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Interoception and embodiment in patients with bilateral vestibulopathy

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1 Interoception and embodiment in patients with 2 bilateral vestibulopathy

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33 Abstract

34 There are tight functional and anatomical links between the vestibular and interoceptive systems, and both
35 systems have shown to fundamentally underlie emotional processes and our sense of a bodily self. Yet,
36 nothing is known about how long-term bilateral vestibulopathy (BVP) influences interoception and its
37 relation to embodiment and the sense of self. We thus compared cardiac interoceptive accuracy, confidence
38 in the performance, and general body awareness in 25 BVP patients and healthy controls using a heartbeat
39 tracking task, self-reports about interoceptive awareness, as well as measures of self-localization and of
40 self-body closeness. Results showed no difference between patients and controls regarding interoceptive
41 accuracy, confidence and body awareness, suggesting that long-term BVP does not influence cardiac
42 interoception. Patients and controls did not differ either regarding self-location and self-body closeness.
43 However, in our overall sample of patients and controls, we found that interoceptive accuracy increased
44 with perceived self-body closeness, suggesting that anchoring the self to the body is generally linked with
45 better cardiac interoception. This result is in line with previous suggestions of an important contribution
46 of interoception to the sense of embodiment.

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69 Introduction

70 Vestibular disorders are typically associated with deficits in balance and eye movements control. In
71 addition to these deficits in reflexes, higher-level functions are often affected [1]. While most research has
72 focused on spatial cognition, recent evidence in healthy participants suggests a vestibular contribution to
73 cognitive and emotional functions, such as own-body perception, mood, empathy, and decision making
74 [2]. In line with this, clinical studies showed that patients with **mainly unilateral peripheral** vestibular
75 **disorders** report increased separation of the self from the body, symptoms of depersonalization and
76 derealization (**reviewed in [3]**), **as well as** higher anxiety and depression (**reviewed in [4]**). Yet, the
77 mechanisms underlying such deficits remain poorly understood, and it has been emphasized that further
78 investigations are needed to better understand the full spectrum of high-level disorders associated with
79 **peripheral** vestibular deficits, in particular with bilateral **vestibulopathy (BVP)** [5].

80 One way through which vestibular disorders may affect own-body and self-perception as well as
81 emotional processes might be a change in the ability to perceive the internal states of the body.
82 Interoception is the sense of the internal physiological condition [6, 7], originating from receptors in the
83 gastrointestinal tract, kidneys, heart, blood vessels, etc. Interoception underpins emotional processes [7],
84 and like the vestibular system, it is fundamental to the multisensory mechanisms underlying own-body
85 and self perception [8–10]. Importantly, the vestibular and interoceptive systems are strongly
86 interconnected at both anatomical and functional levels. **Studies in animals showed that** vestibular signals
87 project to areas processing interoceptive signals in the brainstem, such as in the parabrachial nuclei, and
88 project to the insular cortex [11]. **Conversely, interoceptive signals – such as those generated by**
89 **mechanical stimulation of visceral receptors – can modulate the spontaneous firing rate of vestibular nuclei**
90 **neurons** [12]. At a functional level, both vestibular and interoceptive systems inform about self-motion
91 and gravity [11] and **they** interact to adapt blood pressure [13] **and respiratory pattern [14] to own body**
92 **movement and** orientation. **However**, direct studies investigating the link between vestibular and
93 interoceptive processes are to our knowledge lacking in the field of self-perception. It remains **especially**
94 unclear to what degree **BVP** influences interoception and its relation to embodiment and the sense of self.

95 The present study primarily aims at evaluating the influence of long-term **BVP** on interoception.
96 We measured the ability to perceive interoceptive signals using the heartbeat tracking task (HBTT), **during**
97 **which participants estimated the number of heartbeats felt during a given time interval [15, 16]. The**
98 **hypothesis about how BVP influences cardiac interoception is two-fold in that there is evidence to suggest**
99 **either an increase in interoceptive sensitivity or a decrease in interoceptive sensitivity. On the one hand,**
100 **considering that both vestibular and interoceptive signals contribute to own-body perception, BVP may**
101 **result in a higher reliance on interoceptive signals to maintain stable the perceived anchoring of the self to**
102 **the body, thus resulting in enhanced interoceptive sensitivity. Cross-modal plasticity and higher awareness**
103 **for intact sensory systems have been observed in many instances of sensory deprivation (reviewed in [17]),**
104 **such as in individuals with congenital blindness, showing higher odor awareness and lower odor detection**

105 threshold [18]. This mechanism might be prominent in the perception of gravity, shown to be crucial for
106 the experienced self-location: BVP patients missing head-centered vestibular organs may rely more on
107 information from trunk-centered inner organs typically linked to interoception [19]. On the other hand, the
108 loss of vestibular signals may alter the processing of interoceptive signals in multisensory brainstem and
109 cortical regions, thus decreasing interoceptive sensitivity. In line with this hypothesis is evidence of poorer
110 cardiac interoception in patients with olfactory deficits [20] and in patients with spinal cord injury [21]
111 when compared to healthy participants.

112 The secondary aim of the study is to evaluate the relation between the vestibular system, cardiac
113 interoception and the sense of embodiment. We measured interoceptive awareness using the Body
114 Perception Questionnaire (BPQ) [22]. BPQ scores have been positively correlated with gray matter volume
115 in the right anterior insula, a core region for interoception [23]. Furthermore, we tested two aspects of self-
116 location and analyzed them in relation to interoceptive abilities: (1) *Where* in the body is the self perceived,
117 and (2) *How strong* is the anchoring of the self to the body. Self-location can be measured by asking
118 participants to point on a human silhouette [24, 25]. Studies showed that most participants locate their self
119 either in their head or trunk. Head-locators and trunk-locators may differ on their interoceptive abilities
120 and personality traits [26, 27]. How strong the self is perceived to be anchored to the body can be measured
121 by pictorial descriptions of self-body closeness [28]. We hypothesized that patients with BVP may report
122 self-location differently than controls, potentially more around the trunk, a major egocentric reference
123 frame whose importance might be further increased through higher reliance on somatosensory [29] and
124 interoceptive signals.

125 126 **Methods**

127 *Participants*

128 We tested 25 patients with a BVP and 25 healthy controls matched for sex, age, education and body-mass
129 index (Table 1). All patients had weak responses to a bithermal caloric test with water at 44°C and 30°C
130 (mean slow phase eye velocity < 5°/s; left ear (mean ± SD): 44°C: 1.4 ± 2.3°/s, 30°C: 2.0 ± 2.6°/s; right
131 ear: 44°C: 1.8 ± 2.7°/s, 30°C: 2.5 ± 5.3°/s) and reduced responses to the video head impulse test (gain <
132 0.7; horizontal canals: 0.33 ± 0.27; anterior canals: 0.26 ± 0.23; posterior canals: 0.27 ± 0.24). Otolithic
133 functions were evaluated by cervical vestibular-evoked myogenic potentials (cVEMPs) over the
134 sternocleidomastoid muscles and ocular vestibular-evoked myogenic potentials (oVEMPs) over the
135 inferior oblique muscles. cVEMPs were present in the left ear for 9 patients (p13-n23 amplitude: 104 ± 36
136 μV) and in the right ear for 13 patients (75 ± 47 μV). oVEMPs were present in the left ear for 5 patients
137 (2.3 ± 1.4 μV) and in the right ear for 6 patients (3.4 ± 1.0 μV). Controls had no history of vestibular,
138 neurological, or psychiatric disease. All patients were right-handed (Edinburgh Handedness inventory: 97
139 ± 6%), 23 controls were right-handed (89 ± 13 %) and 2 were left-handed (-100%). All participants had
140 normal or corrected-to-normal vision. Anxiety and depression measured with the Hospital Anxiety and

141 Depression scale [30] did not differ between patients and controls (**Table 1**). All participants were
142 informed about the study and gave written informed consent. Procedures were approved by the Ethics
143 Committee and followed the Declaration of Helsinki.

144 ***Heartbeat tracking task: procedures and analyses***

146 Participants performed the HBTT following established procedures [16]. They sat comfortably on a stool
147 with their arms dangling and counted the heartbeats they felt between two identical sounds, defining six
148 time intervals of 25, 30, 35, 40, 45 and 50 s. They were instructed to count silently, without checking their
149 heartbeat manually by pressing a body part on the floor or against their seat. The experimenter controlled
150 that they followed the instructions. After each second sound, participants verbally indicated how many
151 heartbeats they perceived. The six time intervals were presented once in a randomized order using Superlab
152 4.5 (Cedrus, San Pedro, USA). Participants could take a break for as long as they wanted between trials.
153 Heartbeats were simultaneously recorded using FLAT Active electrodes (Biosemi, Amsterdam, The
154 Netherlands) placed on their sternum and left chest. For each time interval, an interoceptive accuracy score
155 was calculated using the following formula [16]:

$$156 \quad 1 - \frac{| \text{Recorded Heart Beats} - \text{Counted Heart Beats} |}{(\text{Counted Heart Beats} + \text{Recorded Heart Beats})/2}$$

157 Interoceptive accuracy scores can range from -1 to 1, indicating very poor to perfect performance. A mean
158 interoceptive accuracy score was calculated for each participant by averaging the accuracy scores over the
159 six time intervals.

160 Immediately after each trial, participants rated the confidence in their judgment on a vertical,
161 continuous visual analogue scale, using pencil and paper. The upper part of the scale referred to
162 “*Completely confident (perfect perception of my heartbeats)*” and the bottom part to “*Random answer (no*
163 *awareness of my heartbeats)*”. For each time interval, confidence ratings were measured in mm and
164 converted in percentage (Random answer: 0%; Completely confident: 100%). A mean confidence score
165 was calculated for each participant by averaging the accuracy scores over the six time intervals.

166 ***Body awareness***

168 Participants rated 45 items from the body awareness subscale of the BPQ [22]. They rated how aware they
169 are of their bodily processes using a five-point scale ranging from “never” to “always”. One patient did
170 not answer the questionnaire.

171 ***Self-location***

172 Self-location was measured by a pointing task [31] on a computer screen (1366 × 768 pixels). After they
173 read the instructions “*Where do you locate your ‘self’? On this picture representing a body, indicate the*
174 *location (a single point) which according to you best represents the location of the self*”, participants were
175 shown a human silhouette of their own sex, once from the front, once from the back, and once from the
176 profile (**Figure 2A**), in a randomized order. With a computer mouse in their dominant hand they clicked
177 on a point of the silhouette that best described the location of their self. Instructions and pictures were
178

179 presented with PsychoPy [32], which also recorded the coordinates of pointing. One control did not
180 complete the task.

181 *Self-body closeness*

182 Participants reported the perceived closeness between self-body, self-immediate body environment,
183 body-immediate body environment, and self-others using simple pictorial descriptions [28] adapted from
184 the Inclusion of Other in the Self scale [33] (**Figure 3**). They reported the average perception over the last
185 year. Participants selected 1 out of 7 pictorial descriptions of the closeness between, e.g., their self and
186 body, whereby two distinct circles represent clear separation between their self and body (score = 1) and
187 two overlapping circles represent maximal closeness between their self and body (score = 7).
188

189 *Organization of a session*

190 Participants completed the HBTT, BPQ, self-location and self-body closeness tasks in a random order.
191

192 *Statistical analyses*

193 As most of the dependent variables were not normally distributed (Shapiro-Wilk test), we used non-
194 parametric procedures (SPSS 25, IBM, USA): inter-group differences were analyzed using Mann-Whitney
195 U tests and Spearman correlations were used to analyze links between self-body closeness and cardiac
196 interoception. Differences were considered significant for $p < 0.05$.
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200 **Results**

201 *Interoceptive accuracy, confidence and body awareness*

202 We found no significant difference between patients and controls regarding their interoceptive accuracy
203 ($U = 261.5$, $Z = -0.99$, $p = 0.32$) and confidence in their judgment ($U = 287.0$, $Z = -0.50$, $p = 0.62$; **Fig.**
204 **1A**). Similarly, body awareness as measured by BPQ scores did not differ significantly between patients
205 and controls ($U = 287.0$, $Z = -0.02$, $p = 0.98$; **Fig. 1B**).
206

207 *Self-location and its relation to cardiac interoception*

208 Results from the pointing task revealed no significant difference in the coordinates of self-location between
209 patients and controls for the front (x: $U = 246.0$, $Z = -1.49$, $p = 0.14$; y: $U = 273.0$, $Z = -0.98$, $p = 0.33$),
210 back (x: $U = 290.0$, $Z = -0.66$, $p = 0.51$; y: $U = 308.0$, $Z = -0.32$, $p = 0.75$) and side (x: $U = 257.0$, $Z = -$
211 1.28 , $p = 0.20$; y: $U = 296.0$, $Z = -0.55$, $p = 0.59$) views of the body (**Fig. 2A**).
212

213 In a second step, patients and controls were allocated to the *head-locator and trunk-locator* groups,
214 corresponding to any self-location above or below the neck, respectively: 12 patients and 13 controls were
215 head-locators; 13 patients and 11 controls were trunk-locators (**Fig. 2B**). The proportion of head- and
216 trunk-locators was similar in both groups ($\chi^2 = 0.19$, $p = 0.78$). Head- and trunk-locators did not differ
217 regarding their interoceptive accuracy (patients: $U = 69.5$, $Z = -0.46$, $p = 0.64$; controls: $U = 67.0$, $Z = -$
218 0.26 , $p = 0.79$), confidence judgment (patients: $U = 66.0$, $Z = -0.65$, $p = 0.51$; controls: $U = 47.5$, $Z = 1.39$,
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218 p = 0.16) and body awareness (patients: $U = 60.5$, $Z = -0.64$, $p = 0.52$; controls: $U = 51.5$, $Z = -0.89$, $p =$
219 0.37) (**Fig. 2C**). In addition, there was no difference between patients and controls from the head-location
220 group (interoceptive accuracy: $U = 54.5$, $Z = -1.28$, $p = 0.20$; confidence: $U = 68.5$, $Z = -0.52$, $p = 0.60$;
221 body awareness: $U = 76.0$, $Z = -0.05$, $p = 0.96$) and no difference between patients and controls from the
222 trunk-location group (interoceptive accuracy: $U = 69.0$, $Z = -0.14$, $p = 0.88$; confidence: $U = 53.0$, $Z = -$
223 1.07, $p = 0.28$; body awareness: $U = 72.0$, $Z = -0.27$, $p = 0.78$).

224 ***Perceived self-body closeness and its relation to cardiac interoception***

225 **Fig. 3** shows that patients and controls did not differ significantly regarding the perceived strength of
226 closeness between their self and body ($U = 250.0$, $Z = -0.83$, $p = 0.41$), self and immediate body
227 environment ($U = 285.5$, $Z = -0.05$, $p = 0.96$), body and immediate body environment ($U = 262.0$, $Z = -$
228 0.54, $p = 0.59$), or self and others ($U = 282.0$, $Z = -0.13$, $p = 0.90$). However, we note large interindividual
229 variability in these judgments, which were explored in correlation analyzes.

230
231 Our exploratory analyzes significantly related self-body closeness and cardiac interoception. In
232 the overall population, interoceptive accuracy correlated positively with self-body closeness ($\rho = 0.31$, p
233 = 0.03), indicating that stronger anchoring of the self to the body was associated with better cardiac
234 interoception (**Fig. 4A**). Conversely, interoceptive accuracy negatively correlated with self-environment
235 closeness ($\rho = -0.29$, $p = 0.04$), showing that lower anchoring of the self to the body was linked to lower
236 cardiac interoception (**Fig. 4B**). Yet, when considering each group separately, interoceptive accuracy did
237 not correlate with self-body closeness (patients: $\rho = 0.28$, $p = 0.18$; controls: $\rho = 0.37$, $p = 0.07$) and self-
238 environment closeness (patients: $\rho = -0.35$, $p = 0.08$; controls: $\rho = -0.23$, $p = 0.26$).

239 In the overall population, body awareness (BPQ scores) was also positively correlated with self-
240 body closeness ($\rho = 0.31$, $p = 0.03$; **Fig. 4C**), pointing to a link between interoceptive awareness and
241 embodiment. BPQ scores did not correlate with self-body closeness in the patients ($\rho = 0.28$, $p = 0.19$)
242 and in the controls ($\rho = 0.38$, $p = 0.07$) when considered separately. Finally, in the whole population, self-
243 body closeness did not correlate with anxiety ($\rho = -0.23$, $p = 0.11$) and depression ($\rho = -0.20$, $p = 0.16$).
244 However, self-body closeness was negatively correlated with anxiety ($\rho = -0.41$, $p = 0.04$) and depression
245 ($\rho = -0.54$, $p = 0.005$) in the patients, but not the in controls (anxiety: $\rho = -0.16$, $p = 0.44$; depression: $\rho =$
246 0.02, $p = 0.93$).

247 **Discussion**

248
249 The tasks used here revealed no difference between **BVP** patients and a carefully matched control group
250 regarding their interoceptive accuracy, body awareness, self-location, and self-body closeness. Such
251 negative findings are difficult to interpret and it cannot be excluded that differences could be found with
252 other measures of interoception (see [34] for a critical account of the HBTT), or with larger samples.
253 Nevertheless, our results help to better delineate the range of perceptual and cognitive deficits associated
254 with **BVP**. The general trend to publish only positive results might bias the understanding of the patients?

255 symptomatology. Negative findings should thus be reported more systematically in clinical neuroscience
256 to avoid such bias. Furthermore, explorative correlative analyses revealed a relation between interoception
257 and self-body closeness, which might be important to consider in future studies.

258 **No evidence for a change in cardiac interoception in bilateral vestibulopathy**

259 Our results show no **significant** difference between **BVP** patients and controls in the tasks we used,
260 suggesting that a long-lasting **BVP** does not change cardiac sensitivity or interoceptive awareness [35].
261 **The results do not support the hypothesis of increased interoceptive sensitivity, suggesting that BVP does**
262 **not involve higher focus on interoception through higher reliance on signals from trunk-centered inner**
263 **organs. Likewise, the results do not support the hypothesis of decreased cardiac interoceptive sensitivity**
264 **in BVP that may arise from altered interoceptive information processing in multisensory brainstem and**
265 **cortical regions. Our findings contrast with alterations of cardiac interoception also measured with the**
266 **HBTT in patients with olfactory [20] and sensorimotor deficits [21].**

267 **The lack of significant difference found in our study might be explained by several factors. First,**
268 **the absence of effect of BVP on cardiac interoception may reflect a lack of relevance of vestibular signals**
269 **for cardiac interoception or the poor interactions between these systems. This seems in contrast with the**
270 **wealth of data on the anatomical and functional interplay between the vestibular and interoceptive systems,**
271 **including the cardiovascular system [12–14, 36]. There is, for example, evidence that stimulation of the**
272 **semi-circular canals can change the respiratory frequency in healthy participants, whereas this effect is not**
273 **consistent in patients with BVP [14]. Similarly, caloric vestibular stimulation changed heart rate variability**
274 **and blood pressure variability in healthy participant, an effect which was absent in a patient with BVP**
275 **[36]. Second, the absence of effect of BVP on cardiac interoception may be related to the fact that BVP**
276 **patients were tested years after the onset of the disease. Future studies should test whether a similar result**
277 **is found in the acute phase of the BVP. Third, we only assessed cardiac interoception, while other aspects**
278 **of interoception, e.g. related to graviceptors in the viscera, have not been measured. It is still an open**
279 **debate to what extent a common interoceptive ability exists and how much from cardiac interoception can**
280 **be generalized to other interoceptive systems [37]. Future studies should therefore investigate the link**
281 **between vestibular information processing and other interoceptive signals, such as respiratory or gastric**
282 **signals. Although graviceptors in the viscera contribute to encode own-body orientation in healthy**
283 **participants [38], it remains to be established whether this information is used differently in BVP patients**
284 **and if it also contributes significantly to an embodied sense of self.**

285 **No difference in perceived self-location and self-body closeness in bilateral vestibulopathy**

286
287 Self-reports showed no difference between patients and controls regarding *where* in their body the self
288 was perceived and *how strong* the self was perceived as anchored to the body. The vestibular system has
289 been described as crucially involved in **perceiving** self-location within the bodily borders (**reviewed in**
290 **[8]). A higher occurrence of sensations of detachment of the self from the body has been reported in a**

292 sample of 60 patients with mainly unilateral peripheral vestibular disorders than in sex- and age-matched
293 healthy participants [39]. A prospective study in 210 patients suffering from vertigo and dizziness showed
294 that full-blown out-of-body experiences were also more frequent in patients with documented unilateral
295 peripheral vestibular disorders than in sex- and age-matched healthy participants [40]. Second, there is
296 evidence that galvanic vestibular stimulation in healthy participants can modulate the anchoring of the self
297 to the body as measured by tactile perception tasks [41]. Thus, while the vestibular system might be
298 important for an embodied self-location, self-reports used in our study showed no effect of BVP on self-
299 location and on the perceived self–body closeness.

300 In acute peripheral vestibular disorders (and during artificial vestibular stimulation in healthy
301 participants), the central nervous system receives signals from the inner ear about self-motion and self-
302 orientation that are incongruent with visual and somatosensory signals, thereby creating sensory mismatch
303 and perceptual incoherence. By contrast, as vestibular information is missing in BVP patients, it does not
304 conflict with (or confirm) visual and somatosensory encoding of self-motion. We argue that the absence
305 of sensory mismatch in BVP may account for normal self-location and self–body closeness in the present
306 study. In line with this idea, patients with a long history of BVP show similar abilities than controls to take
307 another person’s viewpoint, thus to mentally detached oneself from an embodied self-location [28]. By
308 contrast, this perspective-taking task is influenced by vestibular stimulation on a rotatory chair in healthy
309 participants [42], and is impaired in patients with unilateral vestibular failure (benign paroxysmal
310 positional vertigo and acute vestibular neuritis) [43].

311 The self-localization task and the measure of self–body closeness yielded congruent results with
312 previous studies in younger participants. As in previous studies, both groups localized their self either in
313 their head or trunk [24, 25], and presented a similar degree of self–body closeness using an adaptation of
314 the Inclusion of Other in the Self scale [28]. We also found a similar proportion of head- and trunk-locators.
315 These interindividual differences in the perceived self-location have been related to cultural factors and
316 personality traits [26]. Pioneering studies [e.g. 44] related self-location in the head to the origin of the
317 multimodal, but mainly visual, first-person perspective. Self-location in the trunk, especially near the heart,
318 was found in participants characterizing themselves as emotional, feminine and interpersonally warm [26].
319 Finally, we found no relation between head/trunk-location and interoceptive accuracy or body awareness,
320 and could therefore not support the hypothesis that trunk-locators used cardiac interoceptive information
321 differently.

322 **Higher self–body closeness is associated with better interoceptive accuracy**

323 Independent of the group, we found in an exploratory analysis, that interoceptive accuracy was positively
324 correlated to self–body closeness and negatively correlated with self–environment closeness. This suggests
325 that stronger anchoring of the self to the body, i.e. embodiment, is linked to better capacity to perceive and
326 report cardiac interoceptive signals. In line with this finding, there is evidence that cardiac interoceptive
327 accuracy can predict the malleability of body representations as measured by a multisensory illusion in
328

329 healthy participants (i.e. the rubber hand illusion [45]). Furthermore, body awareness (BPQ scores) also
1 330 increased with self–body closeness, supporting the idea that a stronger sense of embodiment co-occurs
2 331 with higher awareness of signals from internal organs. Finally, we found that self–body closeness
3 332 decreased with increasing anxiety and depression in BFV patients, but not in controls, despite the fact that
4 333 controls and patients do not differ in their anxiety and depression score. A recent prospective study
5 334 reported that anxiety was a predictor of out-of-body experiences in patients suffering from dizziness and
6 335 vertigo, but not in healthy controls [40]. Altogether, these results highlight the interplay between anxiety,
7 336 depression and depersonalization-derealization symptoms in patients with vestibular disorders [40, 46,
8 337 47].
9 338

16 339 **Limitations of the study and perspectives**

18 340 Here, self-location was reduced to the coordinates of a single point in space, although self-location has
19 341 also been defined as a volume occupied by the self in space [8], and has even been linked to peripersonal
20 342 space [48]. Future studies should endeavor to measure self-location in BVP patients using tasks allowing
21 343 3D measures of self-location, e.g. using virtual reality [49], or measures of the peripersonal space
22 344 boundaries. We also note that our negative findings may also be due to the fact that we used only self-
23 345 reports to measure the *perceived* self–body closeness, rather than objective measures. Other measures have
24 346 been proposed where participants explicitly evaluate their self-location and self-identification with an
25 347 avatar shown in a head-mounted display in virtual reality. For example, when participants received a tactile
26 348 stimulation on their back and observed an avatar being stroked at the same time on the same body region,
27 349 they self-identified with the avatar and localized themselves closer to it (i.e., disembodied self-location)
30 350 [49]. It will be important in future studies to investigate how BVP patients experience self–body closeness
31 351 during experimentally-induced sensations of disembodied self-location.
32 352

38 353 **Conclusions**

40 354 The present study should help understand the complex symptomatology of patients with BVP, who present
41 355 with deficits reaching far beyond the well-known imbalance and oscillopsia, including alterations of the
42 356 most fundamental aspects of the self.
43 357
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45 359

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54 362 funding from the Swiss National Science Foundation (grant number: PP00P1_170511).
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365 **Figure Legends**

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3 367 **Figure 1. Cardiac interoception.** (A) Interoceptive accuracy and confidence in the judgment for **BVP**
4 patients (*red*) and healthy controls (*green*). (B) Score to the body awareness scale of the Body Perception
5 368 Questionnaire for **BVP** patients (*red*) and controls (*green*). Box and whiskers plots show medians and
6 369 interquartile ranges (10–90). Means are shown as + and dots are outliers.

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11 372 **Figure 2. Self-location and its relation to cardiac interoception.** (A) Self-location indicated by patients
12 (*red dots*) and controls (*green squares*) on a human silhouette seen from the back, profile and front. (B)
13 373 Histograms show the number of participants according to the y coordinates of self-location. (C)
14 374 Interoceptive accuracy compared in head- and trunk-locators for the patients (*red*) and controls (*green*).
15 375 Box and whiskers plots show medians and interquartile ranges (10–90). Means are shown as + and dots
16 376 are outliers.

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21 379 **Figure 3. Reported self–body closeness.** Seven pairs of circles at the bottom of the figure were presented
22 to participants, who had to indicate which one better represented the perceived degree of closeness between
23 380 two items, such as their self and body. Box and whiskers plots show medians and interquartile ranges (10–
24 381 90). Means are shown as + and dots are outliers.

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29 384 **Figure 4. Relation between self–body closeness, cardiac interoception and body awareness.**
30 385 Correlation between interoceptive accuracy and self–body closeness (A), between interoceptive accuracy
31 386 and self–environment closeness (B) and between body awareness (BPQ score) and self–body closeness
32 387 (C).

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400 **References**

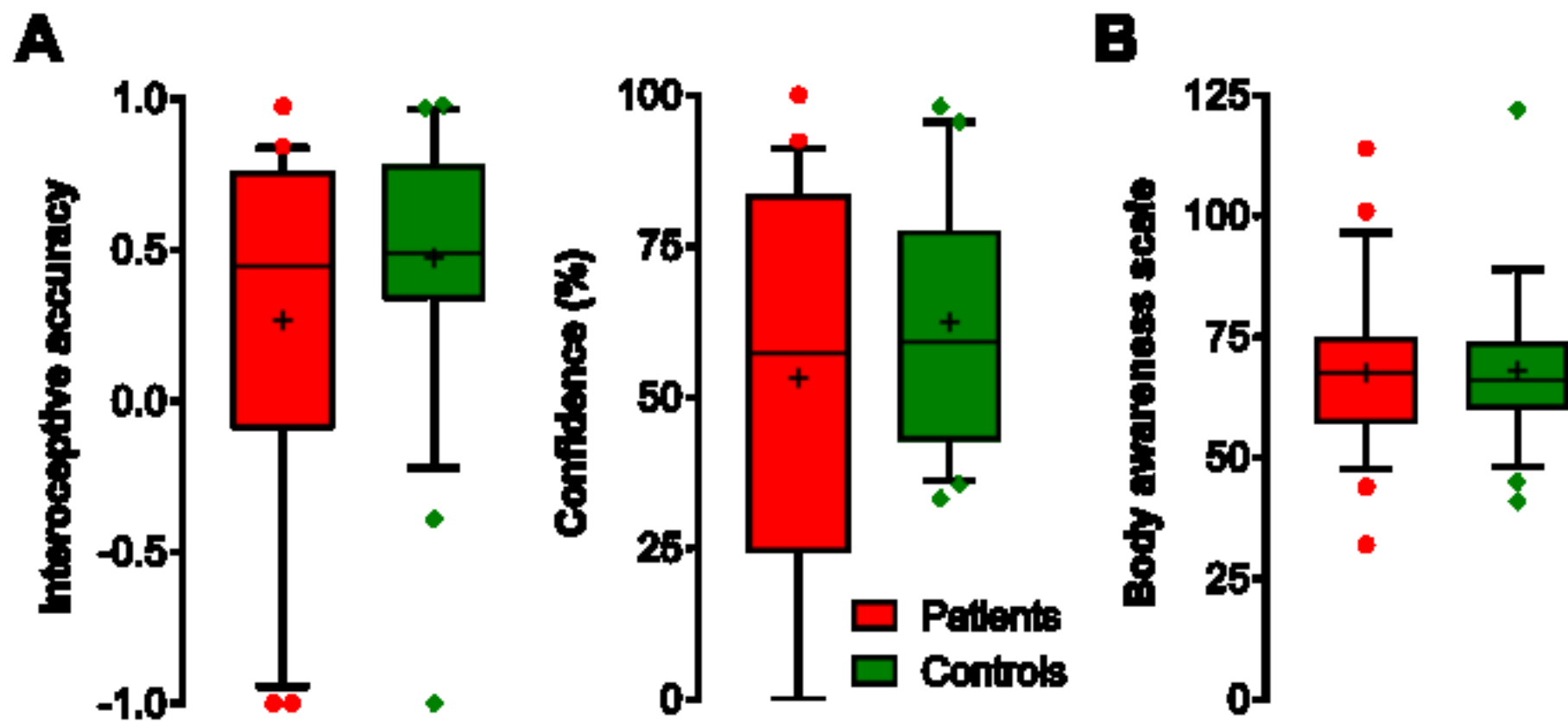
- 1
2 401 1. Smith PF (2017) The vestibular system and cognition. *Curr Opin Neurol* 30:84–89.
3
4 402 <https://doi.org/10.1097/WCO.0000000000000403>
- 5 403 2. Lopez C (2016) The vestibular system: balancing more than just the body. *Curr Opin Neurol*
6
7 404 29:74–83. <https://doi.org/10.1097/WCO.0000000000000286>
- 8
9 405 3. Jauregui-Renaud K (2015) Vestibular function and depersonalization/derealization symptoms.
10 406 *Multisens Res* 28:637–651
- 11
12 407 4. Jacob RG, Furman JM (2001) Psychiatric consequences of vestibular dysfunction. *Curr Opin*
13
14 408 *Neurol* 14:41–46
- 15 409 5. Lucieer F, Duijn S, Van Rompaey V, et al (2018) Full Spectrum of Reported Symptoms of
16
17 410 Bilateral Vestibulopathy Needs Further Investigation—A Systematic Review. *Front Neurol* 9:.
18
19 411 <https://doi.org/10.3389/fneur.2018.00352>
- 20 412 6. Craig AD (2003) Interoception: the sense of the physiological condition of the body. *Curr Opin*
21
22 413 *Neurobiol* 13:500–505
- 23
24 414 7. Khalsa SS, Adolphs R, Cameron OG, et al (2018) Interoception and Mental Health: A Roadmap.
25 415 *Biol Psychiatry Cogn Neurosci Neuroimaging* 3:501–513.
26
27 416 <https://doi.org/10.1016/j.bpsc.2017.12.004>
- 28
29 417 8. Blanke O (2012) Multisensory brain mechanisms of bodily self-consciousness. *Nat Rev Neurosci*
30 418 13:556–571. <https://doi.org/10.1038/nrn3292>
- 31
32 419 9. Azzalini D, Rebollo I, Tallon-Baudry C (2019) Visceral Signals Shape Brain Dynamics and
33
34 420 Cognition. *Trends Cogn Sci (Regul Ed)* 23:488–509. <https://doi.org/10.1016/j.tics.2019.03.007>
- 35 421 10. Park H-D, Blanke O (2019) Coupling Inner and Outer Body for Self-Consciousness. *Trends Cogn*
36
37 422 *Sci (Regul Ed)* 23:377–388. <https://doi.org/10.1016/j.tics.2019.02.002>
- 38
39 423 11. Craig AD (2009) How do you feel-now? The anterior insula and human awareness. *Nat Rev*
40 424 *Neurosci* 10:59–70. <https://doi.org/nrn2555> [pii] 10.1038/nrn2555
- 41
42 425 12. Dutov AM (1974) Responses of neurons of the vestibular nuclei to interoceptive stimulation.
43
44 426 *Bulletin of Experimental Biology and Medicine* 78:849–851
- 45 427 13. Balaban CD, Porter JD (1998) Neuroanatomic substrates for vestibulo-autonomic interactions. *J*
46
47 428 *Vestib Res* 8:7–16
- 48
49 429 14. Jauregui-Renaud K, Gresty MA, Reynolds R, Bronstein AM (2001) Respiratory responses of
50 430 normal and vestibular defective human subjects to rotation in the yaw and pitch planes. *Neurosci*
51
52 431 *Lett* 298:17–20. <https://doi.org/S0304394000017316> [pii]
- 53
54 432 15. Schandry R (1981) Heart beat perception and emotional experience. *Psychophysiology* 18:483–
55 433 488
- 56
57 434 16. Garfinkel SN, Seth AK, Barrett AB, et al (2015) Knowing your own heart: Distinguishing
58
59 435 interoceptive accuracy from interoceptive awareness. *Biological Psychology* 104:65–74.

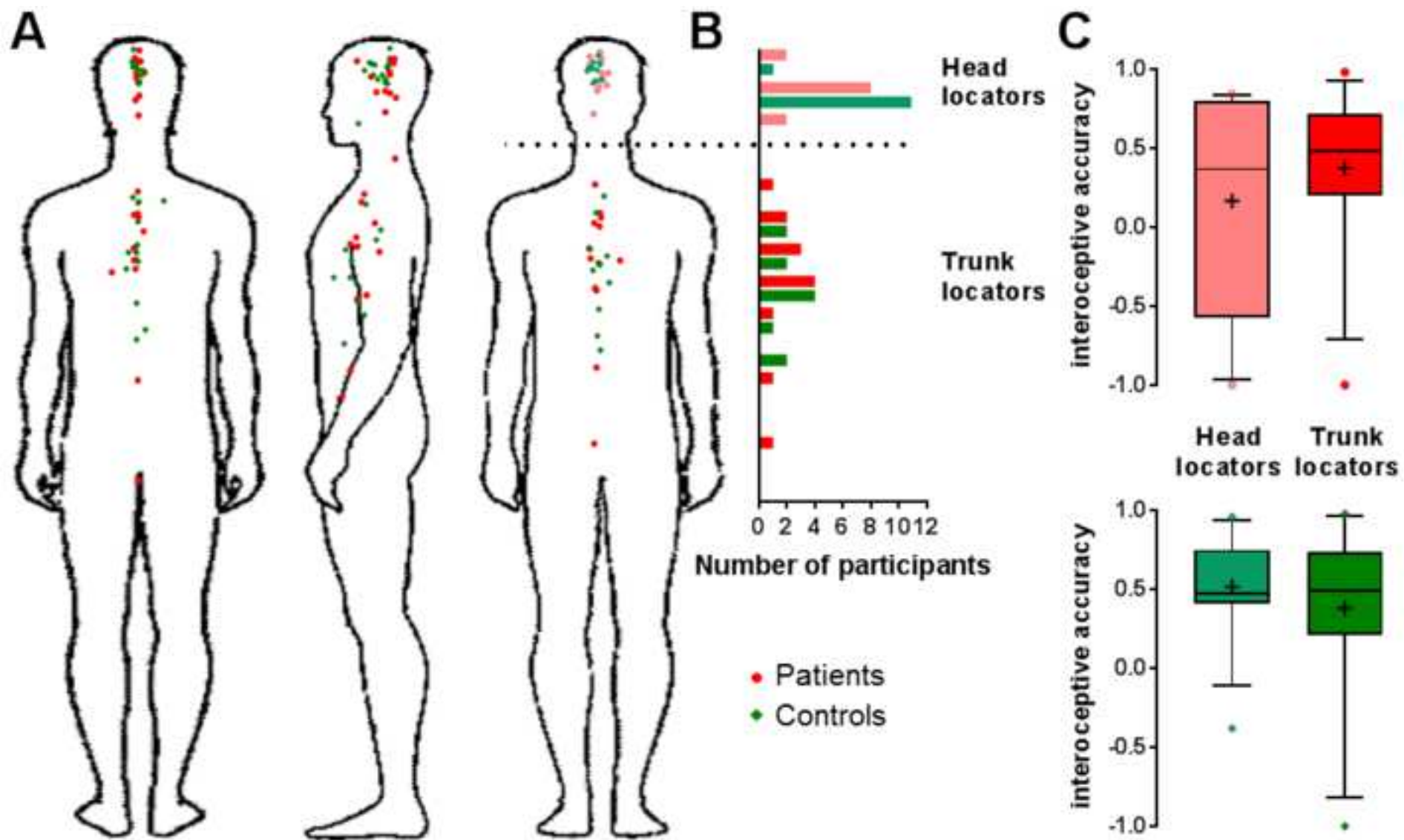
- 436 <https://doi.org/10.1016/j.biopsycho.2014.11.004>
- 1 437 17. Frasnelli J, Collignon O, Voss P, Lepore F (2011) Crossmodal plasticity in sensory loss. *Prog*
2 *Brain Res* 191:233–249. <https://doi.org/10.1016/B978-0-444-53752-2.00002-3>
- 3 438
- 4 439 18. Beaulieu-Lefebvre M, Schneider FC, Kupers R, Ptito M (2011) Odor perception and odor
5 awareness in congenital blindness. *Brain Research Bulletin* 84:206–209.
6
7 440
8 441 <https://doi.org/10.1016/j.brainresbull.2010.12.014>
- 9 442 19. Mittelstaedt H (1992) Somatic versus vestibular gravity reception in man. *Ann N Y Acad Sci*
10 656:124–39
11 443
- 12 444 20. Krajnik J, Kollndorfer K, Notter LA, et al (2015) The impact of olfactory dysfunction on
13 interoceptive awareness. *Psychophysiology* 52:263–268. <https://doi.org/10.1111/psyp.12316>
- 14 445
- 15 446 21. Montoya P, Schandry R (1994) Emotional experience and heartbeat perception in patients with
16 spinal cord injury and control subjects. *J Psychophysiol* 8:289–296
17 447
- 18 448 22. Cabrera A, Kolacz J, Pailhez G, et al (2018) Assessing body awareness and autonomic reactivity:
21 Factor structure and psychometric properties of the Body Perception Questionnaire-Short Form
22 449 (BPQ-SF). *Int J Methods Psychiatr Res* 27:e1596. <https://doi.org/10.1002/mpr.1596>
- 23 450
- 24 451 23. Critchley HD, Wiens S, Rotshtein P, et al (2004) Neural systems supporting interoceptive
26 awareness. *Nat Neurosci* 7:189–95
27 452
- 28 453 24. Starmans C, Bloom P (2012) Windows to the soul: Children and adults see the eyes as the
29 location of the self. *Cognition* 123:313–318. <https://doi.org/10.1016/j.cognition.2012.02.002>
- 30 454
- 31 455 25. Limanowski J, Hecht H (2011) Where do we stand on locating the self? *Psychology* 02:312–317.
32 <https://doi.org/10.4236/psych.2011.24049>
- 33 456
- 34 457 26. Fetterman AK, Robinson MD (2013) Do you use your head or follow your heart? Self-location
36 predicts personality, emotion, decision making, and performance. *J Pers Soc Psychol* 105:316–
37 458 334. <https://doi.org/10.1037/a0033374>
- 38 459
- 39 460 27. Porciello G, Daum MM, Menghini C, et al (2016) Not That Heart-Stopping After All: Visuo-
41 Cardiac Synchrony Does Not Boost Self-Face Attribution. *PLoS ONE* 11:e0160498.
42 461 <https://doi.org/10.1371/journal.pone.0160498>
- 43 462
- 44 463 28. Deroualle D, Toupet M, van Nchel C, et al (2017) Anchoring the Self to the Body in Bilateral
46 Vestibular Failure. *PLoS ONE* 12:e0170488. <https://doi.org/10.1371/journal.pone.0170488>
- 47 464
- 48 465 29. Strupp M, Arbusow V, Dieterich M, et al (1998) Perceptual and oculomotor effects of neck
49 muscle vibration in vestibular neuritis. Ipsilateral somatosensory substitution of vestibular
50 466 function. *Brain* 121:677–85.
51 467
- 52 468 30. Zigmond AS, Snaith RP (1983) The hospital anxiety and depression scale. *Acta Psychiatr Scand*
53 67:361–370
54 469
- 55 470 31. Limanowski J, Hecht H (2011) Where Do We Stand on Locating the Self? *Psychology* 02:312.
56 <https://doi.org/10.4236/psych.2011.24049>
- 57 471
- 58 472 32. Peirce JW (2007) PsychoPy - Psychophysics software in Python. *J Neurosci Methods* 162:8–13
59
60
61
62
63
64
65

- 473 33. Aron A, Aron EN, Smollan D (1992) Inclusion of Other in the Self Scale and the structure of
1 474 interpersonal closeness. *Journal of Personality and Social Psychology* 63:596–612.
2
3 475 <https://doi.org/10.1037/0022-3514.63.4.596>
4
5 476 34. Ring C, Brener J (2018) Heartbeat counting is unrelated to heartbeat detection: A comparison of
6 477 methods to quantify interoception. *Psychophysiology* 55:e13084.
7
8 478 <https://doi.org/10.1111/psyp.13084>
9
10 479 35. Garfinkel SN, Seth AK, Barrett AB, et al (2015) Knowing your own heart: distinguishing
11 480 interoceptive accuracy from interoceptive awareness. *Biol Psychol* 104:65–74.
12
13 481 <https://doi.org/10.1016/j.biopsycho.2014.11.004>
14
15 482 36. Jauregui-Renaud K, Yarrow K, Oliver R, et al (2000) Effects of caloric stimulation on respiratory
16 483 frequency and heart rate and blood pressure variability. *Brain Res Bull* 53:17–23.
17
18 484 [https://doi.org/10.1016/s0361-9230\(00\)00304-x](https://doi.org/10.1016/s0361-9230(00)00304-x)
19
20 485 37. Garfinkel SN, Manassei MF, Hamilton-Fletcher G, et al (2016) Interoceptive dimensions across
21 486 cardiac and respiratory axes. *Philos Trans R Soc Lond, B, Biol Sci* 371:.
22
23 487 <https://doi.org/10.1098/rstb.2016.0014>
24
25 488 38. Trousselard M, Barraud P, Nougier V, et al (2004) Contribution of tactile and interoceptive cues
26 489 to the perception of the direction of gravity. *Brain Res Cogn Brain Res* 20:355–362.
27
28 490 <https://doi.org/10.1016/j.cogbrainres.2004.03.008>
29
30 491 39. Lopez C, Nakul E, Preuss N, et al (2018) Distorted own-body representations in patients with
31 492 dizziness and during caloric vestibular stimulation. *J Neurol* 265:86–94.
32
33 493 <https://doi.org/10.1007/s00415-018-8906-8>
34
35 494 40. Lopez C, Elzière M (2018) Out-of-body experience in vestibular disorders - A prospective study
36 495 of 210 patients with dizziness. *Cortex* 104:193–206. <https://doi.org/10.1016/j.cortex.2017.05.026>
37
38 496 41. Ferrè ER, Lopez C, Haggard P (2014) Anchoring the self to the body: vestibular contribution to
39 497 the sense of self. *Psychol Sci* 25:2106–2108. <https://doi.org/10.1177/0956797614547917>
40
41 498 42. Deroualle D, Borel L, Devèze A, Lopez C (2015) Changing perspective: The role of vestibular
42 499 signals. *Neuropsychologia* 79, Part B:175–185.
43
44 500 <https://doi.org/10.1016/j.neuropsychologia.2015.08.022>
45
46 501 43. Candidi M, Micarelli A, Viziano A, et al (2013) Impaired mental rotation in benign paroxysmal
47 502 positional vertigo and acute vestibular neuritis. *Front Hum Neurosci* 7:783.
48
49 503 <https://doi.org/10.3389/fnhum.2013.00783>
50
51 504 44. Claparède E (1925) Note sur la localisation du moi. *Archives de Psychologie* 19:172–182
52
53 505 45. Tsakiris M, Tajadura-Jiménez A, Costantini M (2011) Just a heartbeat away from one’s body:
54 506 interoceptive sensitivity predicts malleability of body-representations. *Proc Biol Sci* 278:2470–
55 507 2476. <https://doi.org/10.1098/rspb.2010.2547>
56
57 508 46. Tschan R, Wiltink J, Adler J, et al (2013) Depersonalization experiences are strongly associated
58 509 with dizziness and vertigo symptoms leading to increased health care consumption in the German
59
60
61
62
63
64
65

510 general population. *J Nerv Ment Dis* 201:629–635.
1 511 <https://doi.org/10.1097/NMD.0b013e3182982995>
2
3 512 47. Kolev OI, Georgieva-Zhostova SO, Berthoz A (2014) Anxiety changes depersonalization and
4
5 513 derealization symptoms in vestibular patients. *Behav Neurol* 2014:847054.
6
7 514 <https://doi.org/10.1155/2014/847054>
8
9 515 48. Noel J-P, Pfeiffer C, Blanke O, Serino A (2015) Peripersonal space as the space of the bodily
10 516 self. *Cognition* 144:49–57. <https://doi.org/10.1016/j.cognition.2015.07.012>
11 517 49. Nakul E, Orlando-Dessaints N, Lenggenhager B, Lopez C (2020) Measuring perceived self-
12 location in virtual reality. *Sci Rep* 10:6802. <https://doi.org/10.1038/s41598-020-63643-y>
13 518
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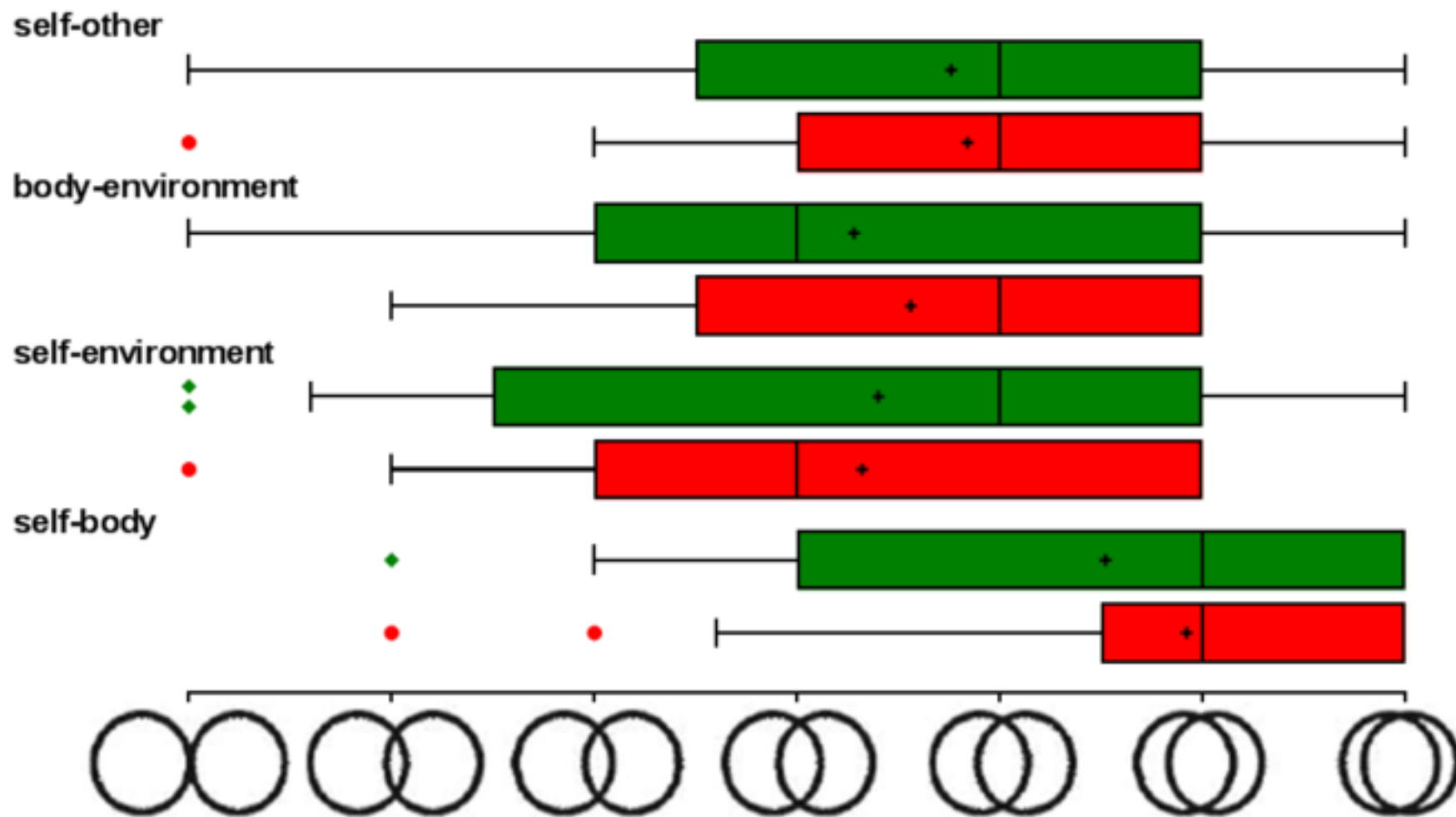


Figure 4



	Patient	Controls	Statistics
Males/Females (n)	11/14	11/14	–
Age (years)	60 ± 13	61 ± 11	t = -0.43, p = 0.67
Education (%)			
Level 1	8	4	$\chi = 3.72, p = 0.45$
Level 2	4	8	
Level 3	16	20	
Level 4	32	12	
Level 5	40	56	
Body-mass index	24 ± 4	24 ± 3	t = -0.10, p = 0.92
Anxiety score	8.3 ± 2.5	7.1 ± 3.1	t = -0.63, p = 0.53
Depression score	4.0 ± 2.4	3.7 ± 2.6	t = 0.34, p = 0.74

Table 1. Demographic and clinical characteristics of BVP patients and healthy controls. Highest education level according to the French education system; Level 1: before high school; Level 2: accomplished high school; Level 3: two years after high school; Level 4: Bachelor's degree, Level 5: Master's degree, Engineering degree, PhD, MD. Mean ± SD. Anxiety and depression scores were measured with the Hospital Anxiety and Depression scale.