participant to adapt confidence to
195 performance), and the lower asymptote as a measure of confidence bias (that is, the capacity to report
196 low confidence estimates when perceptual evidence is low). This approach is agnostic regarding the
197 signals used to compute confidence estimates (i.e., decisional vs. post-decisional locus, see Yeung &
198 Summerfield, 2012; Pleskac & Bussemeyer, 2011), and the mixed model framework allows analysing
199 raw confidence ratings even if they are unbalanced (e.g., in case participants do not use all possible
200 ratings) (Rausch et al., 2015). Second, relying on signal detection theory, we quantified metacognitive
201 sensitivity with meta- d' (Maniscalco & Lau, 2012, 2014), which reflects the amount of perceptual
202 evidence available when performing confidence judgments. Contrary to the logistic regression
203 approach, signal detection theory assumes that confidence judgments are informed by perceptual
204 evidence only, with no contribution of post-decisional processes. The resulting measure of
205 metacognitive sensitivity (meta- d') shares the same dimension as perceptual sensitivity (d'), which
206 allows normalizing one by the other, and deriving an index of metacognitive performance independent
207 of task performance, called metacognitive efficiency (meta- d'/d'). Meta- d' was computed following a
208 resampling of confidence ratings: for a given participant and condition, confidence ratings used in less
209 than 10 trials were merged with the superior rating (e.g., if one participant gave a confidence rating of
210 1 in 6 trials, and of 2 in 18 trials, we merged the two categories in 24 trials with a confidence rating of
211 2). This ensured that the fit by maximum likelihood estimation involved in the computation of meta- d'
212 was performed on a sufficient number of points (Maniscalco & Lau, 2012, implemented in R by
213 Rausch et al., 2015). The tendency to report high or low confidence ratings independently of task
214 performance was quantified with confidence bias, based on the type 2 receiver operating characteristic
215 curve (ROC) which determines the rate of correct and incorrect responses at each confidence level.
216 Specifically, the area between the ROC and major diagonal was divided by the minor diagonal, and
217 confidence bias was defined as the log ratio of the lower and upper area (Kornbrot, 2006).

218 Response times in the intentional binding task were analysed using linear mixed effects regressions,
 219 with condition and delay as fixed effects, intercepts for subjects as random effects, and a by-subject
 220 random slope for the effect of condition and delay. Reaction times below or above 2 standard
 221 deviations away from the mean were discarded for each subject and each delay (corresponding
 222 respectively to 3.7% and 4.2% of total trials in Experiment 2 and 3). As response times were not
 223 normally distributed, they were considered as ordinal data and rank-transformed before linear mixed
 224 modelling (Conover & Iman, 1981). All analyses were performed with R (2016), using notably the
 225 *afex* (Singmann et al., 2015), *BayesFactor* (Morey et al., 2015), *ggplot2* (Wikham, 2009), *lme4* (Bates
 226 et al., 2014), *lmerTest* (Kuznetsova, Brockhoff & Christensen, 2015), and *effects* (Fox, 2003)
 227 packages. In all ANOVAs, degrees of freedom were corrected using the Greenhouse-Geisser method.

228

229 **Results**

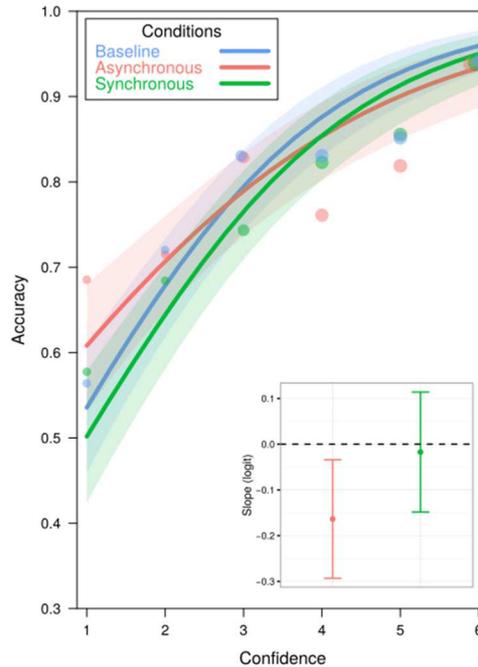
230 **Metacognitive monitoring**

231 *Experiment 1*

232 Regarding the first-order task (temporal order judgment), an analysis of variance revealed that the
 233 SOA corresponding to perceptual threshold differed across conditions ($F(1.83,27.39) = 8.02$, $p =$
 234 0.002 , $\eta_p^2 = 0.35$), with lower SOA in the baseline (mean SOA = 45 ms, SD = 13 ms) vs. synchronous
 235 condition (mean SOA = 53 ms, SD = 14 ms; paired t-test: $p = 0.020$) and in the baseline vs.
 236 asynchronous condition (mean SOA = 56 ms, SD = 15 ms; paired t-test: $p < 0.001$), but no difference
 237 between the synchronous and asynchronous conditions (paired t-test: $p = 0.36$, BF = 0.37). This
 238 implies that the task was easier in the baseline compared to the synchronous and asynchronous
 239 conditions, which is expected considering that participants performed no tapping movement in the
 240 baseline condition. Despite these differences in terms of task difficulty, task performance was equated
 241 with the staircase procedure we used (Levitt, 1971), and no effect of condition on sensitivity (d' :
 242 $F(1.65,24.78) = 0.93$, $p = 0.39$, $\eta_p^2 = 0.06$), criterion ($F(1.56,23.39) = 0.74$, $p = 0.46$, $\eta_p^2 = 0.05$), or
 243 reaction times ($F(1.78,26.71) = 1.48$, $p = 0.24$, $\eta_p^2 = 0.09$) was found, revealing that task performance
 244 was adequately controlled across conditions. Regarding the second order task, we found no effect of
 245 condition on raw confidence ratings ($F(1.94,29.16) = 1.12$, $p = 0.34$, $\eta_p^2 = 0.07$), confidence bias
 246 ($F(1.65,24.68) = 2.4$, $p = 0.12$, $\eta_p^2 = 0.14$), or reaction times for providing confidence ratings
 247 ($F(1.96,29.37) = 0.65$, $p = 0.53$, $\eta_p^2 = 0.04$), revealing that the production of confidence estimates per
 248 se was not impacted by our manipulation.

249 Next, we assessed how confidence ratings tracked first order accuracy, by fitting a mixed effects
 250 logistic regression on task accuracy, with condition and confidence as fixed effects, intercept for
 251 participants as random effects, and a by-subject random slope for the effect of confidence. First, the

252 model revealed higher intercepts in the asynchronous compared to the baseline condition (estimate =
 253 0.46, $Z = 1.99$, $p = 0.047$), and similar intercepts between the baseline and the synchronous condition
 254 (estimate = -0.12 , $Z = -0.12$, $p = 0.60$). This indicates that in the asynchronous condition participants
 255 had a higher first-order accuracy when reporting guessing than in the synchronous and baseline
 256 conditions. Crucially, the model revealed that the relation between confidence and accuracy differed in
 257 the asynchronous vs. baseline condition (estimate = -0.16 , $Z = -2.48$, $p = 0.013$), but not between the
 258 synchronous and baseline condition (estimate = -0.02 , $Z = -0.26$, $p = 0.80$). As can be seen on Fig. 2,
 259 this is reflected by a slope of smaller magnitude in the asynchronous compared to the synchronous and
 260 baseline conditions, which indicates a decrease in the capacity to adapt confidence to task
 261 performance, while task performance was similar across conditions. Importantly, this effect on
 262 metacognitive performance cannot be explained by the difference in SOA reported above, as no slope
 263 difference was found between the synchronous and baseline conditions, while SOA differed between
 264 these two conditions. Plus, another mixed effects logistic regression comparing only the synchronous
 265 and asynchronous conditions revealed different intercepts (estimate = 0.55 , $Z = 2.36$, $p = 0.018$) and
 266 slopes (estimate = -0.14 , $Z = -2.16$, $p = 0.031$), confirming that metacognitive performance was lower
 267 in the asynchronous vs. synchronous conditions, this despite an equal SOA between the two
 268 conditions. We conclude that a specific decrease in metacognitive performance occurred in the
 269 asynchronous condition.



270

271 Figure 2: Mixed logistic regression between task accuracy and confidence in the baseline (blue),
 272 asynchronous (red), and synchronous condition (green) in Experiment 1. Each dot represents the
 273 group-average accuracy for a given level of confidence, with dot size representing the number of total
 274 trials in that specific condition. The shaded area around each fit represents the 95% confidence
 275 interval. The inset plot represents the estimated slope in logit unit in the asynchronous (red) and

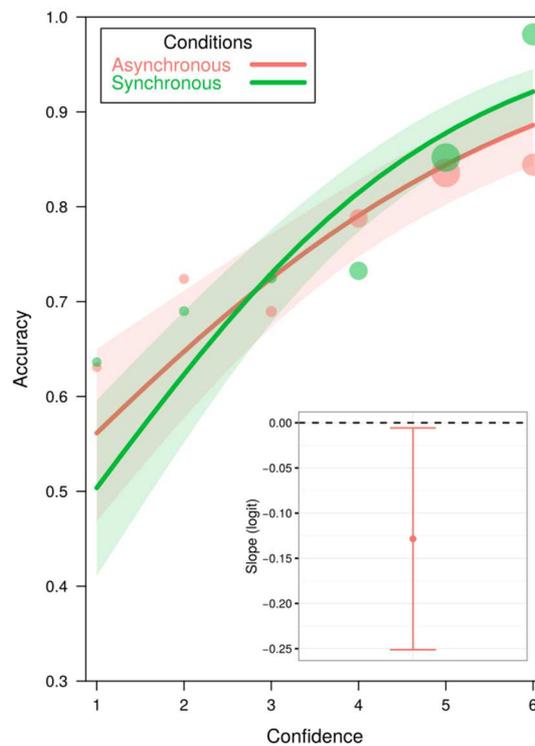
276 synchronous (green) conditions, with respect to the baseline condition (horizontal dashed line). Error
277 bars represent the 95% confidence interval.

278

279 *Experiment 2*

280 We then sought to replicate these findings in Experiment 2. Compared to Experiment 1, a direct
 281 comparison between the synchronous and asynchronous conditions was performed, with no additional
 282 baseline. Analyses of variance revealed no difference in task performance for the temporal order
 283 judgments between the synchronous condition and the asynchronous condition. There was no effect of
 284 condition on SOA ($F(1,16) = 1.35$, $p = 0.26$, $\eta^2 = 0.08$), sensitivity ($F(1,16) = 0.02$, $p = 0.88$, $\eta^2 =$
 285 0.00), criterion ($F(1,16) = 0.88$, $p = 0.36$, $\eta^2 = 0.05$), or reaction times ($F(1,16) = 2.96$, $p = 0.10$, $\eta^2 =$
 286 0.16).

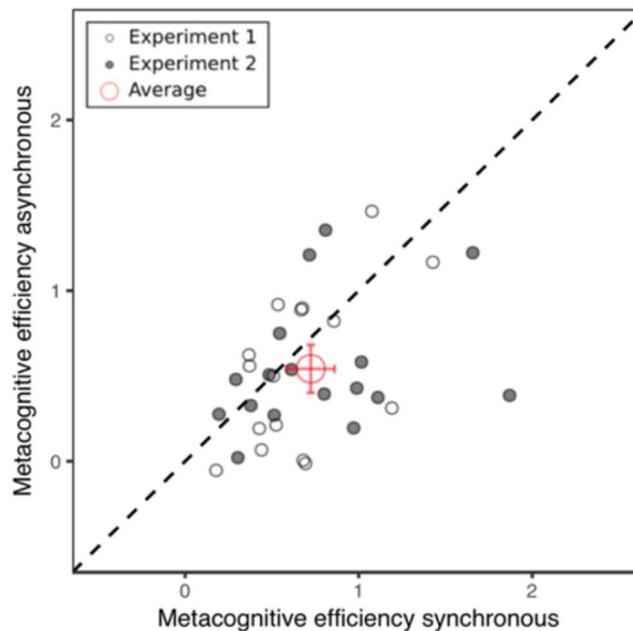
287 Regarding confidence ratings, we found no effect of condition on confidence ($F(1,16) = 0.47$, $p =$
 288 0.50 , $\eta^2 = 0.03$), confidence bias ($F(1,16) = 0.37$, $p = 0.55$, $\eta^2 = 0.02$), or reaction times for
 289 confidence ratings ($F(1,16) = 3.12$, $p = 0.10$, $\eta^2 = 0.16$). The same mixed effects logistic regression as
 290 in Experiment 1 was then used to assess how confidence ratings tracked first order accuracy. The
 291 model revealed similar intercepts between the synchronous and the asynchronous conditions ($z = -$
 292 1.57 , $p = 0.12$) and an effect of condition on the relation between confidence and accuracy ($z = -2.05$,
 293 $p = 0.040$) (see Fig. 3). Similarly to Experiment 1, this indicates a decrease in metacognitive
 294 performance in the asynchronous condition independently of any change in task performance. The fact
 295 that intercepts did not differ between conditions indicates that unlike what we found in Experiment 1,
 296 the tendency to report low confidence (i.e., error detection) was not modulated by our manipulation.
 297 **This difference was not expected and will require further investigation.**



298

299 Figure 3: Mixed effects logistic regression between task accuracy and confidence in the asynchronous
 300 (red), and synchronous condition (green) in Experiment 2. Each dot represents the group-average
 301 accuracy for a given level of confidence, with dot size representing the number of total trials in that
 302 specific condition. The shaded area around each fit represents the 95% confidence interval. The inset
 303 plot represents the estimated slope in logit unit in the asynchronous vs. synchronous condition
 304 (horizontal dashed line). Error bars represent the 95% confidence interval.

305 As an alternative to logistic regressions, we attempted to replicate our findings relying on signal
 306 detection theory to assess metacognitive performance. Specifically, we used the ratio of meta- d'/d' as
 307 an index of metacognitive efficiency, that is the amount of perceptual evidence available to perform
 308 confidence judgements. Lower metacognitive efficiency in the asynchronous vs. synchronous
 309 condition was confirmed in Experiment 1 (one-tailed paired t-test: $t(15) = 2.21$, $p = 0.02$) and in
 310 Experiment 2 (one-tailed paired t-test: $t(16) = 1.88$, $p = 0.04$) (Figure 4). These results based on signal
 311 detection theory confirm our previous results that metacognition is altered in the presence of
 312 sensorimotor conflicts, and rule out any possible confound in terms of first-order task performance.



313

314 Figure 4: Metacognitive efficiency in the asynchronous vs. synchronous condition for each participant
 315 in Experiment 1 (empty dots) and 2 (full dots). Dots lying below the diagonal reflect lower
 316 metacognitive efficiency in the asynchronous condition. The red dot corresponds to the average across
 317 all participants, error bars represent 95% confidence interval.

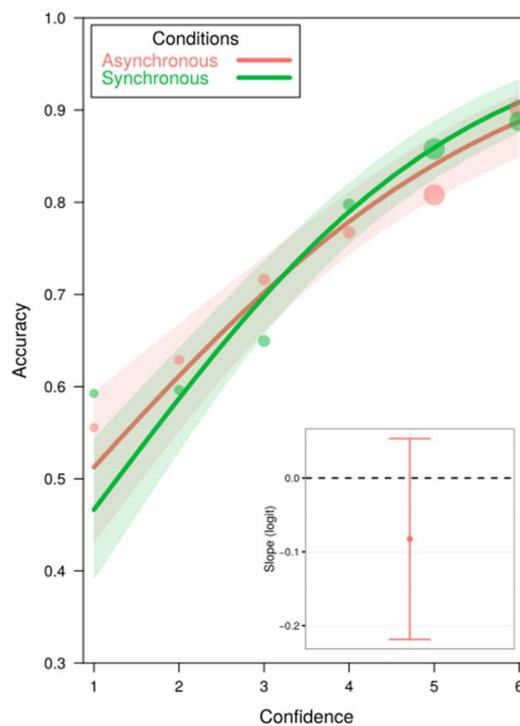
318

319 *Experiment 3*

320 To further define the nature of sensorimotor conflicts susceptible of altering metacognition, we ran a
 321 third experiment identical to Experiment 2, except that the back robot touched the left hand instead of
 322 the trunk, thereby inducing a more local, hand-related, sensorimotor conflict between the right hand
 323 actuating the front robot and the left hand receiving tactile feedback. Following the same analysis

324 strategy, we first ran an ANOVA on participant's temporal order judgments which revealed no
 325 difference in task performance. There was no effect of condition on SOA ($F(1,17) = 4.02$, $p = 0.06$, $\eta_p^2 = 0.19$),
 326 first order sensitivity ($F(1,17) = 0.27$, $p = 0.61$, $\eta_p^2 = 0.02$), criterion ($F(1,17) = 0.27$, $p = 0.61$,
 327 $\eta_p^2 = 0.02$) or reaction times ($F(1,17) = 0.95$, $p = 0.34$, $\eta_p^2 = 0.05$).

328 There was no effect of condition on raw confidence ratings ($F(1,17) = 0.3$, $p = 0.59$, $\eta_p^2 = 0.02$),
 329 confidence bias ($F(1,17) = 1.29$, $p = 0.27$, $\eta_p^2 = 0.07$), or reaction times for confidence ratings ($F(1,17)$
 330 $= 0.3$, $p = 0.59$, $\eta_p^2 = 0.02$). To assess how confidence ratings tracked first order accuracy, the same
 331 mixed effects logistic regression as in Experiment 1 and 2 was used. It revealed similar intercepts ($z =$
 332 -0.94 , $p = 0.35$) and similar slopes ($z = 1.19$, $p = 0.23$) between the synchronous and the asynchronous
 333 conditions (see Fig. 5). Likewise, metacognitive efficiency did not differ across conditions ($F(1,17) =$
 334 0.2 , $p = 0.66$, $\eta_p^2 = 0.01$, $BF = 0.27$). This indicates that metacognitive monitoring was not impacted
 335 when similar sensorimotor conflicts altered limb-based representation instead of trunk-based body
 336 representation.



337

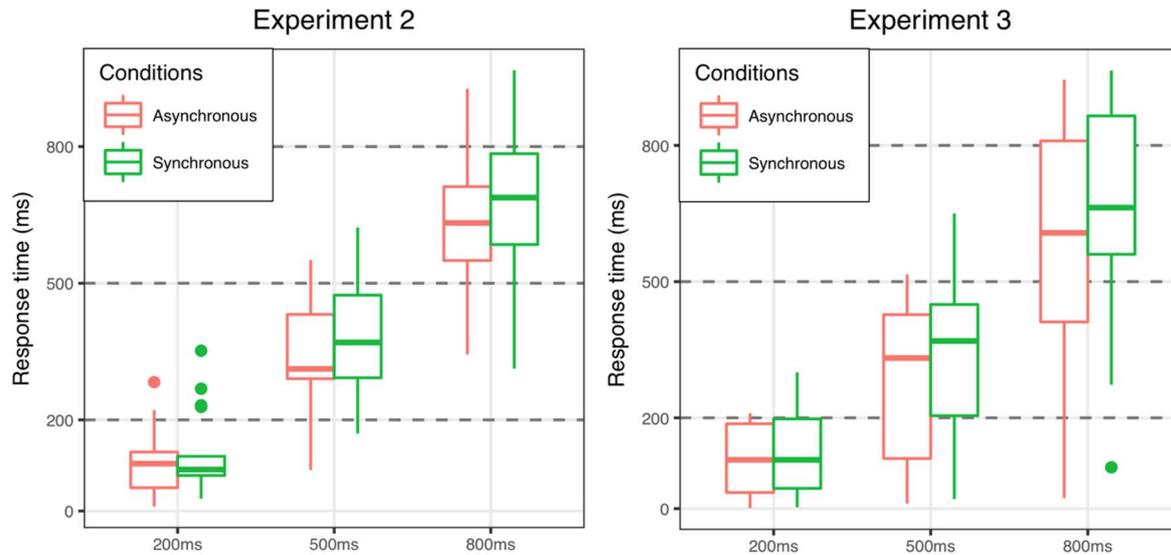
338 Figure 5: Mixed effects logistic regression between task accuracy and confidence in the asynchronous
 339 (red), and synchronous condition (green) in Experiment 3. Each dot represents the group-average
 340 accuracy for a given level of confidence, with dot size representing the number of total trials in that
 341 specific condition. The shaded area around each fit represents the 95% confidence interval. The inset
 342 plot represents the estimated slope in logit unit in the asynchronous vs. synchronous condition
 343 (horizontal dashed line). Error bars represent the 95% confidence interval.

344

345 **Action monitoring**

346 In addition to metacognitive monitoring, we examined the link between sensorimotor conflicts and
347 action monitoring, commonly referred to as the sense of agency (Blakemore and Frith, 2003;
348 Gallagher, 2000; Moore and Obhi, 2012). The sense of agency was quantified using intentional
349 binding (Haggard, Clark, Kalogeras, 2002), an implicit measure in which participants have been
350 shown to underestimate the delay between a voluntary action and its consequence. Here, while
351 actuating the front device with the right hand, participants were asked to press a button with their left
352 hand whenever they felt the urge to do so, and had to estimate the delay between this key press and the
353 onset of a sound played 200, 500, or 800 ms after. In experiment 2, a linear mixed effects on ranked
354 response times revealed no main effect of condition ($F(1,16.01) = 2.85, p = 0.11$), but a main effect of
355 delay ($F(2,15.99) = 93.57, p < 0.001$), showing that participants reported longer durations when the
356 delay between their key press and the sound onset increased. More importantly, the model revealed a
357 significant interaction between delay and condition ($F(2,1888.48) = 3.96, p < 0.02$), indicating that
358 participants judged the intervals as significantly shorter in the asynchronous vs synchronous condition,
359 and that this effect was present mainly for long delay (see Fig. 6, left panel). In other words, we found
360 a relative compression of time between a voluntary action and its outcome, if participants were
361 receiving additional asynchronous vs synchronous sensorimotor stimulation.

362 The same analysis confirmed these results in Experiment 3, where participants actuated the front robot
363 with their right hand, received tactile feedback on their left hand, and used the left hand to press a key
364 whenever they felt the urge to do so. We found a main effect of delay ($F(2,17.28) = 90.23, p < 0.001$),
365 indicating again that participants adapted their response as a function of the delay, and a main effect of
366 condition ($F(1,15.05) = 11.81, p < 0.004$), showing that participants reported overall shorter times in
367 the asynchronous vs. synchronous conditions (i.e., intentional binding). As in Experiment 2, a
368 significant interaction between condition and delay ($F(2,1782.10) = 5.76, p < 0.004$) indicated that this
369 effect was more pronounced at longer delays (see Fig. 6, right panel).



370

371 Figure 6: boxplots of estimated response times as a function of delay in the asynchronous (in red) and
 372 synchronous (in green) conditions in Experiment 2 (left panel) and Experiment 3 (right panel).

373

374 Questionnaire results

375 Regarding the questionnaire results in the 3 experiments we found that participants felt as if they were
 376 touching their own body as significantly higher in the synchronous condition (mean = 2.58, SD = 1.94
 377 for Experiments 1 and 2 and mean = 4.44, SD = 1.15 for Experiment 3) than in the asynchronous
 378 condition (mean = 1.48, SD = 1.30 for Experiments 1 and 2 and mean = 2.72, SD = 1.71 for
 379 Experiment 3; $F(1,32) = 13.36$, $p < 0.001$, $\eta_p^2 = 0.29$ for Experiments 1 and 2 combined and $F(1,17) =$
 380 24.53 , $p < 0.001$, $\eta_p^2 = 0.59$ for Experiment 3). Participants also reported a forward-drift in self-
 381 location in the synchronous condition (mean = 1.12, SD = 1.56) compared to the asynchronous
 382 condition (mean = 0.97, SD = 1.61) for Experiments 1 and 2 ($F(1,32) = 7.49$, $p = 0.01$, $\eta_p^2 = 0.19$). No
 383 other questions were found significantly different between conditions.

384 **Discussion**

385 In three independent experiments, we examined the influence of sensorimotor conflicts on two distinct
386 cognitive functions, namely metacognitive and action monitoring. While sensorimotor conflicts were
387 induced between the right hand and back (Experiments 1 and 2) or between the right hand and left
388 hand (Experiment 3), we asked participants to estimate the confidence they had regarding their
389 performance on a concurrent auditory task (i.e., metacognitive monitoring), or to estimate the delay
390 between a keypress they made spontaneously and an auditory cue (i.e., action monitoring). These two
391 measures served as a proxy to quantify metacognitive performance and intentional binding,
392 respectively.

393 *Sensorimotor processing and metacognitive monitoring*

394 Regarding metacognitive performance, mixed effects logistic regression analyses showed that when
395 receiving asynchronous sensorimotor feedback on their back, participants were less able to adjust their
396 confidence to performance, and overperformed when reporting guessing. This indicates that
397 sensorimotor conflicts may impair metacognitive monitoring. We replicated these results in a new
398 independent group of participants, and ruled out several experimental confounds. First, the possibility
399 that this decrease in metacognitive performance derived from differences at the perceptual level was
400 excluded by equating first-order performance across conditions, and by re-analysing confidence
401 judgments with a signal detection theory approach which accounts for potential differences in first-
402 order performance (Maniscalco & Lau, 2012). Of note, this approach assumes that confidence
403 estimates are computed based on the same evidence as the perceptual task, while the mixed effects
404 logistic regression approach assumes that confidence can be based both on decisional and post-
405 decisional cues (see Pereira et al., 2018 for recent results disentangling decisional and post-decisional
406 contributions to confidence). As metacognitive impairments were found relying on signal detection
407 theory and mixed logistic regression approaches, we cannot determine whether they have a decisional
408 or post-decisional origin. Second, it is unlikely that participants performed poorly in the asynchronous
409 condition simply due to tactile stimuli they could not predict based on their motor behaviour (i.e.,
410 attentional capture). Indeed, we measured similar metacognitive performance in the baseline
411 condition, in which participants passively received tactile stimulation without having to move their
412 right arm to actuate the front robot. Therefore, we argue that this decrease in metacognitive monitoring
413 is neither inherent to deficits at the perceptual level nor due to attentional capture, but rather that it
414 stems from the full-body sensorimotor conflict. Interestingly, this specific decrease in metacognitive
415 monitoring did not occur when the same sensorimotor conflicts were applied on the participants'
416 hands rather than the back. This null result was corroborated by Bayesian analyses supporting the null
417 hypothesis. A possibility is that sensorimotor conflicts applied to the left hand were less potent as the
418 same hand was later used to respond. However, under such scenario we would expect hand

419 sensorimotor conflicts to have no influence on intentional binding either, which is not what we found
420 (see below).

421 The role of sensorimotor processing for metacognitive monitoring has been a topic of recent research,
422 notably with studies showing a role of motor actions for confidence (e.g., Siedlecka, Paulewicz, &
423 Wierzchoń, 2016; Gadjos et al., 2018; Faivre et al., 2018; Pereira et al., 2018). The present study is the
424 first pointing at the specificity of trunk-related signals and bodily self-consciousness for metacognitive
425 monitoring. Trunk-related multisensory processing is known to modulate global and unitary bodily
426 representations, as described in neurological patients suffering from disorders of bodily self-
427 consciousness, and in healthy volunteers experiencing sensorimotor conflicts similar to the one we
428 used (for review see Blanke et al., 2015). By contrast, sensorimotor conflicts restricted to the hand
429 typically induce local changes in bodily self-consciousness, such as illusory ownership in the rubber
430 hand illusion (Botvinick & Cohen, 1998). In light of these findings, we could speculate that
431 metacognitive monitoring is modulated by global and unitary bodily representations rather than local
432 ones, even though a more conclusive assessment would require within-subject comparisons of trunk
433 vs. hand manipulations.

434

435 *Sensorimotor processing and action monitoring*

436 We also estimated how sensorimotor conflicts modulated another aspect of self-monitoring, namely
437 the capacity to monitor one's actions. As an implicit measure, we used intentional binding, defined as
438 the underestimation of the delay between a voluntary action and its consequence (Haggard et al., 2002;
439 Wenke & Haggard, 2009). In two experiments, we measured that intentional binding was stronger in
440 the asynchronous vs synchronous condition, indicating that when participants were exposed to
441 asynchronous sensorimotor conflicts, they perceived actions that were not immediately followed by
442 consequences as their own. This suggests that they monitored the consequences of their actions less
443 accurately in the presence of sensorimotor conflicts known to alter the way they represent their body.
444 As opposed to what we observed for metacognitive monitoring, intentional binding was increased both
445 when sensorimotor conflicts were applied to the trunk or to the hand, suggesting that this effect was
446 not specific to full-body manipulations, but rather to the sensorimotor conflict per se, reminiscent of
447 dynamic temporal recalibrations in sensorimotor pathways (Stetson et al., 2006). The directionality of
448 this effect (i.e., more binding in asynchronous vs. synchronous condition) remains to be further
449 explored. One potential issue here is that the dependent variable (i.e., (a)synchrony between an action
450 performed with the left hand and its auditory consequence) was closely related to the manipulation
451 (i.e., (a)synchrony between an action performed with the right hand and its tactile consequence).
452 Therefore, one possibility is that the observed differences of intentional binding may reflect
453 differences in temporal processing unspecific to action monitoring. Future experiments altering the

454 bodily self with other means than asynchronous multisensory conflicts will allow disentangling these
455 two aspects.

456 *Sensorimotor processing and bodily self-consciousness*

457 The type of sensorimotor conflicts we used are known to induce alterations of bodily self-
458 consciousness, defined as a set of prereflective representations of integrated bodily signals giving rise
459 to self-identification (the conscious experience of identifying with the body) and self-location (the
460 experience of where “I” am in space) (for reviews see Blanke & Metzinger, 2009; Blanke, Slater &
461 Serino, 2015; Ehrsson 2012). Namely, asynchrony between an action and its sensory consequences on
462 the back were found to modulate self-location and to induce the feeling of a presence (Blanke et al.,
463 2014). Therefore, our experimental settings allowed investigating the interplay between bodily self-
464 consciousness and cognitive functions by measuring the quality of metacognitive monitoring while
465 bodily representation was being manipulated through the application of sensorimotor conflicts. Our
466 results suggest that the monitoring of one’s thoughts and actions may rely on integrated bodily signals
467 underlying bodily self-consciousness, even though there was no correlation between questionnaire
468 ratings assessing modulations of bodily self-consciousness and the decrease in metacognitive
469 performance. Of note, other bodily signals that are highly relevant for bodily-self consciousness were
470 found to modulate metacognitive monitoring. Notably, it was shown that disgust cues modulating
471 bodily reactions like heart rate and pupil dilation also modulate confidence judgments, suggesting that
472 interoceptive bodily signals that are independent of the decisional process can guide metacognition
473 (Allen et al., 2016).

474 **Conclusion**

475 Together, our results extend the recent studies documenting the impact of the bodily self on low-level
476 vision (Faivre et al., 2017; see Faivre, Salomon & Blanke, 2015 for review), and semantic processing
477 of words (Canzoneri et al., 2016; Noel, Blanke, Serino & Salomon, 2017), by further showing that the
478 bodily self may serve as a scaffold for high-level mental capacities which enable the monitoring of
479 one’s thoughts and actions. This is broadly consistent with the idea that there exist deep interactive
480 loops between the self, metacognition and perceptual awareness (Cleeremans, 2011; Timmermans,
481 Schilbach, Pasquali & Cleeremans, 2012), an hypothesis that is at the core of Cleeremans’ Radical
482 Plasticity Thesis.

483

484

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