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## Title

### **Heartfelt Self: Cardio-visual integration affects self-face recognition and interoceptive cortical processing**

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## Running title

Heartfelt Self

## **Abstract**

The sense of body-ownership relies on the representation of both interoceptive and exteroceptive signals coming from one's body. However, it remains unknown how the integration of bodily signals coming from *outside* and *inside* the body is instantiated in the brain. Here we used a modified version of the Enfacement Illusion to investigate whether the integration of visual and cardiac information can alter self-face recognition (Experiment 1) and neural responses to heartbeats (Experiment 2). We projected a pulsing shade, that was synchronous or asynchronous with the participant's heartbeat, onto a picture depicting the participant's face morphed with the face of an unfamiliar other. Results revealed that synchronous (vs. asynchronous) cardio-visual stimulation led to increased self-identification with the other's face (Experiment 1), while during stimulation, synchronicity modulated the amplitude of the Heartbeat Evoked Potential, an electrophysiological index of cortical interoceptive processing (Experiment 2). Importantly, the magnitude of the illusion-related effects was dependent of, and increased linearly, with the participants' Interoceptive Accuracy. These results provide the first direct neural evidence for the integration of interoceptive and exteroceptive signals in bodily self-awareness.

**Keywords:** Body Ownership, Heartbeat Evoked Potential, Interoception, Predictive Coding, Self recognition.

## 2 Introduction

3 The sense of body-ownership, that is, the sense of owning and identifying with a particular  
4 body, is a fundamental aspect of self-awareness (Blanke and Metzinger 2009). Body-  
5 ownership has been typically studied through the use of bodily illusions that rely upon the  
6 multisensory integration of exteroceptive signals, such as vision and touch, focusing therefore  
7 on how the body is perceived *from the outside*. More recently, it has been suggested that  
8 interoceptive signals, that is the perception of internal physiological states of the body as  
9 perceived *from within*, may also play an important role for body-ownership (Craig 2009;  
10 Tsakiris et al. 2011). While the effects of exteroceptive signals on producing or altering the  
11 sense of body-ownership have been well documented (for a review see Tsakiris 2010), the  
12 process of integrating interoceptive and exteroceptive signals and the effects that their  
13 integration has on self-awareness are less well understood.

14 A large body of empirical evidence has shown that the integration of exteroceptive  
15 information such as vision and touch can alter the sense of body-ownership for body-parts  
16 and full bodies (see Blanke 2012 and Tsakiris 2010 for reviews). For example, in the now  
17 classic Rubber Hand Illusion (RHI), observing an artificial hand being stroked in synchrony  
18 with strokes applied to one's own hand leads to the subjective incorporation of the rubber  
19 hand as part of one's own body, to "feel like it's my hand" (Botvinick and Cohen 1998).  
20 Beyond ownership over body-parts, other studies have used the same method of multisensory  
21 integration<sup>1</sup> (i.e. visuo-tactile stimulation) to ask whether similar changes would occur in the  
22 representation of one's own face. In the Enfacement Illusion (Tsakiris, 2008; Sforza et al.  
23 2010; Apps et al. 2015), watching another person's face being touched synchronously with

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<sup>1</sup>The use of the term "integration" follows the past literature of bodily illusions that typically rely on the presentation of synchronous or asynchronous multisensory stimuli to alter body-representations (Tsakiris 2010; Blanke 2012). In this literature the term integration is taken to reflect the cause that gives rise to a change in body representations. It should be noted that, in this context, temporal synchrony is a necessary but not sufficient condition for integration to take place. Integration does not occur, for example, when synchronous multisensory stimulation is applied over body parts in anatomically incongruent positions or over on-corporeal objects (Tsakiris, 2010).

24 one's own face evokes changes in self-face recognition, so that we perceive the other  
25 person's face as more similar to one's own. This extension from bodies to faces, which are  
26 arguably the most distinctive features of one's body, suggests that multisensory integration is  
27 a shared critical mechanism for the construction of body-ownership and self-face recognition.  
28 Beyond the known role of exteroceptive information, the role that interoceptive information  
29 may play in body-awareness has remained largely unexplored. The first study to link the  
30 perception of the body *from the outside* with the perception of the body *from the inside*  
31 showed that the illusory sense of ownership of an artificial hand, (i.e. RHI, elicited by  
32 exteroceptive information) is negatively correlated with the individual's interoceptive  
33 accuracy (IAcc), which refers to the ability to detect interoceptive signals, such as one's  
34 heartbeats (Tsakiris et al. 2011). This study provided the first empirical evidence for the  
35 influence of interoception on the integration of body-related sensory signals arising from  
36 different exteroceptive domains. Interestingly, in a way analogous to the effects of IAcc on  
37 the RHI, individual traits of IAcc were shown to predict changes in self-other boundaries  
38 during the Enfacement Illusion (Tajadura-Jimenez et al. 2012a; 2012b). More recently, direct  
39 evidence for the integration of exteroceptive and interoceptive information in body-  
40 ownership comes from two virtual reality studies (Suzuki et al. 2013; Aspell et al. 2013).  
41 Suzuki and colleagues (2013) demonstrated that watching a virtual depiction of the  
42 participant's hand pulsing in synchrony with their own heartbeats induced the subjective  
43 experience of ownership over the virtually projected hand. This effect was not observed when  
44 the cardiac signals were presented out-of-synchrony with the participant's heartbeats.  
45 Interestingly, participants with higher IAcc experienced a stronger illusory sense of  
46 ownership over the virtual hand than participants with lower IAcc. Similarly, Aspell and  
47 colleagues (2013) showed that watching a projection of the participants' body (virtual body)  
48 surrounded by an illuminating silhouette flashing synchronously, as opposed to

49 asynchronously, with their own heartbeat led to enhanced self-identification and greater shift  
50 in self-location towards the virtual body. These studies indicate that the integration of sensory  
51 information across the interoceptive and exteroceptive domains via cardio-visual synchrony  
52 can alter body-ownership.

53 We here capitalise on these recent findings to investigate for the first time the neural  
54 dynamics underpinning this integration of multisensory bodily signals coming from *outside*  
55 and from *within* the body. To explore this question, we first provide a proof of concept  
56 behavioural study that tests the effect of cardio-visual stimulation on self-recognition using a  
57 modified version of the Enfacement Illusion. Next, we used electroencephalography (EEG) to  
58 investigate if the neural responses to own heartbeats are modulated by the integration of  
59 interoceptive and exteroceptive signals.

60 In Experiment 1, we projected a pulsing shade, that was synchronous or asynchronous with  
61 the participant's heartbeats, onto a picture that depicted the face of an unfamiliar other  
62 morphed with the participant's own face. Before and after this cardio-visual stimulation,  
63 participants carried out a self-other face recognition task to assess the changes that cardio-  
64 visual stimulation caused in the mental representation of their own face. In experiment 2 we  
65 used a similar procedure and, in addition, during the cardio-visual stimulation we measured  
66 participants' heartbeat evoked potential (HEP) – an electrophysiological index of cortical  
67 processing of cardiac signals (Pollatos and Schandry 2004). This allowed us to investigate  
68 changes in the brain mechanisms associated with cardiac processing during the cardio-visual  
69 stimulation. Based on past results (Tsakiris et al. 2011; Suzuki et al. 2013) that highlight the  
70 critical role of interoceptive accuracy in the integration of exteroceptive and interoceptive  
71 information we measured the participants levels of IAcc using the mental tracking task  
72 (Schandry 1981), an established measure of the ability to monitor heartbeats.

73 We hypothesised that synchronous (as opposed to asynchronous) cardio-visual stimulation  
74 would lead to changes in the mental representation of one's face (Aspell et al. 2013; Suzuki  
75 et al. 2013; Tajadura-Jimenez et al. 2012a). Behaviourally this would be reflected in changes  
76 in the self-face recognition task after synchronous stimulation, as well as by explicit reports  
77 in the subjective questionnaire. Moreover, the effects of synchronous cardio-visual  
78 stimulation would be greater in those individuals with higher levels of IAcc (Suzuki et al.  
79 2013; Azevedo et al. 2016), as measured by the mental tracking task. We also hypothesised  
80 that shifts in self-face representation due to cardio-visual stimulation would lead to changes  
81 in the cortical response to cardiac signals, i.e. the HEP component. Moreover, HEP amplitude  
82 changes would rely on the individuals' trait IAcc, such that HEP modulation was expected to  
83 be greater in individuals with higher as opposed to lower IAcc.

## 84 **Experiment 1:**

### 85 **Material and Methods**

#### 86 *Participants*

87 A total of 36 (24 females; mean age=21, s.d.=3.1) healthy volunteers took part in this  
88 experiment. Data from 4 participants was excluded from analyses due to incorrect  
89 interpretation of the visual analogue scale (VAS) used to collect ratings in the self-face  
90 recognition task. Additionally, analyses looking at changes in the Point of Subjective  
91 Equality (see below) for each condition revealed the presence of 3 outliers ( $\pm 2.5$  s.d. from  
92 the mean). Thus, the final sample comprised 29 (18 females; mean age=21.2, s.d.=3.3)  
93 participants.

#### 94 *Stimuli*

95 Stimuli used during the *cardio-visual stimulation* period consisted of photos of the  
96 participant's face with a neutral expression morphed with the face of a same gender

97 unfamiliar other. The stimulus set comprised 8 different unfamiliar models (4 females; 4  
98 males), selected from our in-house database, that had never been seen by the participants  
99 prior to the experiment. To avoid carry over effects from one condition to the other, each  
100 participant was presented with two unfamiliar gender-matched models, one presented in the  
101 synchronous condition, one presented in the asynchronous condition (see below). Models  
102 associated with the synchronous and asynchronous condition were randomly used across  
103 participants. That is, each participant was presented only with 2 of these faces, and each face  
104 was randomly presented to some participants in the synchronous conditions and to other  
105 participants in the asynchronous conditions. The photographs of the participant's face were  
106 taken in a separate session, prior to the experimental session. These non-mirror-reversed  
107 photos were morphed with Fantamorph (v4.0.8 Abrosoft, <http://www.fantamorph.com>) and  
108 edited with Photoshop software (Adobe Systems, San Jose, CA). Pictures presented during  
109 the stimulation period included hair, ears and upper torso. The presentation of coloured  
110 pictures aimed to present participants with highly realistic images to maximise the effect of  
111 the enfacement illusion (Tsakiris, 2008; Sforza et al. 2010; Paladino et al. 2010; Tajadura-  
112 Jimenez et al. 2012a, 2013). Conversely, pictures shown in the self-recognition task were  
113 desaturated (i.e. black and white) and cropped to hide hair, ears, and neck (Figure 1). This  
114 was done to prevent features unrelated to face morphology from interfering with judgments  
115 of self-recognition. It is worth noting that this is the common procedure in enfacement  
116 illusion studies (e.g. Tajadura-Jimenez et al. 2013). Two degrees of morphing were used  
117 during the stimulation period: 40%-self/60%-other (hereafter referred to as 40/60) and 60%-  
118 self/40%-other (hereafter referred to as 60/40). The 40/60 morphed stimulus served as the  
119 experimental condition because this stimulus contained a greater percentage of the other's  
120 face, and we were principally interested in testing whether synchronous cardio-visual  
121 stimulation with that stimulus would alter self-recognition performance. The 60/40 morphed



122 stimulus served as the control condition as it contained a larger percentage of the self, and we  
123 did not expect self-face recognition performance to be affected in this case.

#### 124 *Experimental procedure*

125 Participants were comfortably sited in an armchair with a standard 3-lead  
126 electrocardiogram (ECG) attached to their chest to monitor their heart activity throughout the  
127 session (Powerlab, ADInstruments, [www.adinstruments.com](http://www.adinstruments.com)). A hardware-based function  
128 detected each R-wave to synchronise stimuli presentation with the participants' heartbeats.

129 The main experimental procedure was organised in four blocks, each comprising the  
130 following sequence of tasks: *Pre-Stimulation Face Recognition Task – Cardio-Visual*  
131 *Stimulation – Post-Stimulation Face Recognition Task – Questionnaire* (Figure 1A). Each  
132 block began with the presentation of the participant's photo (100% self) for 5 seconds,  
133 followed by the photo of a same gender unfamiliar other (100% other) for 5 seconds.  
134 Participants were instructed that a set of morphing images of these two photos would be  
135 presented in that block.

136 Stimulation consisted of periodic pulses of decreased luminosity over the upper torso and  
137 face leaving constant the luminosity of the background (see Figure 1C). Each of these pulses  
138 had a duration of 100ms and they could be presented either synchronously or asynchronously  
139 with the participant's own heartbeats. During the synchronous stimulation, pulses were  
140 presented 200ms after each ECG's R-wave. This time window was selected to coincide with  
141 the period of maximum subjective perception of heartbeats (Brener et al. 1993; Suzuki et al.  
142 2013). In the asynchronous conditions, pulses mimicked the rhythm of another person's  
143 previously recorded heart at rest with a heart rate 10% faster or slower than the participant's  
144 heart rate (estimated from the 20 heartbeats immediately preceding the onset of the cardio-  
145 visual stimulation period of each block). Faster or slower asynchronous rhythms were

146 counterbalanced across participants. Thus, each of the four blocks was characterised by the  
147 synchronicity of the stimulation and degree of morphing: *synchronous 40/60*; *synchronous*  
148 *60/40*; *asynchronous 40/60*; *asynchronous 60/40*. Information regarding the cardio-visual  
149 synchrony stimulation was never mentioned to participants. Instead, they were told that the  
150 ECG recordings had the purpose of measuring cardiac responses to the perception of faces  
151 with different degrees of self-other morphing.

152 Before and after the cardio-visual stimulation, participants carried out the face recognition  
153 task. They were presented with a randomised series of black and white photos reflecting  
154 different degrees of morphing - from 20% self/ to 80% self in steps of 2%. A black template  
155 was imposed to these photos to remove non-facial attributes (e.g., background, hair, ears)  
156 (Figure 1). Participants were asked to rate each photo on a VAS (ranging from 0-100) “*how*  
157 *similar is this face to your own?*” Extremes of the scale were anchored with “*mostly similar*  
158 *to me*” (100) and “*least similar to me*” (0). This task allowed to estimate the degree of  
159 morphing for which participants judged to equally represent “other” and “self” traits,  
160 hereafter referred to as *point of subjective equality* (PSE). PSE was estimated by fitting the  
161 participants’ ratings for each picture into a logistic function, and corresponds to the central  
162 point, 50%, of this fitted psychometric curve. The comparison of the PSEs assessed  
163 previously and subsequently to cardio-visual stimulation allows estimating changes in self-  
164 other mental representation due to the stimulation (Sforza et al. 2010; Tajadura-Jimenez et al.  
165 2012b). It should be noted that by combining pre and post stimulation PSE measurements  
166 with between-participants randomised counterbalancing of faces used in synchronous and  
167 asynchronous conditions we were able to control, or at least greatly minimise, any general  
168 non-specific effects of similarity differences between self and other face at baseline.

169 The *questionnaire* consisted in 5 questions (see Table 1), 3 of which related to changes in  
170 self-other face representation due to visual stimulation (Q1, Q2, Q3) (Tajadura-Jimenez et al.

171 2012a) and two related to the pulsing rhythm (Q4, Q5) (cf. Aspell et al. 2013). Participants  
 172 answered on a VAS (ranging from 0-100) with the labels “*I disagree*” and “*I agree*”  
 173 presented at the two extremes of the scales.

174 After the completion of the 4 experimental blocks, participants carried out the *mental*  
 175 *tracking task* (Schandry 1981), a standard measure of the IAcc that reflects the ability to  
 176 accurately identify and perceive heartbeats. Participants were asked to silently count their  
 177 heartbeats, without feeling their pulse, during four trials of 25, 35, 45 and 100 seconds.  
 178 Reported and measured heartbeats were compared to estimate an index of IAcc using the  
 179 following equation (Schandry 1981):

$$(1 \div 4) \times \sum_{i=0}^4 [1 - ((\text{recorded items} - \text{counted items}) \div \text{recorded items})]$$

## 180 *Debriefing*

181 To understand if participants detected or had any suspicion about the synchrony between the  
 182 pulses and their own heartbeats, at the end of the experimental session, we asked them the  
 183 following questions: “*What do you think the purpose of this experiment was?*” and “*Did*  
 184 *anything about the experiment seem strange to you, or was there anything you were*  
 185 *wondering about?*” Only one participant mentioned a possible contingency between  
 186 heartbeats and pulses, confirming that the processes mediating cardio-visual integration are  
 187 largely implicit (Azevedo et al. 2016). We did not disclose the relationship between  
 188 heartbeats and pulses so that participants remained naïve for the EEG session.

## 189 **Results**

### 190 *Point of Subjective Equality (PSE)*

191 Our main analyses was focused on changes in the representation of self-other faces due to  
192 cardio-visual stimulation as measured by the change in the PSE at each condition. Data was  
193 submitted to a repeated measures ANOVA with 2 Time (Pre-stimulation; Post-stimulation) x  
194 2 Synchrony (Synchronous; Asynchronous) x 2 Morphing (40/60; 60/40) as within-subject  
195 factors. The analysis revealed a main effect of Time ( $F(1,28)=12.21$ ,  $p=0.002$ ), and a main  
196 effect of Synchrony ( $F(1,28)=5.84$ ,  $p=0.022$ ), as well as an interaction Time x Morphing  
197 ( $F(1,28)=5.44$ ,  $p=0.027$ ), and an interaction Synchrony x Morphing ( $F(1,28)=5.0$ ,  $p=0.034$ ).  
198 However, the critical 3-way interaction Time x Synchrony x Morphing ( $F(1,28)=0.17$ ,  
199  $p=0.68$ ) and the interaction Time x Synchrony ( $F(1,28)=0.85$ ,  $p=0.36$ ) were not significant.  
200 Because trait ability to monitor heartbeats may moderate participants' susceptibility to  
201 cardio-visual synchronicity effects (Suzuki et al. 2013) analyses were re-run with individual  
202 IAcc scores as covariates in the ANOVA. Indeed, the analysis showed that IAcc moderated  
203 the 3-way interaction - Time x Synchrony x Morphing x IAcc ( $F(1,27)=7.96$ ,  $p=0.009$ ), that  
204 was now significant ( $F(1,27)=7.14$ ,  $p=0.013$ ). The Time x Synchrony x IAcc ( $F(1,27)=4.80$ ,  
205  $p=0.038$ ) was also significant. These results show that the ability to monitor own heartbeats  
206 modulates changes in one's own representation of self-other faces due to cardio-visual  
207 stimulation. To follow up on this effect, we subtracted pre-stimulation values from post-  
208 stimulation ( $\Delta$ PSE) ratings and performed planned comparisons in separate ANCOVAs for  
209 the 40/60 and 60/40 conditions, with Synchrony (Synchronous; Asynchronous) as single  
210 within-subject factor and IAcc as covariate. Results revealed an effect of Synchrony in the  
211 40/60 condition ( $F(1,27)=14.1$ ,  $p=0.001$ ; effect of IAcc:  $F(1,27)=16.6$ ,  $p<0.001$ ) but not in the  
212 60/40 ( $F(1,27)=0.04$ ,  $p=0.84$ ; effect of IAcc:  $F(1,27)=0.08$ ,  $p=0.9$ ). This effect is illustrated  
213 by the correlation between IAcc and the  $\Delta$ PSE for the synchronous minus the asynchronous  
214 40/60 condition ( $r=0.617$ ,  $p<0.001$ ; Figure 2C).

215 *Questionnaires*

216 Separate analyses were carried out for the questions referring to enfacement effects  
217 (Questions 1-3) and questions referring to the subjective experience of the flashing  
218 (Questions 4-5). In the former case, an ANOVA with 3 Questions (Q1; Q2; Q3) x 2  
219 Synchrony (Synchronous; Asynchronous) x 2 Morphing (40/60; 60/40) was carried out. The  
220 analysis showed a main effect of the factor Questions ( $F(1,28)=6.45$ ,  $p=0.003$ ) and an  
221 interaction Questions x Synchrony ( $F(1,28)=4.6$ ,  $p=0.014$ ). There were no other main effects  
222 or interactions (all  $ps>0.05$ ). Thus, responses to the two Morphing conditions were averaged  
223 for each question. Planned comparisons between responses to the synchronous and  
224 asynchronous conditions for each question were performed. Synchrony had an effect on  
225 responses to Q2 ( $t(1,28)=2.69$ ,  $p=0.012$ ), but not responses to Q1 ( $t(1,28)=-0.27$ ,  $p=0.79$ )  
226 neither to Q3 ( $t(1,28)=-1.6$ ,  $p=0.12$ ). To further explore the relation between the subjective  
227 responses and participants' IAcc, we included IAcc as covariate in the ANOVA. However,  
228 we did not observe any interaction of IAcc with Synchrony effects (all  $ps>0.05$ ). Analyses on  
229 Questions 4-5 did not reveal a significant effect or interaction with Synchrony (all  $ps>0.05$ ).

### 230 **Discussion – Experiment 1**

231 We observed that synchronous (vs. asynchronous) cardio-visual stimulation induced changes  
232 in the participant's recognition of their own face. In particular, the comparison between PSE  
233 values obtained before and after the cardio-visual stimulation in the synchronous, as opposed  
234 the asynchronous condition, reveals that the cardio-visual stimulation increased the perceived  
235 similarity between self and other faces. This pattern of results is comparable to the effects of  
236 visuo-tactile induction of the Enfacement illusion (Tsakiris 2008; Tajadura-Jimenez et al.  
237 2012a; Sforza et al. 2010). These studies demonstrated unidirectional changes in the self-  
238 other distinction, showing changes in self-face recognition, but not in the recognition of the  
239 other's face. Self-recognition judgements depend on a comparison between the visual percept  
240 and a stored mnemonic representation of how a particular person (or the self) looks like

241 (Apps et al. 2012; Legrain et al. 2011). As with previous studies, the observed changes in  
242 self-recognition performance seem to reflect an updating in the mental representation of one's  
243 own facial appearance. Moreover, these results are in line with previous studies that reported  
244 feelings of body ownership of a virtual reality avatar and a virtual hand (Aspell et al. 2013;  
245 Suzuki et al. 2013) under conditions of cardio-visual stimulation. Overall, the results support  
246 the view that the integration of interoceptive and exteroceptive information is a critical  
247 mechanism for self-other distinction and for the construction or updating of self-face mental  
248 representations.

249 Interestingly, the effect of synchronous cardio-visual stimulation on self-recognition was  
250 dependent on individual trait levels of IAcc. Specifically, these stimulation-induced changes  
251 in self-other distinction increased linearly with IAcc. Thus, cardio-visual stimulation was  
252 particularly effective among those individuals who are, as a trait, better able to accurately  
253 perceive their own heartbeats. Even if participants were not aware of the contingency  
254 between their heartbeats and the pulses (as confirmed during debriefing), the presumably  
255 great sensitivity that individuals with higher IAcc have to interoceptive bodily signals  
256 facilitated the implicit integration of their cardiac activity with the visual stimulus depicting  
257 the other's face.

258 While both the behavioural task and the questionnaire data revealed that cardio-visual  
259 synchrony induces changes in self-face representation similar to those experienced with the  
260 classical enfacement illusion, we observed that trait levels of IAcc only correlated with  
261 behavioural changes, but not with subjective reports. This can be explained by the fact that  
262 while the face-recognition task (used to estimate  $\Delta$ PSE) measures fine-grained shifts in self-  
263 face perception, the questionnaires rely on introspective evaluations to quantify the subjective  
264 experience of the illusion and thus constitute a coarser measure.

265 Having established a behavioural effect, we next investigated, for the first time, if this change  
266 in the mental representation of self- faces caused by the integration of interoceptive with  
267 exteroceptive (i.e. visual) signals is reflected at the level of cortical interoceptive processing,  
268 by focusing on changes in the neural responses to heartbeats, i.e. HEP, during the cardio-  
269 visual stimulation.

## 270 **Experiment 2:**

### 271 **Material and Methods**

#### 272 *Participants*

273 Participants from Experiment 1 were contacted and invited to take part in Experiment 2. A  
274 total of 24 participants agreed to participate. Participants were neurologically unimpaired and  
275 received reimbursement for their participation. One participant was excluded from the sample  
276 due to excess of artifacts in the EEG signal (see EEG analysis) resulting in a total of 23  
277 participants (9 males; mean age=21.9; s.d=3.71). Participants gave their informed consent,  
278 with approval by the Ethics Committee, Department of Psychology, Royal Holloway  
279 University of London. Experiment 2 was performed 1.5-5 months after Experiment 1.

#### 280 *Experimental procedure*

281 Participants were seated in a dimly lit, sound-attenuated and electrically shielded chamber in  
282 front of a monitor at a distance of 80 cm. Participants' ECG was recorded following the same  
283 procedure as in Experiment 1. The ECG was recorded throughout all the experimental phases  
284 where there was cardio-visual stimulation.

285 Stimuli consisted of morphed pictures of the participants' upper torso and a face containing  
286 40% of the participants' facial features and 60 % of the features of a gender-matched  
287 unfamiliar other (i.e., 40/60 degree of morphing). The 40/60 pictures were selected from  
288 Experiment 1 because, as expected, the effect of synchronous cardio-visual stimulation on the

289 PSE ratings was observed in the 40/60 synchronous (experimental) condition but not in the  
290 60/40 synchronous (control) condition. There were 8 unfamiliar models (4 male, 4 female).  
291 Participants' face was morphed with faces of two randomly assigned models, one used in the  
292 synchronous condition and the other in the asynchronous condition. Besides, the stimulus set  
293 included pictures of the upper body and face of two owls. Pictures were approximately 1200  
294 x 960 size and they were presented in a white background. As in Experiment 1, stimulation  
295 consisted of periodic pulses of decreasing luminosity of the upper torso and face leaving  
296 constant the luminosity of the background. The pulse length was 100ms and was presented  
297 either synchronously or asynchronously with the participant's own heartbeats.  
298 The experiment contained 48 blocks of 90 seconds length, presented randomly. There were 4  
299 block types, each presented 12 times. The experiment consisted of 2 experimental conditions,  
300 where participants were presented with the 40/60 morphed faces either in synchrony  
301 (synchronous experimental block) or asynchrony with their own heartbeats (asynchronous  
302 experimental block). In addition, there were 2 control conditions, where participants were  
303 presented with pictures of owls presented in synchrony (synchronous control block) or  
304 asynchrony (asynchronous control block) with their heartbeats. After each block, participants  
305 were presented with one question of a 6 item questionnaire, including the 3 questions related  
306 to changes in self-other face representation due to the visual stimulation (Tajadura-Jimenez et  
307 al. 2012a), and the 2 questions related to the pulsing rhythm used in Experiment 1. The  
308 additional question "*How distracted were you during this block?*" anchored by the  
309 expressions "*not at all*" and "*very much*" was also included to control for attention to the  
310 stimuli. Participants answered to each question twice for each condition, in a fully  
311 randomised way.  
312 *EEG and ECG recording*



313 EEG was recorded with Ag-AgCl electrodes from 64 active scalp electrodes mounted on an  
314 elastic electrode cap, according to the International 10/20 system, using ActiveTwo system  
315 (AD-box) and Actview software (BioSemi, Amsterdam, Netherlands; 512 Hz sampling rate;  
316 band-pass filter 0.16-100Hz (down 3 dB); 24 bit resolution). Electrodes were referenced to  
317 the Common Mode Sense and Driven Right Leg electrodes and rereferenced to the average  
318 reference off-line. As in the behavioural study, the ECG signal was recorded with a standard  
319 3-lead ECG attached to participants' chest (Powerlab, ADInstruments,  
320 www.adinstruments.com). The R-peaks of the EGC were identified using a hardware-based  
321 detection algorithm. The onset of the R-waves were marked in the EEG recording. The  
322 average number of trials (heartbeats) contributing to the HEP were 1039 in the experimental  
323 synchronous condition; 1044.74 in the experimental asynchronous condition; 1050.91 in the  
324 control synchronous condition; and 1053.7 in the control asynchronous condition.  
325 Importantly, there were no significant differences in number of heartbeats between conditions  
326 ( $F(3,66)=0.597, p>0.05$ ).

### 327 *EEG data analysis*

328 Off-line EEG analysis was performed using Vision Analyzer software (BrainProducts). The  
329 data was digitally low-pass-filtered at 30 Hz. The data was then submitted to ICA as  
330 implemented in Vision Analyzer to correct for ocular and cardiac-field artifacts (CFAs)  
331 (Terhaar et al. 2014). The CFAs were corrected by removing the independent components  
332 (most often one, or two) whose timing and topography resembled the characteristics of the  
333 CFAs. The CFA represents a challenge to the analysis of the HEP because the averaging of  
334 the data around the R-peak amplifies the CFA becoming time-locked to the heartbeat (Luft  
335 and Bhattacharya, 2015). However, the ICA method has been shown to be of high efficiency  
336 in the removal of the independent components representing cardiac-field artifacts from the  
337 EEG signal, specifically within the time window where the HEP typically occurs, i.e. 200-

338 400ms (e.g. Terhaar et al. 2014; Park et al. 2014; Luft and Bhattacharya 2015) (see also  
339 figure 3D). To compute the HEP the EEG signal was epoched into 750ms segments, starting  
340 150ms before the R-wave onset. Segments were baseline corrected using an interval from -  
341 150 to -50ms before the R-wave onset. The period ranging from -50ms to 0ms was not  
342 considered to avoid the inclusion of artifacts related to the QRS complex of the ECG signal  
343 when computing the baseline correction of the signal (e.g. Canales-Johnson et al. 2015).  
344 Moreover, in the present experimental design, longer baseline periods should be avoided as,  
345 for participants with faster heart rates, this period may partially overlap with late components  
346 of visual evoked responses to the pulsing stimulus of the immediately preceding trial.  
347 Automatic artifact rejection was combined with visual inspection for all participants ( $\pm 100$   
348  $\mu\text{V}$  threshold; 0.05% mean percentage of the data was rejected due to excessive amplitude).  
349 The minimum percentage of trials per condition included in the analysis was 82%  
350 (percentage of trials did not significantly differ between conditions;  $p > 0.05$ ). The signal was  
351 re-referenced to the arithmetic average of all electrodes. Single-subject ERP for each  
352 Condition (Experimental; Control) and Synchrony (Synchronous; Asynchronous) were  
353 calculated and used to compute ERP grand averages across subjects.  
354 The HEP has a frontal-to-parietal distribution with higher amplitudes over the right, as  
355 opposed to the left, hemisphere (Dirlich et al. 1997; Pollatos and Schandry 2004; Kern et al.  
356 2013; Schulz et al. 2015). Previous studies have defined the HEP as a positive deflection in  
357 fronto-central sites. However, the polarity of the HEP seems to vary across studies according  
358 to factors such as the task, sites, and time window analysed (Gray et al. 2007; Couto et al.  
359 2014; Canales-Johnson et al. 2015). In the current study, analyses were restricted to 6 regions  
360 of interests (ROIs) (Figure 3A), defined according to the widespread distribution of the HEP  
361 topography and on the basis of the aforementioned studies. To estimate the effects of the  
362 cardio-visual stimulation on neural responses to heartbeats, mean voltages of the HEPs time-

363 locked to R-wave onset were computed at the group level using a non-parametric  
364 randomisation test controlling for multiple-comparisons (Maris and Oostenveld 2007).  
365 Subject-wise activation time courses were extracted at the selected ROIs and were passed to  
366 analysis procedure of FieldTrip, the details of which are described by Maris and Oostenveld  
367 (2007). Subject-wise activation time courses were compared to identify statistically  
368 significant temporal clusters using a FieldTrip-based analysis (Oostenveld et al. 2011) of one  
369 ROI at a time (Canales-Johnson et al. 2015; Couto et al. 2014).

370 To test for the interaction effects between the Synchrony effect and the group (experimental  
371 vs. control) on HEP amplitudes, and the possibility that this effect is mediated by the  
372 participants' IAcc (as shown in experiment 1), we first computed the Synchrony effect  
373 (calculated by subtraction of amplitudes at each time point on the asynchronous trials from  
374 the synchronous trials) in both the experimental and control group. Then we calculated the  
375 difference linked to the Synchrony effect in the experimental vs. the control group at each  
376 time point, and we called it "difference Synchrony effect". We then passed the subject-wise  
377 activation time courses to the analysis procedure of Fieldtrip. In brief, this procedure  
378 regresses the "difference Synchrony effect" (computed as described above) on the predictor,  
379 i.e. participants' IAcc, at each corresponding temporal point in the subject-wise activation  
380 time courses using the independent sample regression coefficient T-statistics. FieldTrip uses a  
381 nonparametric method (Bullmore et al. 1999) to address the multiple comparison problem. t-  
382 values of adjacent temporal points whose p-values were less than 0.05 were clustered by  
383 adding their t-values, and this cumulative statistic is used for inferential statistics at the  
384 cluster level. This procedure, that is, the calculation of t-values at each temporal point  
385 followed by clustering of adjacent t-values was repeated 5000 times, with randomised  
386 swapping and resampling of the subject-wise averages before each repetition. This Monte

387 Carlo method results in a nonparametric estimate of the P-value representing the statistical  
388 significance of the identified cluster.

## 389 **Results**

### 390 *Modulation of HEP amplitudes*

391 The results of the cluster-based permutation test revealed significant modulations of the HEP  
392 amplitude as indicated by a significant negative cluster between 195 and 289ms after the R-  
393 wave onset ( $p=0.005$ ) in the right centro-parietal ROI (Figure 3A). This time window is in  
394 accordance with the latencies reported in previous HEP studies, i.e. 200-400ms, where the  
395 cortical processing of cardiac signals takes place (Schandry, et al. 1986; Pollatos and  
396 Schandry 2004; Yuan et al. 2007; Fukushima et al. 2011; Kern et al. 2013; Canales-Johnson  
397 et al. 2015). Moreover, it minimises overlapping between the HEP and the VEP associated to  
398 the visual pulse starting at 120ms after the onset of the pulse (i.e., 200ms after the R wave).  
399 Based on the results of the cluster-based permutation analysis, we performed a correlation  
400 analysis (2-tailed) between IAcc and the HEP difference linked to the Synchrony effect (i.e.  
401 Synchronous vs Asynchronous) in the experimental vs. the control condition in the right  
402 centroparietal ROI between 195 and 289ms. This analysis revealed that the higher the IAcc  
403 the greater the HEP difference of the Synchrony effect in the experimental synchronous  
404 condition ( $r= -0.632$ ,  $p=0.001$ ; Figure 3E).

405 In addition, to ensure that the differences observed between conditions in the HEP cannot be  
406 explained by differences in the ECG signal, we analysed the ECG trace mimicking the  
407 analysing procedure followed in the HEP analysis. The results of the cluster-based  
408 permutation test on the ECG did not reveal any significant cluster of significant interactions  
409 at  $p<0.05$ , corrected for multiple comparisons.

410 Overall, these results show that the presentation of a 40/60 morphed face (i.e., containing  
411 40% of the participants' features) whose luminosity changed in rhythmic pulses

412 synchronously to the participants' heartbeats led to amplitude changes of the HEP component  
413 in the 195-289ms time window at centro-parietal sites in the right hemisphere. The  
414 interaction shown in Figure 3A,D illustrates the changes in HEP amplitude during the  
415 synchronous compared to asynchronous experimental cardio-visual stimulation, and to the  
416 control conditions, in which visual stimulation was perceived over the face of an owl. In  
417 other words, it demonstrates the distinct effect that synchronous cardio-visual stimulation has  
418 on HEP amplitudes when perceiving someone else's face vs an owl face. Importantly, such  
419 modulation of HEP amplitude was dependent on the individuals' trait levels of IAcc.  
420 Furthermore, the correlation analysis showed that the stimulation-induced changes on the  
421 HEP amplitude increased linearly with IAcc (see Figure 3E).

#### 422 *Questionnaires*

423 In line with Experiment1, we carried out separate analyses for the questions referring to the  
424 enfacement effects (Questions 1-3), the subjective experience of the pulsing (Questions 4-5)  
425 and attention to the task (Question 6). Regarding the enfacement questions, the interaction  
426 between 3 Questions (Q1; Q2; Q3) x 2 Synchrony (Synchronous; Asynchronous) x 2  
427 Condition (Experimental; Control) was not significant ( $F(1,44)=0.01$ ,  $p=0.99$ ). However, the  
428 critical interaction Synchrony x Condition was significant ( $F(1,22)=4.46$ ,  $p=0.046$ ), as well as  
429 the main effects of Synchrony ( $F(1,22)=10.13$ ,  $p=0.004$ ) and Condition ( $F(1,22)=102.83$ ,  
430  $p<0.001$ ). Given that the analysis did not show a main effect of Question, nor in interaction  
431 ( $p>0.05$ ), we collapsed responses to Q1, Q2 and Q3 and performed planned comparisons  
432 between the synchronous and asynchronous cardio-visual stimulation in both the  
433 experimental and the control condition. Results showed significant differences between  
434 synchronous and asynchronous trials in the experimental condition ( $t(1,22)=2.88$ ,  $p=0.009$ )  
435 but not in the control condition ( $t(1,22)=0.78$ ,  $p=0.44$ ). Regarding the questions about the  
436 subjective experience of pulsing (Q4-Q5), there were not significant main effects of the

437 factors Condition ( $F(1,22)=0.37, p=0.55$ ), nor Synchrony ( $F(1,22)=3.48, p=0.076$ ), neither  
438 significant interactions (all  $p>0.05$ ). Likewise, there was no significant main effect, nor in  
439 interaction, for the question referring to attention to the task (all  $p>0.05$ ).

440 We also explored a possible relationship between subjective reports of enfacement and i) the  
441 magnitude of HEP changes and ii) individual levels of IAcc. For that, HEP changes and IAcc  
442 scores were included, in separate analyses, as covariates in the Condition x Synchrony  
443 ANOVA on the subject reports of enfacement (average responses to Questions 1-3). Neither  
444 IAcc ( $p>0.05$ ) nor HEP changes ( $p>0.05$ ) were found to have an effect over any main effect  
445 or interaction.

## 446 **Discussion - Experiment 2**

447 Experiment 2 shows that synchronous cardio-visual stimulation resulted in significant  
448 changes in the participants' subjective reports, as well as changes in the electrophysiological  
449 processing of cardiac signals. We observed reduced HEP amplitude during the synchronous,  
450 as opposed to the asynchronous, stimulation in the experimental condition, while no effects  
451 were observed in the control condition. In accordance with earlier findings (Gray et al. 2007;  
452 Couto et al. 2014; Canales-Johnson et al. 2015), the pattern of interaction in Figure 3A shows  
453 an HEP component represented by a deflection across parietal sites in the right hemisphere.  
454 This might reflect the importance of the right hemisphere in the integration of interoceptive  
455 and exteroceptive bodily related signals (Craig, 2009) and in self-recognition extending  
456 previous evidence on the key role of the right hemisphere to process information relative to  
457 the self (Keenan et al. 2000).

458 Furthermore, the effects of cardio-visual synchrony on HEP amplitude were dependent on  
459 individual trait levels of IAcc. In particular, the amplitude reduction of the HEP increased  
460 linearly with IAcc. Past studies have shown a link between individual differences in IAcc and

461 HEP amplitudes, such that individuals with higher IAcc show greater HEP amplitude than  
462 those with lower IAcc when they focus on their heartbeat (Pollatos and Schandry 2004; Yuan  
463 et al 2007). We here show IAcc-dependent modulations of HEP amplitudes when the brain  
464 integrates interoceptive and exteroceptive signals.

## 465 **General discussion**

466 Across two experiments, we focused on the mechanisms underpinning the integration of  
467 information originating from *outside* and from *within* our bodies, through cardio-visual  
468 stimulation. We investigated how this integration relates to changes in the mental  
469 representation of one's self, as assessed by changes in self-recognition. We report three key  
470 findings. First, we show that cardio-visual stimulation, i.e. perceiving a pulsing stimulus in  
471 synchrony with one's own heart over someone else's face, leads to changes in self-  
472 recognition and increases self-other perceived similarity. Second, we reveal that synchronous  
473 cardio-visual stimulation over another person's face was associated with the modulation of  
474 the HEP amplitude, an index of cortical representation of cardiac processing. Third, these  
475 changes in HEP were dependent on individual trait levels of IAcc, so that participants with  
476 higher IAcc exhibit greater changes on HEP amplitude, in comparison to participants with  
477 lower IAcc.

478 How does the change of neural activation locked to heartbeats reflects the experimentally  
479 induced changes of bodily self-consciousness? In the classic exteroceptive ways of inducing  
480 illusions of ownership, there is an initial inter-sensory conflict (e.g. between felt and seen  
481 touch). To solve this conflict, the brain attenuates the importance of incoming proprioceptive  
482 and somatosensory inputs and assigns greater salience to visual information (Tsakiris 2010;  
483 Apps and Tsakiris 2014; Zeller et al. 2015). This results in a recalibration of visual-tactile  
484 coordinates (i.e. touch referral) that leads to an updated sense of body-ownership. In support

485 of this idea, neuroimaging data shows that ownership of an artificial hand in the RHI, or with  
486 a virtual body in the full body illusion, is linked to changes in neural activity in the  
487 somatosensory cortex (Tsakiris et al. 2007; Zeller et al. 2015; Evans and Blanke 2013; Aspell  
488 et al. 2012; Lenggenhager et al. 2011). In particular, Tsakiris and colleagues (2007) found  
489 that the degree of proprioceptive drift, an objective index of strength of the illusion, was  
490 linearly correlated with decreased activity in the somatosensory cortex. Moreover, Zeller and  
491 colleagues (2015) demonstrated an amplitude reduction of the somatosensory evoked  
492 potentials (SEPs) to brushstrokes delivered to the participants' hand synchronously to  
493 brushstrokes delivered to the artificial hand placed in an anatomically congruent, vs.  
494 incongruent, position. This reduction in SEP was interpreted as decreased processing of own  
495 somatosensory signals allowing to solve the multisensory conflict experienced by the RHI.

496 In our study, we observed changes in HEP amplitude when one's heartbeat sensations were  
497 congruent with the visual cues originating from someone else's face, creating the subjective  
498 experience of self-other merging. These results suggest that during cardio-visual stimulation,  
499 i.e. one's heartbeat projected onto someone else's face, the external representation of what  
500 seems to be inherently private information to the self creates a conflict (i.e. heartbeats being  
501 simulated by an external agent). Consistently with previous research, this conflict may be  
502 solved by attenuating the salience of interoceptive sensations leading to reduced HEP  
503 amplitudes relative to the control conditions. Overall, these findings complement and  
504 advance previous evidence on cortical attenuation during classical bodily illusions,  
505 demonstrating that the cortical processing of interoceptive signals may be subject to the same  
506 principles as somatosensory signals (Zeller et al. 2015).

507 Our findings add to the growing body of literature suggesting the HEP as an important index  
508 of cortical processing of afferent cardiovascular activity (Leopold and Schandry 2001). The  
509 magnitude of HEPs has been consistently associated to the representation of the bodily



510 aspects of emotional processing (Müller et al. 2015; Fukushima et al. 2011; Couto et al. 2014;  
511 Luft and Bhattacharya 2015) and self-processing (Schulz et al. 2015; Pollatos and Schandry  
512 2004; Canales-Johnson et al. 2015). Of particular relevance for the present study is the recent  
513 finding of reduced HEP amplitudes among individuals suffering from depersonalisation/  
514 derealisation disorder (Schulz et al. 2015). In this study, the authors established a close link  
515 between altered experiences of bodily self and the cortical processing of heartbeats. Our  
516 results expand these findings by showing that *dynamic* and *on-line* modulations of heartbeat  
517 processing are related to shifts in the mental representation of one's self in healthy  
518 individuals. In specific, HEP modulation is likely to reflect a mechanism by which the brain  
519 attempts to reduce the multisensory conflict by attenuating the cortical representation of own  
520 heartbeat signals to allow the updating of self-representations. Overall, our results support the  
521 idea of plasticity of self-representations under circumstances of simultaneous integration of  
522 exteroceptive and interoceptive signals related to the body. They provide a direct link  
523 between the brain mechanisms processing on-line interoceptive bodily signals and the  
524 process of identifying with a face, a crucial aspect of self-awareness.

525 Could there be alternative explanations to our results? Recent studies have shown  
526 bidirectional links between the amplitude of neural responses to heartbeats and visual  
527 processing (Park et al. 2014, Salomon et al., 2016; Fukushima et al. 2011; Couto et al. 2014;  
528 Luft and Bhattacharya 2015). Interestingly, recent research showed reduced cortical  
529 processing (van Elk et al., 2014) and reduced insula activity (Salomon et al., 2016), a key  
530 region in the processing of interoceptive signals, to stimuli presented synchronously with the  
531 participant's heartbeats. Could therefore the modulation of the HEP observed in our study  
532 reflect a purely visual effect driven by synchrony? Crucially, we did not find any significant  
533 changes in the HEP amplitude in the synchronous control condition, i.e. synchronous  
534 stimulation over the owl's face. This therefore suggests that the HEP amplitude reduction

535 observed in the synchronous experimental condition cannot be explained by pure visual  
536 effects. It is also worth noting that previous physiological and electrophysiological data has  
537 shown a partial overlap between the HEP and the electrocardiac field up to 450ms after the  
538 R-wave (Dirlich et al. 1997) suggesting that the observed HEP amplitude changes could be  
539 partially explained by the differences in the temporal occurrence of the CFA between  
540 synchronous vs. asynchronous stimulation. Although we cannot entirely rule out this  
541 possibility, there are three reasons why this is unlikely. Firstly, the temporal dynamics of the  
542 CFA were identical in both the experimental and the control synchronous condition.  
543 However, the modulation of HEP was only observed in the former. Secondly, we submitted  
544 the EEG data to ICA, which has been shown to be highly efficient to remove CFA from  
545 HEPs (Terhaar et al. 2014; Park et al. 2014; Luft and Bhattacharya 2015). Moreover, analyses  
546 of the ECG did not reveal significant differences between the conditions. Thus, we are  
547 confident that the observed HEP reduction is a consequence of the illusory experience of self-  
548 other merging due to cardio-visual integration.

549 Previous research by our group has shown that individuals with lower IAcc are particularly  
550 susceptible to bodily illusions relying on exteroceptive cues, such as the RHI (Tsakiris et al.  
551 2011) and the enfacement illusion (Tajadura-Jimenez et al. 2013). Then, we suggested that  
552 individuals with lower IAcc displayed a more malleable self- representation in response to  
553 exteroceptive cues. Interestingly, here, and in line with the findings of Suzuki and colleagues  
554 (2013; see also Azevedo et al. 2016), we observed the opposite pattern. Specifically,  
555 individuals with higher IAcc revealed greater incorporation of other's features related to the  
556 integration between one exteroceptive signal and one interoceptive signal. These results may  
557 initially seem at odds with the former. However, the role played by IAcc in the classic  
558 methods of induction of the illusion (Tsakiris et al. 2011; Tajadura-Jimenez et al. 2013) and  
559 in the cardio-visual adaptations (see present experiments, and Suzuki et al. 2013; Aspell et al.

2014) is likely to be very different. While cardiac information is not directly involved in the induction of visual-tactile illusions, in cardio-visual stimulation paradigms interoceptive cues are part of the induction mechanism. Moreover, because heart sensations are considerably faint and people differ greatly in their ability to attend, monitor and process cardiac signals at a higher cortical level (e.g. HEPs), IAcc crucially determines the extent to which the illusion is experienced. Individuals with higher IAcc, presumably, have greater access to their cardiac signals. This would facilitate the integration of their cardiac signals with the other's face leading to a greater incorporation of the other's facial features in the mental representation of their own face in comparison to lower IAcc. Furthermore, the greater HEP amplitude reduction observed in individuals with higher IAcc seems to indicate high flexibility in the process of interoceptive signals at the cortical level (Barrett and Simons 2015).

Recent theoretical proposals have suggested that self-processing can be characterised by the principles of Predictive Coding (PC) (Fotopoulou 2012; Apps and Tsakiris 2014; Seth 2014; Sel 2014; Barrett and Simons 2015). According to this view, the sensory input is compared with internal models, which are constantly updated by compiling the statistical regularities of past inputs (Friston and Kiebel 2009). Within predictive coding models of self-awareness (Apps and Tsakiris 2014; Seth 2014) one's body is processed in a Bayesian manner as the most likely to be "me". That is, one's own body is the one which has the highest probability of being "mine" as other objects are probabilistically less likely to evoke the same sensory inputs. This information can be considered as highly abstract with respect to the low-level properties of the stimuli and it can only be represented as "self" when different streams of multisensory information are integrated. That is, the self-face will only be recognised as "self" when a visual stimulus has been processed hierarchically for its low level visual properties, its configural features and then its identity. The self-face will therefore be represented as an abstract, supramodal representation of visual input e.g. this is a face, that I

585 have seen before, that I am familiar with, and that is associated with congruent corollary  
586 discharge, vestibular, somatosensory and interoceptive information. Such probabilistic  
587 representation arises through the integration of information from hierarchically organised  
588 unimodal systems in higher-level multimodal areas. This process entails that probabilistic  
589 representations are created through the integration of top-down “predictions” about the body  
590 and of bottom-up “prediction errors” (PEs) from unimodal sensory systems that are then  
591 explained away. Importantly, within predictive coding, priors, predictions and associated  
592 predictions errors are all represented in terms of precision. “Precision” refers to the inverse  
593 variance associated with each probability distribution and is thus a measure of their relative  
594 salience and reliability (Friston 2009). Precision operates both within and between  
595 modalities. Within any modality, at each level of the hierarchy and taking account of the  
596 given context, the brain weighs the relative precision of PEs that informs or revises  
597 expectations at higher level of the hierarchy (Hohwy 2012; Brown et al. 2013).

598 The use of cardio-visual stimulation employed in the present experiments allowed us to test  
599 empirically whether the brain will attenuate the visual or the interoceptive information. The  
600 neural evidence presented in Experiment 2 that is indicative of a reduction of the HEP in the  
601 critical test condition suggests that interoceptive information is attenuated. In a way these  
602 results are comparable to the attenuation of somatosensory signals in the classic visuo-tactile  
603 stimulation during the Rubber Hand Illusion (Zeller et al. 2015; Limanowski and  
604 Blankenburg 2015). Importantly, predictive coding models allow us to test how contextual  
605 factors influence information processing as the precision of predictions and predictions errors  
606 may vary considerably across different contexts (see also Apps and Tsakiris 2014). For  
607 example, visual information may be more precise in the context of self-recognition, while in  
608 the absence of visual input or at night, when vision becomes imprecise, the relative precision  
609 of interoceptive signals necessarily increases (Pezzulo 2014). Therefore, the relative precision

610 of PEs and priors across sensory modalities is constantly being updated. Thus, as shown here,  
611 in contexts that rely heavily on visual information, i.e. self-recognition, interoceptive signals  
612 are attenuated, possibly at higher order cortical areas, under conditions of cardio-visual  
613 synchrony. In accordance, the HEP amplitude reduction provides evidence of a  
614 neurophysiological mechanism throughout which the sensory input is attenuated to update the  
615 mental representations of one's self according to the external evidence.

616 In conclusion, this study provides new insights on the integration of multisensory bodily  
617 signals coming from *outside* and from *within* the body and its influence in self-face  
618 representation. We designed two experiments that investigated whether synchronous cardio-  
619 visual stimulation can enhance self-identification with the face of another and the cortical  
620 processing of such an altered experienced. Our data showed that multisensory integration of  
621 heartbeat sensations with the visual exteroceptive information of the face of another leads to  
622 an illusory sense of identification with the other's face, and to an amplitude reduction of the  
623 HEP component. No such effects were found when the interoceptive and exteroceptive  
624 signals were presented in an asynchronous manner. We therefore provide direct neural  
625 evidence for the integration of interoceptive and exteroceptive signals in bodily self-  
626 awareness.

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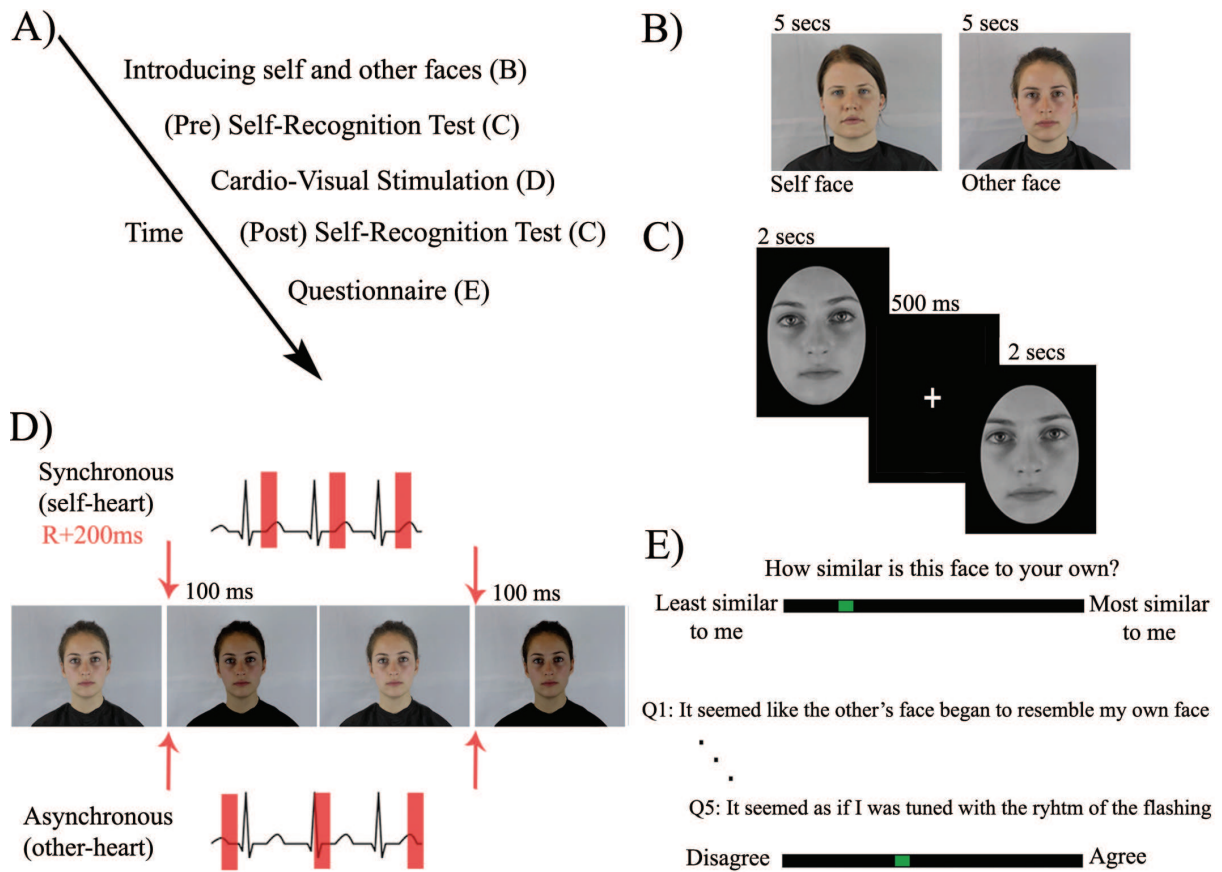
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766 **Figures:**

767

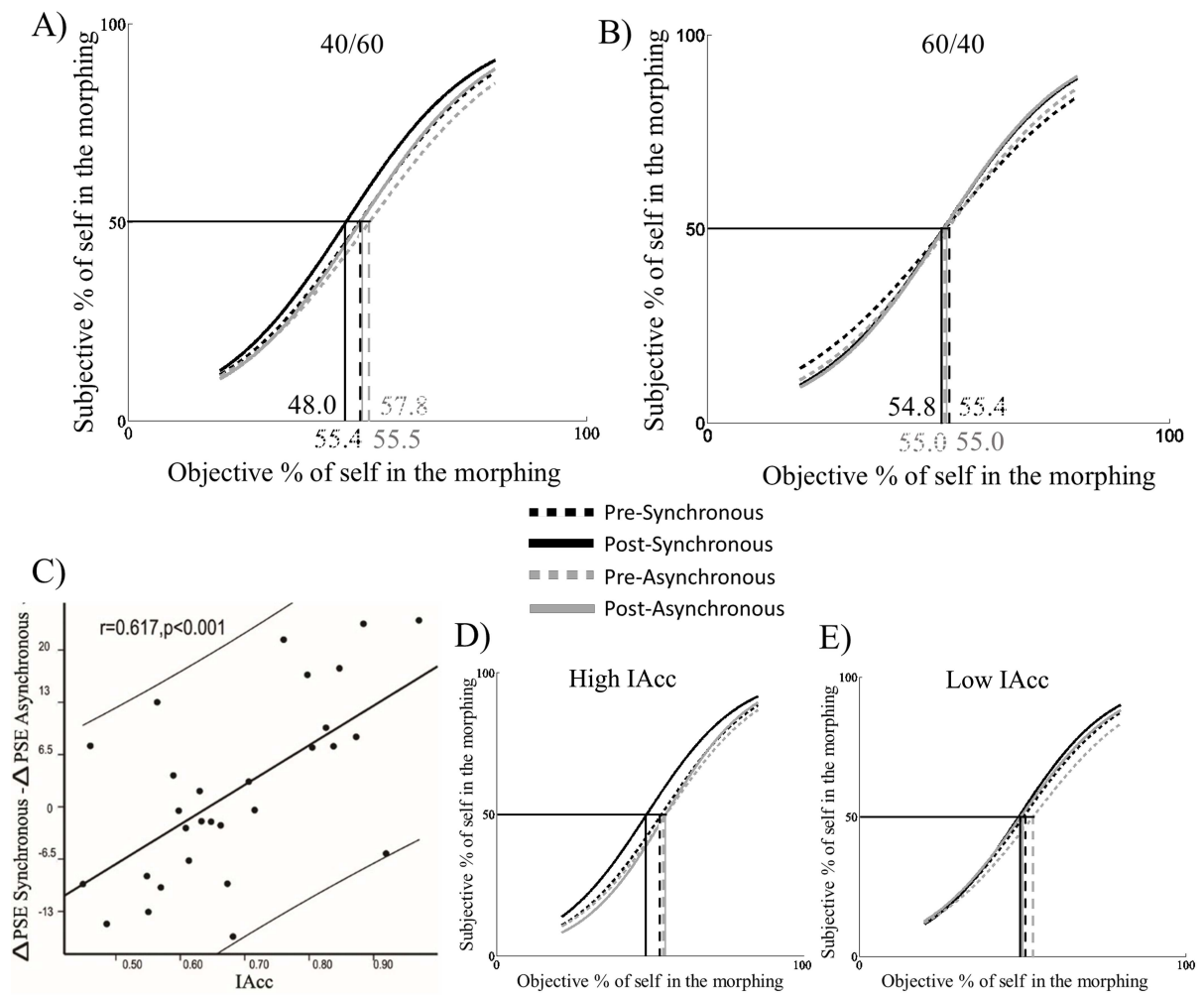
768 **Figure 1**

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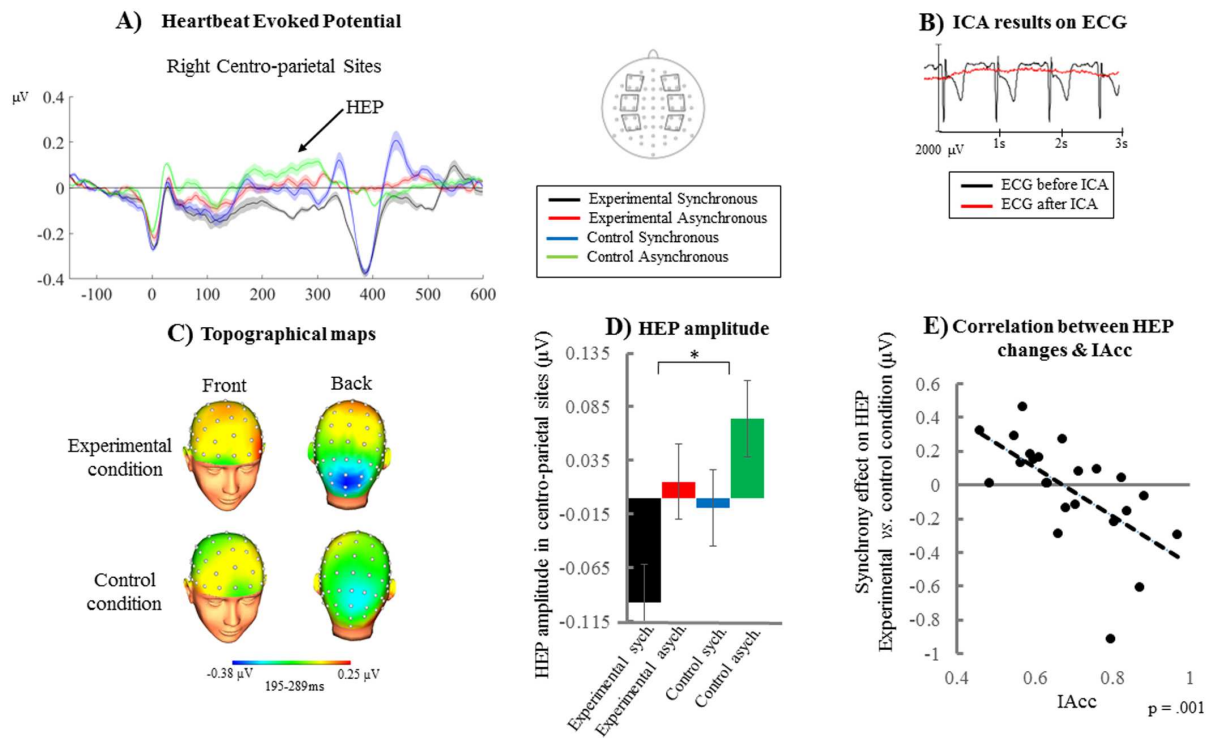
770 **Figure 2**

771



772 **Figure 3**

773



774 **Table 1**

Questions	Study 1				Study 2			
	Synchronous		Asynchronous		Synchronous		Asynchronous	
	40/60	60/40	40/60	60/40	Face	Owl	Face	Owl
Q1- It felt like the other's face was my face	54.2 (32.0)	47.2 (34.2)	48.5 (31.4)	58 (30.4)	59.5 (30.2)	8.5 (17.3)	44.3 (33.8)	7.8 (17.6)
Q2 - It seemed like the other's face began to resemble my own face	66.4 (27.8)	69.5 (27.9)	58 (28.6)	61.5 (31.8)	59.3 (30.3)	8.3 (16.5)	46.3 (32.9)	6.3 (14.0)
Q3 - It seemed like my own face began to resemble the other person's face	61.6 (25.9)	63.6 (28.4)	67.0 (26.6)	68 (29.7)	56.3 (30.9)	6.8 (15.5)	44.1 (30.2)	8.2 (16.3)
Q4 - It seemed as if the flashing was inside or going through my body	40.4 (32.6)	35.4 (32.0)	30.4 (26.9)	34.6 (31.4)	54.7 (26.7)	43.3 (29.8)	37.9 (27.0)	37.4 (30.1)
Q5 - It seemed as if I was tuned with the rhythm of the flashing	62.5 (29.8)	52.4 (29.9)	61.2 (29.1)	48.5 (29.0)	55.5 (28.2)	58.3 (27.9)	52.8 (29.4)	54.9 (29.2)
Q6 - How distracted were you during this trial	-	-	-	-	45.8 (27.6)	47.8 (24.6)	44.8 (26.5)	53.1 (24.0)



776 **Caption to figures:**

777 Figure 1. Schematic representation of the experimental protocol. *A)* Timeline of each block;  
778 *B)* Self and other faces presented at the beginning of the block; *C)* Self-recognition test  
779 carried out before and after the *D)* cardio-visual stimulation procedure; *E)* Questionnaire on  
780 the subjective experience associated with the stimulation administered at the end of each  
781 block.

782 Figure 2. *A)* Cardio-visual stimulation induced changes in the mental representation of  
783 self/other faces as reflected by a shift in the Point of Subjective Equality (PSE) after  
784 synchronous (vs. asynchronous) in the 40/60 condition but *B)* not in the 60/40 condition. In  
785 the former condition, participants accepted more facial features of the “other” in the morphed  
786 pictures judged to equally represent “self” and “other”. Interestingly, this effect was linearly  
787 dependent on individual levels of IAcc, such that cardio-visual interaction effects were  
788 stronger in higher interoceptors. This relationship is represented by the *C)* positive correlation  
789 between IAcc scores and the difference between PSE changes in the synchronous and  
790 asynchronous conditions. For illustration purposes PSEs pre- and post-stimulation for each  
791 40/60 condition are represented separately for *D)* Higher and *E)* Lower interoceptors.

792 Figure 3. *A)* R-locked HEP in the experimental synchronous (black) and asynchronous (red)  
793 conditions, and in the control synchronous (blue) and asynchronous (green) conditions, over  
794 frontal, central, and parietal sites in the right hemisphere. Although the enhanced reduction of  
795 the HEP amplitude seems to be greater in frontal sites, the statistical analysis including IAcc  
796 as a covariate shows that the HEP changes occur across all sites in the right hemisphere. *B)*  
797 ECG channel of a selected participant before (black) and after (red) applying ICA. This  
798 shows the effectiveness of ICA to remove CFA. *C)* Topographical maps showing differential  
799 HEP activity (synchronous trials – asynchronous trials) in the experimental and control  
800 conditions. *D)* HEP amplitude in the selected frontal ROI. *E)* Negative correlation between

801 IAcc scores and the synchrony effect (computed as the difference between synchronous and  
802 asynchronous trials) in the experimental *vs.* the control condition.

803 **Caption to tables:**

804 Table 1. Questionnaire scores in Experiment 1 and Experiment 2. Average (and SD) ratings  
805 for each question.