

1 **Title: Induced illusory body ownership in Borderline Personality Disorder**

2
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46 **Abstract**

47 **Background:** One aspect of selfhood that may have relevance for Borderline Personality
48 Disorder (BPD) is variation in sense of body ownership. We employed the rubber hand illusion
49 (RHI) to manipulate sense of body ownership in BPD. We extended previous research on
50 illusory body ownership in BPD by testing: 1) two illusion conditions: asynchronous &
51 synchronous stimulation, 2) relationship between Illusion experience and core BPD symptoms,
52 and 3) relationship between illusion experience maladaptive personality traits.
53

54 **Methods:** Participants (24 BPD, 21 control) underwent RHI procedures. We measured illusion
55 strength (questionnaire responses), proprioceptive drift (perceived shift in physical hand
56 position), BPD symptoms (DIB-R score), and maladaptive personality traits (PID-5).
57

58 **Results:** For subjective illusion strength, we found a main effect of group (BPD > HC, $F = 11.94$
59 $p = 0.001$), and condition (synchronous > asynchronous, $F(1,43) = 22.80$, $p < 0.001$). There was
60 a group x condition interaction for proprioceptive drift ($F(1,43) = 6.48$, $p = 0.015$) such that
61 people with BPD maintained illusion susceptibility in the asynchronous condition. Borderline
62 symptom severity correlated with illusion strength within the BPD group, and this effect was
63 specific to affective symptoms ($r = 0.481$, $p < 0.01$). Across all participants, trait psychoticism
64 correlated with illusion strength ($r = 0.481$, $p < 0.01$).
65

66 **Conclusion:** People with BPD are more susceptible to illusory body ownership than are healthy
67 controls. This result is consistent with the robust clinical literature describing aberrant physical
68 and emotional experience of self in BPD. A predictive coding interpretation of these results
69 holds promise to develop testable mechanistic hypotheses for experiences of disrupted bodily
70 self in BPD.
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80 **1. Introduction**

81 *1.1. The embodied self in Borderline Personality Disorder*

82 *1.1.1. Self-disturbance is a core feature of BPD*

83 Aberrations of self-experience and identity are considered a core symptoms of
84 Borderline Personality Disorder (BPD) [1]. Self-disturbance is characterized by a markedly
85 persistent unstable sense of self that can be realized by dramatic shifts in self-image, shifting
86 goals and values, and feelings of emptiness, dissociation, and non-existence [2, 3]. These
87 experiences are distressing and dangerous; in a qualitative study, Brown et al. [4] found that
88 more than 50% of women with BPD and history of self-harm endorsed disturbances in self-
89 experience, such as emptiness, numbness, or feeling dead, as reasons for non-suicidal self-
90 injury .

91

92 *1.1.2. Bodily experience is disrupted in BPD*

93 One aspect of selfhood that may have relevance for pathologies of self in BPD is the experience
94 of body ownership. Indeed, abnormal bodily experiences in BPD are common, including bodily
95 dissociation [5], altered pain perception [6], and deficits in interoception (the awareness and
96 processing of internal bodily signals) [7].

97 Mechanistically, sense of body ownership is constituted by integration of sensorimotor
98 (external) and interoceptive (internal) signals [8]. Neural computations on these signals
99 generate a probabilistic, and therefore malleable, model of self-representation [9]. For a healthy
100 person, sense of body ownership is stable and taken for granted, while in certain mental
101 disorders such as BPD, sense of body ownership may be more variable and plastic.
102 Experimental paradigms that directly manipulate the experience of body ownership have the
103 potential to elucidate aberrations in embodied self-experience in BPD.

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107 *1.2. Probing the embodied self: The Rubber Hand Illusion*

108 Illusions can test the plasticity of body ownership by manipulating integration of self and
109 non-self stimuli. One paradigmatic body illusion is the Rubber Hand Illusion (RHI) [10]. During
110 the task, a participant's hidden hand is stroked in synchrony with an appropriately positioned
111 and visible rubber hand (**Figure 1**). The RHI can induce the feelings that the rubber hand
112 belongs to the participant (subjective illusion) and that the participant's own hand has moved
113 toward the rubber hand (proprioceptive drift). Typically, the RHI is measured by a self-report
114 questionnaire of illusory experience (adapted from [10]) and the spatial magnitude of
115 proprioceptive drift [11].

116 It is theorized that the RHI results from the multimodal (e.g. visuo-tactile) integration of
117 sensory events in peri-personal space: an area including and immediately surrounding the body
118 that is implicated in maintaining a dynamic cortical representation of the body [12]. RHI
119 induction is sensitive to visuospatial plausibility and the timing of sensory stimulation, such that
120 unrealistic placement of the rubber hand and temporally asynchronous stroking have been
121 found to attenuate illusory body ownership in healthy participants [13, 14].

122 Eshkevari et al. [15] highlight two factors that promote induction of the rubber illusion.
123 One factor, "visual capture," occurs prior to visuo-tactile stimulation, whereby a sense of body
124 ownership results from over-weighting of the visual stimulus of the rubber hand over
125 proprioceptive information of the real hand. The other factor, which entails simultaneous seen
126 and felt touch of the fake and real hand during simultaneous stroking, results in the illusion of
127 rubber hand ownership via the multisensory integration of temporally co-occurring visual and
128 tactile stimulation. Empirical data from healthy participants and computational modelling of
129 rubber hand ownership demonstrate that the illusion can occur without tactile stimulation (first
130 factor) and is enhanced by temporally synchronous (vs. asynchronous) stroking of fake and real
131 hands [16]. Importantly, increased susceptibility to the first factor, which occurs in both

132 synchronous and asynchronous conditions (as it occurs prior to tactile stimulation) may indicate
133 imprecise bodily representations that result in the overweighting of exteroceptive information
134 [16] [15].

135

136 *1.3. Pathologies of illusory body ownership*

137 The RHI has been conducted across a range of mental disorders in which anomalous
138 self-experience has been implicated and which share clinical overlap with BPD, including
139 schizophrenia [11], body dysmorphic disorder [17], and eating disorders [15, 18]. These
140 conditions are associated with increased susceptibility to the RHI as measured by self-report
141 questionnaire [18], proprioceptive drift [17] or both [11, 15]. Increases in subjective measures of
142 the illusion and proprioceptive drift have also been demonstrated in pharmacological models of
143 psychosis (i.e. ketamine) in healthy participants, implicating NMDA hypofunction and
144 augmented neural oscillations in the gamma-range that promote cross-modal binding [13]. This
145 interpretation was bolstered by the finding of maintained illusory experience in an asynchronous
146 version of the RHI with pharmacologic challenge, highlighting the methodological importance of
147 administering the task in both synchronous and asynchronous versions.

148 The vividness of the illusion has also been linked to schizotypy in healthy participants
149 [19], suggesting that altered body ownership may be a marker of psychosis-proneness.
150 However, the interpretation of these results is limited as task demand characteristics of the
151 illusion questionnaire may not have been controlled for. In particular, the original Botvinick &
152 Cohen [10] questionnaire was designed to include target and non-target items to control for
153 suggestibility, but to our knowledge no clinical study has adequately assessed group differences
154 in the relative endorsement of target and non-target items on the RHI questionnaire.
155 Furthermore, target items (which probe the illusions of touch, causality, and ownership,
156 respectively) sequentially probe qualitatively more encompassing aspects of the illusion. For
157 example, people who minimally experience the illusion may only endorse the illusion of touch

158 (feeling the touch on the location where the rubber hand is touched), while those who
159 experience a stronger illusory experience may also endorse ownership of the rubber hand (that
160 the rubber hand is their hand). However, differences in the relative endorsement of individual
161 target items, both between and across clinical groups, has not been previously directly
162 tested. Close examination of target item responses and attention to dimensional symptomology
163 can reveal trait markers across diagnostic thresholds that may influence illusion susceptibility.

164

165 *1.4. The current study: Probing body plasticity in BPD*

166 To date, there has been one study examining illusory body ownership using the RHI in
167 people with current and remitted BPD [20]. That study analyzed findings in a synchronous
168 version of the task only, and found increased subjective experience of the illusion, but similar
169 proprioceptive drift, in people with BPD compared to HCs. However, group differences in the
170 relative endorsement of target and non-target items was not accounted for. Additionally, the
171 authors found a small but significant correlation between illusory body ownership and state and
172 trait dissociation after controlling for BPD symptom severity. We extend these findings by (1)
173 testing group differences in the relative endorsement of target vs. non-target items, (2) probing
174 responses to individual target items to explore more granular group differences in illusory
175 experience, (3) directly testing hypotheses about asynchronous stimulation, and (4) exploring
176 relationships between illusory body ownership and BPD symptom phenotypes and dimensional
177 measures of maladaptive personality.

178 In the current study, we conducted the RHI task with people with BPD and healthy
179 controls (HC) in temporally synchronous and asynchronous conditions. We made the following
180 hypotheses:

181

182

183 **H1. Illusion strength would be greater in BPD vs HC groups in both synchronous and**
184 **asynchronous conditions.**

185 *We hypothesized that people with BPD would be more susceptible to the illusion as measured*
186 *by both subjective questionnaire responses (H1.1) and proprioceptive drift (H1.2). This*
187 *difference has been observed most strongly in synchronous condition in other settings;*
188 *however, some increase in susceptibility in clinical groups has also been observed in the*
189 *asynchronous condition. We are the first to report asynchronous condition results in BPD.*

190
191 **H2.1. Tactile illusion strength would be greater than ownership illusion strength.**

192 **H2.2. The illusion of ownership, but not the illusions of perception or causality, will be**
193 **more strongly endorsed in BPD than in HC.**

194 *Some RHI studies descriptively report differential endorsement of target questions: Q1 (tactile*
195 *illusion) versus Q2 (causality), Q3 (ownership), however these differences have not been*
196 *directly tested. Given self-disturbance in BPD, we hypothesized that pair-wise comparisons of*
197 *target-item endorsement would reveal specific increased endorsement of Q3 in BPD vs HC*
198 *across conditions.*

199 **H3 (exploratory). Illusion strength would positively correlate to psychotic-like symptoms**
200 **and traits.**

201 *In BPD, cognitive-perceptual disturbances are common, and psychotic-like traits are present in*
202 *undiagnosed people in the general population. Given previous work linking RHI illusion strength*
203 *to ketamine intoxication, psychosis, and schizotypy, we explored correlation of RHI illusion*
204 *strength to psychotic-like experiences in BPD and HC, as well as BPD symptom clusters in BPD*
205 *group.*

206
207
208 **2. Methods**

209 **2.1. Subjects**

210 This study was approved by the Yale Institutional Review Board. Results for this study
211 were collected as part of a larger battery of experimental tasks. Results from those tasks as well
212 as the recruitment strategy for these participants are described in detail elsewhere [21, 22].
213 Briefly, women aged 18-65 were recruited from the community. HCs had no current psychiatric
214 conditions, and BPD participants had no current substance dependence and no primary
215 psychotic disorder according to intake interview assessment (see **supplement 1**).

216

217 *2.2. Symptom and self-report scales*

218 HC and BPD participants completed a series of well validated self-report symptom
219 scales and structured clinical interviews including: the Beck Anxiety Inventory (BAI) [23], Beck
220 Depression Inventory (BDI-II) [24], The Personality Inventory for DSM-5 (PID-5) [25], The
221 Structured Clinical Interview for DSM-IV Personality Questionnaire [26], and the Revised
222 Diagnostic Interview for Borderlines (DIB-R) [27]. Please refer to **supplement 2** for information
223 on scale validation and subscales.

224

225 *2.3. Rubber hand illusion paradigm*

226 Participants wore a non-latex glove on their right hand, sat in front of a table, and placed
227 their right hand into an open cardboard box (**Figure 1**). All participants underwent RHI
228 procedures on their right hand only as it was previously demonstrated that laterality and
229 handedness had no effect on the subjective experience of the illusion or magnitude of
230 proprioceptive drift, the two main outcomes measures for the task in the current study [28].

231 In the box, the participant's right hand was occluded from their view, but not from the
232 view of the experimenter who sat across the table facing the participant. A gloved life-sized
233 rubber hand was positioned so that the hand was visible to the participant on the medial end of

234 the box. A cloth was then draped over the participant's shoulder covering both the real right arm
235 and the arm of the rubber hand.

236 Before induction of the illusion, participants made an initial estimate of the spatial
237 location on their occluded right hand via a numbered ruler that was placed on top of the box.
238 Each participant then underwent synchronous and asynchronous versions of the task, each
239 lasting 3 minutes. In the synchronous condition, an experimenter used the brush of a paintbrush
240 to provide soft simultaneous touch at 1 Hz frequency in the proximal to distal direction along the
241 middle phalanges of the real index finger and an equivalent location on the rubber hand.
242 Procedures for the asynchronous condition were identical except that brush strokes were offset
243 in time by 0.5 seconds (resulting in alternating touch on the real and rubber hands).

244

245 *2.3.1. Measure of subjective experience of the illusion*

246 After synchronous and asynchronous conditions, participants completed a questionnaire
247 adapted from Botvinick & Cohen [10] to assess their subjective experience of the illusion (**Table**
248 **1**). Variations of this questionnaire have been used widely in RHI research [17]. Similar to
249 previous studies, the first three items ("target") were used to create an index score as they are
250 more strongly and consistently endorsed than the other items, and they reflect expected illusory
251 experience [17]. The remaining items ("non-target") have historically been included to control for
252 suggestibility and task demand characteristics as they are endorsed only minimally by healthy
253 samples [17]. However, they are often endorsed in clinical psychiatric populations and during
254 pharmacologic challenge (e.g. ketamine) [13]. For each condition, a cumulative "target item"
255 score was created as the average rating across items 1-3 and a cumulative "non-target item"
256 score was created as the average rating across items 4-9. Significantly higher target scores
257 compared to non-target scores was used as an indicator of successful induction of the illusion.

258

259 *2.3.2. Measure of proprioceptive drift*

260 Proprioceptive drift refers to the extent to which participants estimated their hand as
261 being closer to the rubber hand after induction of the illusion. Participants estimated the position
262 of their hidden right index finger before stimulation, and then at 30 second intervals during
263 stimulations (6 times over 3 minutes of stimulation) by referring to a numbered ruler placed on
264 top of the box. At each interval, participants were reminded not to move their hand. At each
265 interval, the position of the ruler was jittered to prevent participants from anchoring on previous
266 estimates [29]. Proprioceptive drift was calculated as the difference in estimated hand location
267 between the pre-trial estimate and average of the six post-trial estimates. Positive values, then,
268 refer to post-trial estimates that are closer to rubber hand than initial estimates. Positive drift
269 values are consistent with successful induction of the illusion.

270

271 *2.4. Planned statistical analyses:*

272 Parametric tests were conducted for analyses on main outcome variables (subjective
273 experience questionnaire and proprioceptive drift) as values for skewness and kurtosis were all
274 within -2 to 2, indicating normal univariate distribution [30].

275 To test for successful induction of the illusion in each group, we conducted a 2 x 2
276 analysis of variance ANOVA to compare the effects of condition (synchronous vs.
277 asynchronous) and item-type (target vs. non-target) on subjective endorsement of the illusion.

278 Separate 2 x 2 ANOVAs were used to assess impact of group (HC vs. BPD) and
279 condition (synchronous vs. asynchronous) on target item endorsement (hypothesis H1.1) and
280 proprioceptive drift (hypothesis H1.2). ANOVAs were further explored with post-hoc t-tests. To
281 assess for specificity of target versus non-target item endorsement, we performed a one-way
282 ANCOVA to assess for group differences (HC vs. BPD) in target item endorsement using non-
283 target item endorsement as a covariate.

284 Repeated measures ANOVA test (2 group x 2 condition x 3 target items) was employed
285 to test for differential endorsement of individual target items (hypothesis H2.1 and H2.2).

286 Lastly, we performed Pearson correlations to explore the relationships between RHI
287 measures and symptom scales. Correlations were one-tailed unless stated otherwise to test for
288 positive correlations (hypothesis H3).

289 Alpha values were set to 0.05 for primary analyses and, more conservatively, to 0.01 for
290 post-hoc analyses and correlations. We report effect sizes using Cohen's D for t-tests, and
291 partial eta squared for ANOVAs.

292

293 **3. Results**

294 3.1. Participant characteristics

295 Twenty-four women were enrolled in the BPD group and 21 women were enrolled in the
296 HC group. HC and BPD groups were matched on age, years of education, and race (**Table 2**).
297 The BPD group was significantly more symptomatic on measures of BPD symptom severity
298 (SCID-II, BSL, DIB-R), depression (BDI), and anxiety (BAI) (**Table 2**).

299

300 3.2. *Induction of illusory limb ownership*

301 In both BPD and HC groups, target items were endorsed more strongly than non-target
302 items in the synchronous condition. Furthermore, target items were more strongly endorsed in
303 the synchronous condition compared to asynchronous condition (see **supplement 3** for
304 statistics) Taken together, these results suggest that we were able to successfully induce the
305 RHI in BPD and HC groups.

306

307 3.3. *Self-Report RHI Questionnaire*

308 *H1.1. Subjective illusion strength would be greater in BPD vs HC groups in both synchronous*
309 *and asynchronous conditions.*

310 To test hypothesis H1.1, we tested for group differences in mean target item
311 endorsement using a 2 group x 2 condition repeated measures ANOVA (**Figure 2A, 2B**). We
312 found a significant main effect of group (BPD > HC, $F(1,43) = 11.94$, $p = 0.001$, $\eta^2 = 0.22$) and of
313 task condition (synchronous > asynchronous, $F(1,43) = 22.80$, $p < 0.001$, $\eta^2 = 0.35$). No
314 significant interaction was found ($F(1,43) = 1.72$, $p = 0.681$, $\eta^2 < 0.01$).

315 To determine whether group differences in target item endorsement in the illusion
316 inducing condition (synchronous) could be accounted for by task demand characteristics or
317 suggestibility, we conducted a one-way ANCOVA to test for a difference between BPD and HC
318 groups in target item endorsement while controlling for responses to non-target items. We found
319 that the effect of group remained significant when we controlled for the non-target items ($F(1,42)$
320 $= 4.40$, $p = 0.042$, $\eta^2 < 0.1$) suggesting that group differences in target item responses do reflect
321 differences in the magnitude of illusory experience.

322

323 *H2.1. Tactile illusion strength would be greater than ownership illusion strength.*

324 *H2.2. Greater subjective illusion in BPD would be accounted for by ownership illusion.*

325 To test hypotheses H2.1 and H2.2, we conducted a repeated-measures ANOVA (2 groups x 2
326 conditions x 3 target items) (**Figure 2C, 2D**). We found a main effect of group ($F(1,43) = 11.94$,
327 $p = 0.001$, $\eta^2 = 0.22$), condition ($F(1,43) = 22.80$, $p < 0.001$, $\eta^2 = 0.35$), and target item ($F(1,43)$
328 $= 26.16$, $p < 0.001$, $\eta^2 = 0.38$). While condition x group, item x group, and condition x item
329 interactions were non-significant, we found a significant group x item x condition interaction
330 ($F(1,43) = 4.89$, $p = 0.032$, $\eta^2 = 0.10$). Post-hoc tests to unpack this 3-way interaction revealed
331 that pair-wise comparison between Q1 and Q2 in the synchronous condition is significant in the
332 control but not BPD group (control: $t(20) = 3.12$, $p = 0.005$, $d = 0.68$; BPD: $t(23) = 1.75$, $p =$
333 0.094 , $d = 0.36$). Other pairwise comparisons did not differ significantly by group.

334 To examine hypothesis H2.1, we conducted post-hoc t-tests comparing Q1 (tactile
335 illusion) and Q3 (ownership illusion) in each condition. In all participants taken together, Q1 was

336 more strongly endorsed than Q3 in both conditions (synchronous: $t(44) = 4.17, p < 0.001, d =$
337 0.63 ; asynchronous: $t(44) = 4.79, p < 0.001, d = 0.72$). Of note, Q2 and Q3 were endorsed
338 comparably across conditions (Synchronous: $t(44) = 1.61, p = 0.114, d = 0.24$; Asynchronous:
339 $t(44) = 0.87, p = 0.39, d = 0.13$). This suggests that the illusion of touch (i.e. feeling the touch on
340 the rubber hand) was more easily induced by the RHI, while illusions of causality (i.e. felt touch
341 was caused by touch on rubber hand) and ownership ("I felt as if the rubber hand were mine")
342 indicate more severe body illusion experiences that are more difficult to induce.

343 To examine hypothesis 2.2, we conducted post-hoc t-tests comparing group differences
344 in individual target item endorsement. In the synchronous condition, BPD and HC groups
345 comparably endorsed Q1 ($t(43) = 1.59, p = 0.120, d = 0.48$). Compared to HC, BPD endorsed
346 Q2 ($t(43) = 2.58, p = 0.013, d = 0.77$) and Q3 more strongly ($t(43) = 2.48, p = 0.017, d = 0.74$);
347 however, these differences did not achieve statistical significance at $\alpha = 0.01$. In the
348 asynchronous condition, BPD endorsed Q1 more strongly ($t(43) = 2.77, p = 0.009, d = 0.83$)
349 compared to HC. Additionally, BPD endorsed Q2 more strongly, ($t(43) = 2.34, p = 0.025, d =$
350 0.70), but not at the statistical significance level of $\alpha = 0.01$. Lastly, BPD and HC endorsed
351 illusion of ownership at comparable levels $t(43) = 1.21, p = 0.233, d = 0.36$) in the asynchronous
352 condition. In summary, contrary to our hypothesis, group differences in target item endorsement
353 appear to be driven by different items in synchronous and asynchronous conditions. While in the
354 synchronous condition group differences appear to be driven by differential endorsement of Q2
355 (illusion of causality) and Q3 (illusion of ownership), in the asynchronous condition, they are
356 accounted for by differential endorsement of Q1 (tactile illusion) and, to a lesser extent, by Q2
357 (illusion of causality).

358

359 *3.4. Proprioceptive Drift*

360 *H1.2. Proprioceptive illusion strength would be greater in BPD vs HC groups in both*
361 *synchronous and asynchronous conditions.*

362 To test hypothesis H1.2., we explored group differences in proprioceptive drift using 2 x
363 2 repeated measures ANOVA (group x condition) (**Figure 3**). Main effect of group (BPD vs HC,
364 $F(1,43) < 0.001$, $p = 0.99$, $\eta^2 < 0.01$) and of task condition (synchronous vs asynchronous, $F(1,$
365 $43) = 2.19$ $p = 0.15$, $\eta^2 = 0.05$) were not significant. However, a significant group x condition
366 interaction was found ($F(1,43) = 6.48$, $p = 0.015$, $\eta^2 = 0.13$). Post hoc paired sample T-tests
367 demonstrated that, contrary to our hypothesis, while the HC group had significantly reduced
368 proprioceptive drift in the asynchronous condition ($t(20) = 2.90$, $p = 0.009$, $d = 0.63$), the BPD
369 group had no significant difference in drift across conditions ($t(23) = 0.75$, $p = 0.462$, $d = 0.094$)
370 (**Figure 3**). We also found weak to moderate relationships between target item endorsement
371 and proprioceptive drift that did not meet our significance cut-off of $p < 0.01$ (see **supplement**
372 **4**).

373

374 3.5. Symptom/Trait Correlations

375 *H3. Exploratory: Illusion strength would positively correlate to psychotic-like symptoms and*
376 *traits.*

377 3.5.1. BPD symptoms

378 We investigated whether BPD symptom severity and BPD symptom clusters relate to
379 illusion strength in the clinical group. To do so, we conducted one-tailed Pearson correlations
380 between DIB total (unscaled score) and subscale (affect, cognition, impulsivity, and
381 interpersonal relationship sections) scores (unscaled) and the following RHI measures: target-
382 item score, item-3 (“I felt as if the rubber hand was my hand”) and proprioceptive drift in the
383 synchronous condition (statistics in **Table 3**). We limited correlations to the synchronous
384 condition to limit multiple comparisons and to focus on the more illusion-inducing condition. At
385 the $\alpha = 0.01$ level, we found that target-item index score and item-3 endorsement were related
386 to the affect subscales with correlations in the large effect range. Proprioceptive drift was not
387 related to BPD symptom severity or symptom clusters within the clinical group.

388

389 *3.5.2. Dimensional personality assessment*

390 Next, we examined the relationship between RHI and dimensional measures of
391 maladaptive personality traits across all participants. To do so, we conducted one-tailed
392 Pearson correlations between PID-5 personality trait domains (negative affect, detachment,
393 antagonism, disinhibition, and psychoticism) and the following RHI measures: target-item score,
394 item-3 (“I felt as if the rubber hand was my hand”) and proprioceptive drift in the synchronous
395 condition (**Table 3**). At the $\alpha = 0.01$ level, only trait-psychoticism was significantly related to the
396 target-item index score and item-3 endorsement, with correlations observed in the medium-
397 effect range. Proprioceptive drift was not significantly related to clinical traits at the $p < 0.01$
398 level.

399 Of note, six participants (four BPD and two HC) did not complete the PID-5. The two HC
400 participants were comparable to other HCs in age, education, BDI, BAI and RHI outcomes. The
401 four BPD participants were both highly symptomatic and appeared to have higher target item
402 endorsement in the synchronous condition. Thus, these results likely underestimate the
403 correlation between maladaptive traits and subjective response to the illusion. Note that the
404 very small sample size was prohibitive of inferential statistics.

405

406 **4. Discussion**

407 To our knowledge, this is the second study investigating illusory body ownership in BPD.
408 We extend the previous report by directly assessing findings in the asynchronous condition,
409 analyzing differential endorsement of self-report items, and identifying further associations with
410 clinical and personality trait variables. In the paragraphs to follow, we will interpret RHI behavior
411 in BPD within a predictive coding account of bodily self [31, 32], which posits that
412 representations self are probabilistically generated through integration of top-down predictions

413 about the body and bottom-up “prediction errors” of sensory inputs across interoceptive and
414 exteroceptive domains.

415 We hypothesized that compared to HC, people with BPD would have greater target item
416 endorsement (H1.1) and larger proprioceptive drift (H1.2) in both synchronous and
417 asynchronous conditions. H1.1 was supported: BPD had greater target item endorsement in
418 both conditions. Contrary to H1.2, we found a significant group x condition interaction on drift
419 measurements: BPD and HC had comparable drift during synchronous stimulation. However,
420 during asynchronous stimulation, BPD had maintained drift while HC had significantly reduced
421 drift.

422 As hypothesized, we found increased body plasticity in BPD as measured by subjective
423 endorsement of illusory experience. Bekrater-Bodmann et al. [20] reported increased subjective
424 experience of the illusion; we clarified this finding by demonstrating that this group difference
425 remained significant after controlling for the endorsement of non-target items, suggesting that
426 increased target item response reflects alterations in the magnitude of illusory experience. We
427 also extend their findings by demonstrating increased susceptibility in both synchronous *and*
428 *asynchronous* conditions, indicating that illusion susceptibility occurs generally, rather than
429 specifically during synchronous stimulation. While Bekrater-Bodmann et al. [20] employed
430 asynchronous stimulation merely as a manipulation check, others have compared RHI results
431 across conditions (e.g. [13, 15, 17]) to elucidate possible mechanisms underlying abnormalities
432 in illusory body ownership. For example, Morgan et al. [13] found maintained illusory experience
433 from synchronous to asynchronous stimulation during ketamine (an NMDA antagonist)
434 challenge in healthy participants. NMDA antagonism (a model for early psychotic illness) is
435 thought to weaken top-down signaling, leading to over-weighting of bottom-up input, even when
436 the bottom-up signals are inconsistent. In the asynchronous RHI condition (a state of
437 inconsistent bottom-up signals), the weaker top-down signaling produces a large prediction

438 error regarding self-attribution, putatively resulting in illusion experience. In BPD, illusion
439 susceptibility across synchronous and asynchronous conditions may similarly indicate weak top-
440 down signaling regarding body-ownership.

441 RHI induction is hypothesized to arise from two processes [15]: 1) visual capture, which
442 occurs prior to tactile stimulation, whereby rubber hand ownership is experienced via integration
443 of visual and proprioceptive inputs of the fake and real hands, respectively; and 2), temporal
444 integration of visual and tactile input during synchronous stroking. Studying RHI in eating
445 disorders, Eshkevari et al. [15] interpreted maintained illusion susceptibility in asynchronous
446 conditions as a heightened sensitivity to visual capture over distorted bodily signals. This
447 interpretation was bolstered by the finding that interoceptive deficits were a significant predictors
448 of illusory body ownership in ED. Importantly, interoception (i.e. the processing and awareness
449 of internal bodily signals) is theorized as a central modality in stabilizing mental representations
450 of bodily-self in predictive coding frameworks (e.g.[8, 32, 33]). Accordingly, the precision
451 associated with prediction error of sensory input—the confidence or uncertainty ascribed to it—
452 modulates the integration of bottom-up and top-down information flow, such that low precision-
453 weighted prediction errors are less likely to update (top-down) prior beliefs. In the RHI, the
454 stability of body ownership is maintained by the relative precision of interoceptive vs
455 exteroceptive input. Reduced certainty, or “trustworthiness,” ascribed to interoceptive signals
456 leads to the overweighting of exteroceptive input (e.g. seeing the rubber hand) during the task,
457 resulting in increased susceptibility to the illusion (see [34] for empirical support). BPD is
458 associated with deficits in interoceptive processing [35]. However, the relationship between
459 interoception and body plasticity was not directly assessed in this study. Future research can
460 assess the extent to which interoceptive processing, e.g. as measured by heart beat evoked
461 potentials [35, 36], or heart beat detection [37], though see [38] for methodological limitations),
462 mediates illusory body ownership in BPD and serves as a common mechanism of illusion

463 susceptibility across personality, eating, and body-image disorders, for which there are
464 symptomatic and clinical overlap [39, 40].

465 Contrary to H1.2, we found that BPD had comparable drift in both task conditions, while
466 HC had significantly reduced drift in the asynchronous condition. While in previous studies, drift
467 has been used as a “behavioral proxy” of rubber hand ownership (e.g. [41, 42]), Rohde, Di Luca
468 and Ernst [43] found subjective endorsement of the illusion and drift to be separate and
469 dissociable phenomena. In our sample, drift magnitude did not correlate with endorsement of
470 RHI questionnaire items. Interestingly, Kaplan et al. [17] found that individuals with body
471 dysmorphic disorder (BDD) demonstrate similar findings to our BPD sample such that they
472 evidenced comparable drift in both conditions. They interpret this result in light of findings in
473 healthy participants [43], that proprioceptive drift occurs to an equal extent during synchronous
474 stroking and in a “just vision” condition (wherein participants estimate hand location after looking
475 at rubber hand without tactile stimulation), while asynchronous stroking reduces drift by
476 disrupting visio-proprioceptive integration. Kaplan et al. [17] posit that with regards to bodily
477 awareness, people with BDD are less susceptible to the illusion-extinguishing effects of the
478 asynchronous condition. If BPD shares a similar mechanism underlying maintained drift across
479 conditions with BDD, this would be consistent with our proposed BPD self-model that is biased
480 towards incorporating (even inconsistent) exteroceptive information in the setting of
481 interoceptive deficits.

482 To our knowledge, differential endorsement of target-items has never been directly
483 studied. Taking a closer look at responses to the RHI questionnaire, we hypothesized that the
484 illusion of perception (Q1) would be more strongly endorsed than the illusion of ownership (Q3)
485 (H2.1), and that greater subjective illusion strength in BPD would be accounted for by the
486 illusion of ownership (H2.2). H2.1 was supported: across groups and conditions, Q1 (illusion of
487 perception) was more strongly endorsed than Q3 (illusion of ownership). Contrary to H2.2., we
488 found that group differences in target-item endorsement were driven by different questions in

489 both conditions. H2.1 confirms our common-sense assumption that a tactile illusion is more
490 easily inducible than the illusion of rubber hand ownership. Considering target item
491 endorsement in the synchronous condition, we found comparable endorsement of Q1, but
492 differential endorsement of Q2 and Q3 across groups, suggesting that similar perceptual
493 experiences led to differential endorsement of statements regarding the relationship between
494 real and rubber hands (i.e., that they are causally linked, or that the rubber hand is experienced
495 as one's own). Taken together, these findings are consistent with a predictive coding account of
496 self-recognition [31], wherein more abstract multimodal self-representations are encoded at
497 higher levels within a hierarchical model of self-processing. Intermediate-level beliefs are
498 constrained by top-down expectations as well as sensory bottom-up information lower in the
499 hierarchy. Thus, during the synchronous stroking, we hypothesize that the prediction error
500 caused by RHI procedures could be accounted for at the level of a perceptual experience for
501 healthy participants; whereas in BPD, RHI procedures lead to updating of more abstract self-
502 representations, and therefore endorsement of causation and ownership illusions (Q2 and Q3,
503 respectively). Similarly, while asynchronous stroking was sufficient to eradicate the illusion in
504 HCs, the BPD group maintained an attenuated experience of the illusion (Q1 endorsement)
505 related to perceptual experience.

506 Lastly, we performed exploratory correlations to assess the relationship between clinical
507 traits and illusory experience. We hypothesized that psychotic-like experiences would be
508 uniquely related to RHI illusion strength (H.3). In addition to linking illusion strength
509 with psychotic-like experiences, we also found strong associations with affective symptoms in
510 both the BPD group (as measured by the DIB affect subscale) and across the whole sample (as
511 measured by PID-5 trait negative affect). While the link between psychotic-spectrum experience
512 and RHI has been demonstrated in other settings (e.g. [19] [13] [13]), we are the first to
513 demonstrate this association within BPD, providing further evidence that body plasticity may
514 track psychosis-proneness trans-diagnostically. Finding a link between dissociation and RHI

515 susceptibility in BPD, Bekrater-Bodman et al. [20] posit that altered NMDA neurotransmission
516 may underlie altered body plasticity in the condition. This suggestion is bolstered by
517 neurochemical evidence [44] implicating glutamatergic signaling in the anterior cingulate cortex
518 (ACC) in BPD. Importantly, the ACC and the insular cortex have been identified as central
519 structures for interoception [35]. Computational perspectives on mood and emotion suggest that
520 emotional states reflect the certainty (or precision) regarding the interoceptive consequences of
521 action, such that negative emotion “contextualize events that induce expectations of
522 unpredictability” ([45], p. 2278). Thus, state negative affect may contribute to overweighting of
523 exteroceptive input during RHI procedures in the setting of low precision-weighted interoceptive
524 input. Clarifying the contribution of state, e.g. affect, and trait, e.g. emotion regulation [35],
525 characteristics to the plasticity of body ownership also may elucidate the relationship between
526 emotion arousal and clinical states such dissociation and depersonalization associated with
527 BPD [5]. Alterations in body plasticity may also inform our understanding of interpersonal
528 difficulties in the condition. BPD is associated with a two-fold increase in preferred interpersonal
529 distance in live dyadic contexts compared to healthy controls, suggesting alteration in embodied
530 peri-personal space [21]. Given the theoretical links between interoception, emotion, and theory
531 of mind [46], targeting body awareness (e.g. through mindfulness practice [47, 48]) may be an
532 important focus, especially for people with BPD whose symptom profiles are high in self-
533 disturbance and psychoticism.

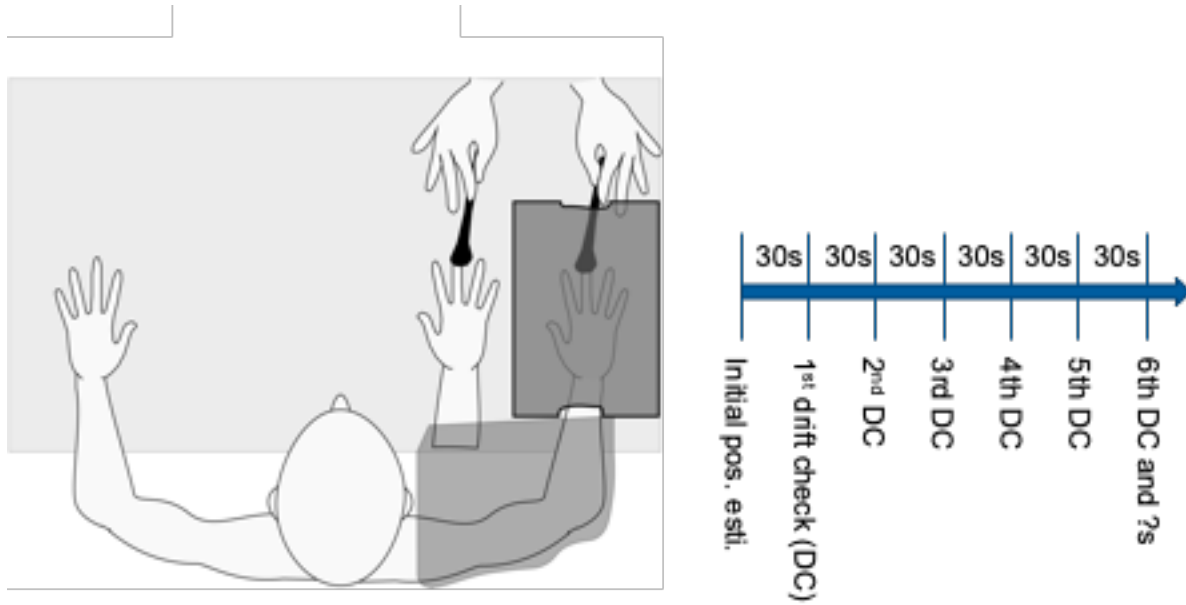
534 The findings from this work are best understood within the context of several limitations.
535 Sample size was small, and subjects were all women. The small sample size prohibits
536 examination of the impacts of potentially interesting demographics (race, sexual orientation,
537 age) and co-morbidities on outcome. Inclusion of only biologically female, female-identified
538 subjects for the study was important to decrease potential sources of variability in results given
539 the small sample, but does limit generalizability of results. From a task set-up perspective, we
540 did not include a baseline acclimation period to test for illusion induction from visual stimulus

541 alone prior to tactile stimulation. This has been done in a non-clinical sample [16] and would
542 enable the direct assessment of the relative contribution of visual capture vs. integration of
543 visuotactile stimulation in producing enhanced illusory experience in clinical population.
544 Furthermore, in a computational model, Majed, Chung, & Shams [16], demonstrated that the
545 perception of body ownership as measured by the RHI can be described as a Bayesian causal
546 inference. Future research applying this modeling techniques to clinical data can further probe
547 to what extent increased body plasticity in BPD is driven by weakening of top-down
548 representations of body-schemas vs bottom-up integration of interoceptive and exteroceptive
549 input.
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552 **Table 1: RHI Questionnaire Items (target items in bold)**

Item	Wording
1	It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.
2	It seemed as though the touch I felt was caused by the paint brush touch the rubber hand.
3	I feel as if the rubber hand were my hand.
4	I felt as if my real hand was drifting toward the rubber hand.
5	It seemed as if I might have more than one right hand or arm.
6	It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand.
7	It felt as if my real hand were turning 'rubbery'.
8	It appeared visually as if the rubber hand was drifting towards my hand.
9	The rubber hand began to resemble my own real hand, in terms of shape, texture, or some other visual feature.

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562 **Figure 1: Rubber Hand Illusion setup.** Participant's gloved right hand is placed in cardboard
563 box obstructing it from view. A life-like gloved rubber hand is placed medial to the box. A cloth is
564 draped across right shoulder, covering the wrist of the rubber hand and the cardboard box
565 proximally, where the participant's real hand enters. During illusion induction, the participant is
566 instructed to visually focus on the rubber hand while an experimenter provides brushstrokes to
567 the middle phalanges of the real hand (through an opening in the cardboard box) and an
568 equivalent location on the rubber hand for 3 minutes. Hand localization ("drift") estimates are
569 taken at 30 second intervals. The questionnaire is administered once after each stimulation
570 condition (synchronous, asynchronous).

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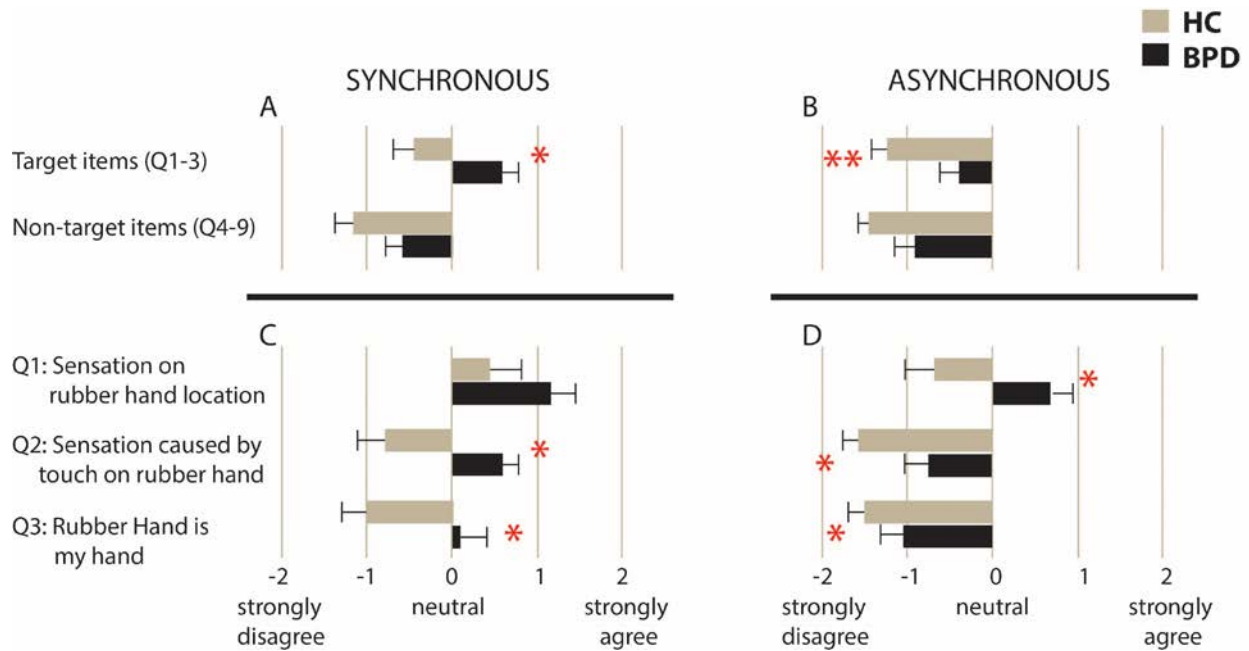
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	BPD	HC	Statistics
n	24	21	
Age (yrs)	33.17 (12.47)	31.10 (13.13)	t = 0.54; p = 0.59
Education (yrs)	13.96 (2.46)	15.02 (2.45)	t = -1.45; p = 0.15
<u>Race</u>			Chi square = 3.19; df = 2; p = 0.74
Asian	8.30%	9.50%	
Black	16.70%	28.60%	
Hispanic	4.20%	19%	
White	66.70%	42.90%	
Not Reported	4.20%	0%	
BAI	24.83 (12.80)	7.35 (10.05)	t = 4.92; p < 0.001
BDI	23.04 (12.71)	2.52 (4.52)	t = 7.39; p < 0.001
DIB-R (unscaled)	28.00 (6.55)	3.19 (4.17)	t = 14.90; p < 0.001
SCID-II self report	9.75 (3.51)	0.95 (1.40)	t = 11.31; p < 0.001
BSL-23	36.25 (21.42)	3.95 (4.32)	t = 7.219; p < 0.001

Table 2: Participant Characteristics Mean results are reported followed by standard deviations in parentheses. Groups were matched on age, education, and race. All participants were female. BPD group participants reported significantly more anxiety, depression, and BPD symptoms than did HC participants.

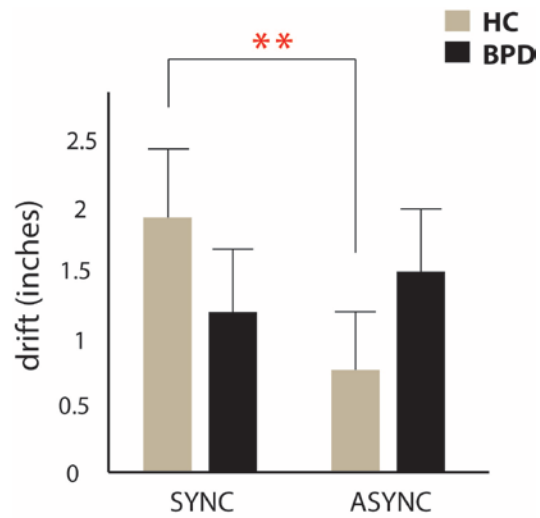
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591 **Figure 2: RHI Questionnaire Responses.** Averaged mean scores for target and nontarget items
592 in synchronous (2A) and asynchronous conditions (2B). Error bars denote standard error of the
593 mean. Means for individual target items are displayed for both synchronous (2C) and
594 asynchronous (2D) conditions. * $p < 0.05$; ** $p < 0.01$

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604 **Figure 3: Proprioceptive drift.** Mean drift toward rubber hand following six 30 second trials of
605 synchronous (sync) or asynchronous (async) stimulation. Error bars represent standard error of
606 the mean. ** $p < 0.01$

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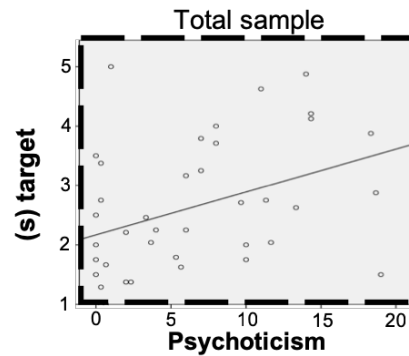
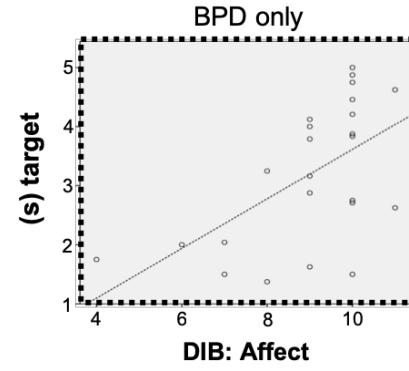
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	Scale	(s) Drift	(s) target	(s) Q3
BPD only	DIB: Total score	0.019	.384*	.400*
	DIB: Affect	0.092	.481**	.680**
	DIB: Cognition	-0.289	.411*	.358*
	DIB: Impulsivity	0.283	0.256	0.075
	DIB: Interpersonal	0.095	-0.041	0.107
Total sample	NegativeAffect	-0.172	.309*	0.183
	Detachment	0.026	.368*	.325*
	Antagonism	.335*	0.256	0.121
	Disinhibition	-0.067	0.228	0.173
	Psychoticism	0.101	.440**	.393**



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Table 3: Relationship between illusion susceptibility, BPD symptom clusters and maladaptive traits. The table displays Pearson correlations coefficients between proprioceptive drift, target-item endorsement, item three endorsement in the synchronous condition, and clinical/personality variables. On the right side are the scatterplots for the relationship between average target item endorsement in the synchronous condition and DIB affect in the BPD group (upper panel) and trait psychoticism as measured by PID-5 in the whole sample (lower panel).

* $p < 0.05$, one tailed; ** $p < 0.01$, one tailed

Note: DIB-R = Diagnostic Interview for Borderlines-revised. DIB-R includes affect, cognition, impulsivity, and interpersonal sub-scales. PID-5 = Personality Inventory for DSM-5 which has scales for the following maladaptive traits: negative affect, detachment, antagonism, disinhibition, and psychoticism. (s) Drift = proprioceptive drift in synchronous condition. (s) targ = average target-item response in synchronous condition. (s) Q3 = response to item 3 on RHI questionnaire in the synchronous condition: "I feel as if the rubber hand were my own."

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647 **Supplement 1: Methods- Recruitment and enrollment**

648 Women aged 18-65 were recruited from the community and local clinics through flyers
649 and online advertisements. Initial screening was performed over telephone using the BPD
650 section of the Diagnostic Interview for Personality Disorders [49] and questions to assess for
651 exclusion criteria. Based on results of the screen, participants were invited to the laboratory and
652 informed consent was obtained. Participants were then screened in person using the Structured
653 Interview for DSM-IV [50], and the Revised Diagnostic Interview for Borderlines (DIB-R) [27].
654 To be enrolled in the study, HCs had no current psychiatric conditions, and BPD participants
655 had no current substance dependence and no primary psychotic disorder. On DIB-R, enrolled
656 HCs scored ≤ 4 (scaled total), and enrolled BPD participants scored ≥ 8 (scaled total). Enrolled
657 participants had no history of neurologic injury or illness. We also collected information on
658 participant self-reported race and education level.

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660 **S2: Symptom and self-report scale**

661 The Beck Anxiety Inventory (BAI) is a 21-item self report scale that has established
662 reliability (Cronbach's alpha 0.94) and validity ($r = 0.54$ versus diary reports of anxiety) in an
663 initial psychometric validation study [51, 52]. In our sample, 20 HC subjects and 23 BPD
664 subjects completed the scale.

665 The Beck Depression Inventory (BDI-II) is a 21-item scale with established reliability
666 (Cronbach's alpha 0.9) and validity ($r = 0.71 - 0.86$ versus a range of commonly used
667 depression scales) in large meta-analysis [53]. In our sample, 21 HC subjects and 23 BPD
668 subjects completed the scale.

669 The Personality Inventory for DSM-5 (PID-5) is a 220 item self-rated personality trait
670 scale that assesses personality trait facets. The facets can be grouped into 5 broader trait
671 domains: Negative Affect, Detachment, Antagonism, Disinhibition, and Psychoticism. Domain
672 scales have established reliability (Cronbach's alpha ranging from 0.84-0.96 for trait domains)

673 and validity ($r = 0.44-0.67$; median $r = 0.53$ for each train domain compared to conceptual
674 counterpart of the Personality Psychopathology Five [25, 54]. In our sample, 18 HC subjects
675 and 20 BPD subjects completed all trait domain scales. 1 HC subject completed subscales for
676 antagonism, disinhibition, and psychoticism only.

677 The Structured Clinical Interview for DSM-IV Personality Questionnaire was not initially
678 designed as a stand-alone instrument, but it has been found to have few false-negatives, and to
679 be reliable compared to the clinician-administered version [55] [56]. In our sample, 21 HC
680 subjects and 24 BPD subjects completed this questionnaire.

681 The Revised Diagnostic Interview for Borderlines (DIB-R) [27], is a diagnostic interview
682 used to diagnose BPD with established internal reliability (e.g. Cronbach's $\alpha = 0.82$ in an
683 adolescent sample) [57], and validity (for cutoff of scaled score of 8, the DIB-R had a sensitivity
684 of 0.82, a specificity of 0.80, compared to clinician-assessed DSM-III diagnostic criteria) [27].
685 The interview consists of 186 standard questions and 108 scores. Responses are totaled to
686 score 22 descriptive statements reflecting features of BPD. Scores are then totaled for
687 diagnostic determination and symptom burden assessment. Symptom burden is additionally
688 characterized into 4 symptom-cluster subscales: affect, cognition, impulsivity, and interpersonal
689 relationships. In our sample, 21 HC subjects and 24 BPD subjects completed this questionnaire.

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692 **S3: Results- Induction of illusory limb ownership**

693 For each group (HC and BPD), we conducted a 2 x 2 ANOVA test to compare the
694 effects of condition (synchronous/asynchronous) and item-type (target/non-target) on subjective
695 endorsement of the item. We found a main effect of condition in both groups, with greater
696 endorsement after synchronous than asynchronous stimulation (**BPD**: $F(1,23) = 12.59$, $p <$
697 0.005 , mean score sync = 2.98, SE 0.19, mean score async = 2.31, SE 0.20, **HC**: $F(1,20) =$
698 11.87 , $p < 0.05$, mean score sync = 2.25, SE = 0.20, mean score async = 1.67, SE 0.17), . We

699 also found a main effect of question type with greater endorsement of target versus non-target
700 items (**BPD**: $F(1,23) = 17.60, p < 0.001$, mean score target = 3.02, SE = 0.18, mean score non-
701 target = 2.27, SE 0.20, **HC**: $F(1,20) = 11.13, p < 0.005$), mean score target = 2.16, SE = 0.19,
702 mean score non-target = 1.75, SE 0.16. Taken together, these results suggest that we were
703 able to successfully induce subjective experience of the RHI in both BPD and HC groups. Also,
704 the synchronous condition is more illusion-inducing than the asynchronous condition, and the
705 target items are more strongly endorsed than the non-target items.

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709 **S4: Results- Relationship between proprioceptive drift and RHI questionnaire**

710 Across groups, there were weak correlations that fell short of statistical significance
711 between proprioceptive drift and target item endorsement in the synchronous ($r = 0.20, p =$
712 0.099 , one-tailed) and asynchronous ($r = 0.22, p = 0.072$, one-tailed) conditions. While this
713 relationship was not significant in the HC group, there was a moderate relationship with trend-
714 level significance in the synchronous condition ($r = 0.32, p = 0.066$, one-tailed) and a moderate
715 statistically significant relationship in the asynchronous condition ($r = 0.45, p = 0.013$, one-tailed)
716 in the BPD group.

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