CORTEX 185 (2025) 270–285

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Research report

The tangled threads: Unveiling the interplay between the sense of body ownership and the sense of agency in impacting the bodily-self representation in eating disorders

Marcella Romeo [a,b], Livia Colle [c,e], Dize Hilviu [c], Paola Longo [d], Emiliano Ricciardi [b], Giovanni Abbate-Daga [d], Francesca Garbarini [a,e,f] and Carlotta Fossataro [a,f,*]

[a] MANIBUS LAB, Psychology Department, University of Turin, Turin, Italy
[b] MoMiLab, IMT School for Advanced Studies Lucca, Lucca, Italy
[c] Psychology Department, University of Turin, Turin, Italy
[d] Eating Disorders Centre, Department of Neuroscience, University of Turin, Turin, Italy
[e] NIT, Neuroscience Institute of Turin, Turin, Italy
[f] Human Science and Technologies, University of Turin, Turin, Italy

ARTICLE INFO

Article history:
Received 29 July 2024
Revised 10 February 2025
Accepted 19 February 2025
Received 29 July 2024
Action editor Alessandro Farnè
Published online 6 March 2025

Keywords:
Eating disorders
Anorexia nervosa
Bulimia nervosa
Sense of body ownership
Sense of agency

ABSTRACT

The feeling of owning a body (body ownership) and controlling its actions (sense of agency) contributes to the emergence of the bodily-self representation, whose alteration is at the root of the central psychopathology of Eating Disorders (EDs). Yet, studies addressing these aspects in EDs provided inconsistent results. Here, we simultaneously test body ownership and sense of agency in EDs compared to controls by exploiting different rubber hand illusion (RHI) paradigms (i.e., classic visuo-tactile, passive and active visuo-motor versions). In any RHI versions, no differences in the susceptibility to the illusion between EDs patients and controls emerged at the body ownership questionnaire, thus suggesting a normal multisensory integration mechanism. Crucially, correlation analysis revealed that a higher level of body dissatisfaction is associated with increased susceptibility to RHI, as measured by the body ownership questionnaire. Interestingly, patients with a bulimic variant of EDs reported agency toward the fake hand in the visuo-tactile RHI, revealing an abnormal sense of agency in absence of voluntary movement. Moreover, in the visuo-motor RHI, EDs patients exhibited a proprioceptive drift both in synchronous and asynchronous conditions. Hence, our results revealed a dissociation between explicit and implicit RHI measures, showing a more plastic bodily-self representation when the RHI enlists hand movements, leading to a stronger visual-capture of proprioception. This study contributes to

* *Corresponding author*. Department of Psychology, University of Turin Via Verdi 10, 10124 Turin, Italy.
E-mail address: carlotta.fossataro@unito.it (C. Fossataro).
https://doi.org/10.1016/j.cortex.2025.02.011

understanding the intricate link between body ownership and agency, shedding light on the role of voluntary actions in driving the sense of self in EDs.

1. Introduction

Body awareness is the ability to recognize our body parts as a unitary construct. It refers to the perceptual status of our body, which makes bodily sensations seem unique to oneself, suggesting the feeling that our own body belongs to us (i.e., the sense of body ownership) (Blanke, 2012; Blanke et al., 2015; Crucianelli et al., 2024; Grivaz et al., 2017; Salvato, Richter, et al., 2020; Seghezzi et al., 2019). This feeling is considered a mental state always present in our minds (Crucianelli et al., 2022; Garbarini et al., 2020; Tsakiris, 2010; Tsakiris et al., 2010). Interestingly, it is possible to dissociate between the sense of body ownership and the sense of agency (Pia et al., 2020; Tsakiris et al., 2010): the first one is the feeling of inhabiting our own body; the second one is responsible for ascribing the self-generated motor actions to ourselves, in contrast to others' actions. While body ownership could be considered as continuous and ever-present, since it originates from afferent sensory signals alone, the sense of agency is produced by voluntary actions and underpinned by efferent motor signals and sensorimotor feedbacks (Fossataro et al., 2020; Pyasik et al., 2021; Tsakiris et al., 2010). Hence, bodily ownership and sense of agency together play a key role in the construction of the bodily-self representation. Three models have been proposed to explain the relationship between the sense of agency and the sense of body. A first "independent" model described sense of agency and sense of body ownership as two different and separated processes, subserved by different brain areas and networks, with no regions shared by the two phenomena (Tsakiris et al., 2010). Conversely, the "additive" model stated that the sense of agency cannot be disentangled by the sense of body ownership. Specifically, the sense of agency generated by the execution of voluntary movements always comprises the sense of body ownership, and additionally includes components specific for the sense of agency. Thus, in this view, the two processes share a common neural network and additional brain areas that specifically subserve sense of agency. Recently, it has been proposed a third "interactive" model promoting the interdependence between body ownership and agency, as they are associated with specific brain networks for each of the two processes, which are bound together by a set of common brain areas (Seghezzi et al., 2019). Although the bodily-self representation is typically taken for granted, it can be selectively altered in several pathological conditions, both of cerebrovascular origins, such as somatoparaphrenia (Gandola et al., 2012; Romano et al., 2014; Romano & Maravita, 2019; Salvato et al., 2016, 2018, 2023) and pathological embodiment (Errante et al., 2022; Pia et al., 2020), and mental disorders, such as Eating Disorders (EDs) (Eshkevari et al., 2012; Keizer et al., 2014), Borderline Personality Disorders (Neustadter et al., 2019), Schizophrenia (Graham-Schmidt et al., 2016; Lee et al., 2021) and Autism Spectrum Disorders (Cascio et al., 2012; Galigani et al., 2021).

Within psychiatric conditions in which alterations of the bodily-self representation has been reported, EDs stand out among the others given that bodily-self representation has increasingly been recognized at the root of the central psychopathology (Floris & Panero, 2024), as evidenced by the growing number of studies investigating this aspect within the domain of eating disorders (Ambrosecchia et al., 2023; Bellard et al., 2022; Campione et al., 2017; Carey & Preston, 2019; Crucianelli et al., 2016; Eshkevari et al., 2012, 2013, 2014; Ferroni et al., 2024; Longo et al., 2024; Urgesi et al., 2011, 2012, 2014). Although the role of bodily-self representation in ED psychopathology is emerging in cognitive neuroscience, clinical studies rarely address this concept in the theoretical models and in the treatment practice (American Psychiatric Association, 2013; McLean & Paxton, 2019; Troscianko & Leon, 2020), thus suggesting the need of a deep understanding of the bodily-self related issues. Actually, the pathological focus on the body seems to have worsened after the COVID-19 pandemic (Martini et al., 2023). It is well known that most EDs patients are affected by a significant and pathological alteration of bodily experience which leads to altered eating behaviours, such as abnormal consumption or a severe and persistent restriction of food intake, with consequent compromise the individuals' physical and mental health and their social and professional activity (American Psychiatric Association, 2013). The main two severe conditions are Anorexia Nervosa (AN), characterized by a persistent restriction of calories intake with consequent weight loss, and it may occur in two different forms, namely Restricting Type (AN-R: patients lose weight restricting their caloric intake sometimes to the extent of fasting, and/or engage in excessive physical activity) or Binge-Purging Type (AN-BP: episodes of overeating are followed by compensatory behaviors such as vomiting, laxative or diuretic, and physical activity), and Bulimia Nervosa (BN), dominated by recurrent episodes of binge eating followed by inappropriate compensatory behaviours (American Psychiatric Association, 2013). In both diagnostic variants of AN the weight is significantly low than what is expected for gender, age and developmental course, while in BN the patients could be normal weight or overweight. The key clinical characteristics associated with AN and BN are negative body image, lack of self-confidence, impulsivity, perfectionism, fear of failure (performance anxiety), mood intolerance and self-criticism (Izydorczyk, 2022; Martini et al., 2021; Noordenbos & Lammers, 2018). Importantly, a distorted body image and representation is at the core of EDs aetiology and maintenance (American Psychiatric Association, 2013): patients with EDs overestimate their weight and shape and are extremely concerned about their appearance. This disturbance is deep and pervasive (Marzola et al., 2020), and some studies described alterations even in implicit body-

related components such as body schema and sense of agency (Colle et al., 2023; Gadsby & Williams, 2018). All of that contributes to the often reported feelings of disgust, alienation, and shame towards the body (Glashouwer et al., 2019; Panero et al., 2022). Furthermore, EDs have a dysfunctional system for evaluating self-worth that contributes to the maintaining of the disorder. Indeed, whereas most people evaluate themselves based on their perceived performance in a variety of domains of life (e.g., the quality of relationships, work, parenting, sporting ability, etc.), patients with EDs judge themselves primarily, or even exclusively, based on their eating habits, body shape or weight and their ability to control them. Hence, their lives become centred on controlling eating, body-shape and weight to achieve thinness and avoid weight gain. Finally, their unhealthy eating behaviour is the means for achieving a strong sense of self (Bruch, 1974; Fairburn et al., 2003).

Over the past few years, a growing number of studies have taken an interest in understanding the bodily-self representation in EDs (Caglar-Nazali et al., 2014), exploring whether and to what extent the body representation is altered across different EDs categories. However, the obtained results are controversial (Carey & Preston, 2019; Case et al., 2012; Eshkevari et al., 2012; Keizer et al., 2014). For example, to explore the perceptual stability of the sense of body ownership in EDs a few studies exploited the Rubber Hand Illusion (RHI) (Botvinick & Cohen, 1998), a well-known experimental paradigm that allows to induce an illusory feeling of ownership over a fake hand by creating a multisensory conflict across visual, tactile and proprioceptive channels [either in a visuo-tactile version (Botvinick & Cohen, 1998) or in a visuo-motor version (Kalckert & Henrik Ehrsson, 2012; 2014,b), see methods for details]. Studies that exploited the visuo-tactile RHI showed that EDs individuals experienced the illusion significantly more strongly than controls, suggesting a more plastic bodily-self representation in EDs (Eshkevari et al., 2012, 2013; Keizer et al., 2014). In line of these, a study by Zopf and collaborators provided compelling evidence that visual-proprioceptive body location perception is altered in AN patients (Zopf et al., 2016). Indeed, to estimate the hand location EDs are more influenced by external visual hand information, relying less on proprioceptive signals. This suggests that the AN bias toward external visual body information could be due to an altered processing of afferent proprioceptive signals. The first and the only study that exploited the visuo-motor RHI to investigate the stability of the sense of agency and its interaction with body ownership within EDs population is a study by Carey & Preston (2019). The study showed that both EDs and controls displayed a similar subjective experience of illusory ownership and agency towards the fake hand, thus supporting the view of a normal bodily-self representation in EDs. However, since this study jointly investigated the sense of body ownership and agency through the active visuo-motor RHI, the specific contribution of the sense of agency and the sense of body ownership in giving rise to bodily-self representation cannot be disentangled. The lack of difference between controls and EDs in body ownership and agency may be explained by the enhancement of subjective body ownership as a result of subjective agency induced by the illusion condition within the visuo-motor RHI.

Against this background, the aim of the present study is to independently test the sense of body ownership and the sense of agency in the same group of EDs patients affected by either restrictive and bulimic variants of EDs. To this aim, we exploited the three types of RHI, such as the classic visuo-tactile RHI version (Botvinick & Cohen, 1998) and the visuo-motor RHI (Kalckert & Henrik Ehrsson, 2012; 2014,b) in both its active and passive forms. We anticipate that patients with EDs will exhibit a stronger illusion of ownership in the visuo-tactile RHI compared to healthy controls. This expectation is supported by previous studies that have focused specifically on the alterations of sense of body ownership in EDs (Eshkevari et al., 2012, 2013; Keizer et al., 2014). On the contrary, in line with a previous study (Carey & Preston, 2019), in the visuo-motor RHI we may expect to confirm that the contribution of active movements, engaging more sensory information including cutaneous afferents signalling skin stretching and also muscle spindle receptors and joint receptors (Proske & Gandevia, 2012), would ground patients to their sense of self restoring the RHI effects at the level observed in controls. Furthermore, the comparison between the active and the passive version of the visuo-motor RHI would allow us to disentangle the contribution of the efferent signals from the motor commands in giving rise to the feeling of body ownership either when the finger is moved voluntarily or when it is not as in the passive RHI. Moreover, we tested whether the patients' susceptibility to the RHI may be related to the severity of eating-related symptoms assessed by the administered self-report questionnaires. Finally, we have also explored whether the body mass index (BMI) could have a significant role in driving the susceptibility to the RHI.

2. Material and methods

2.1. Participants

A total of 71 female participants was enrolled for the present research, 31 of them as healthy control group (HC) and 40 as experimental group (ED). Within the ED group, 20 participants were diagnosed with Anorexia Nervosa Restrictive Type (AN-R), 20 participants with Anorexia Nervosa Binge/Purging Type and Bulimia Nervosa (16 individuals with AN-BP and 4 with BN), according to the criteria of the DSM-5 (American Psychiatric Association, 2013). Participants diagnosed with a bulimic variant of EDs (i.e., AN-BP and BN) were grouped in one category (AN-BP/BN) since they show a similar behavioural pattern in relation to the binge purging behaviours of the disorders (Cuthbert & Kozak, 2013) [see also (Sagiv et al., 2019) for a similar grouping method]. The three groups showed a significant difference when comparing their BMI ($F_{(2,57)} = 42.040$; $p < .001$; partial $\eta^2 = .59$). Specifically, AN-R patients are significantly different compared to both AN-BP/BN ($p < .0001$) and HC group ($p < .00001$), and AN-BP/BN group is significantly different compared to HC group ($p = .0098$). However, it is worth noticing that the BMI information is available for only 20

healthy participants. Concerning the pharmacology treatment, in both AN-R and AN-BP/BN groups most of the patients were under pharmacological treatment. Specifically, 14 out of 20 AN-R patients and 17 out of 20 AN-BP/BN patients took at least one psychotropic drug. The Fisher exact test did not detect any difference between the two experimental groups (AN-R and AN-BP/BN) ($\chi^2(1) = 1.29$; $p = .22$). All patients were recruited at the Eating Disorders Centre—University of Turin, AOU Città della Salute e della Scienza in Turin, Italy. Patients had not to be affected by comorbid schizophrenia, schizo-affective disorder, bipolar disorder or organic mental syndrome. The HC group had to report no history of current or previous psychiatric illness. Substance and/or alcohol use or dependence were considered as exclusion criteria. No significant distinction was observed in the age among the three groups (HC, AN-R and AN-BP/BN; $F_{(2,68)} = 2.93$; $p = .06$; partial $\eta^2 = .08$). However, they differentiate at the educational level ($F_{(2,68)} = 30.98$; $p < .001$; partial $\eta^2 = .48$) since the HC group present a higher number of years of education compared to the other two groups. All subjects signed the informed consent. In accordance with the Declaration of Helsinki, the experimental procedure was approved by local ethics committee of both the University of Turin (Prot. n. 3167, 1/02/2016) and Città della Salute e della Scienza (Prot. n. 0017116, 13/02/2019). See Table 1 for demographical and clinical information.

To estimate the sample size of the experiment we exploited previous RHI data from our lab (Fossataro et al., 2018) and G-Power software has been used to estimate, in an a priori analysis, the sample size in a paired t test (two tailed), using Cohens' d = .94; $\alpha = .05$; Power (1-β err prob) = .95. A total sample size of 17 subjects was indicated. However, we estimated, conservatively, a larger sample size because we planned to analysed data by means of a more complex model, including three types of RHI and three experimental groups. For this reason, we recruited 20 AN-R patients and 20 AN-BP/BN and 31 healthy controls which is in line with the sample of a previous RHI study on ED by Carey and Preston (Carey & Preston, 2019).

2.2. Experimental procedure

Participants underwent three versions of the RHI paradigm, leading to three experimental procedures: *visuo-tactile*, *visuo-motor active* and *passive* (see Fig. 1). The RHI was performed in a vertical setting, as in a previous study by Kalckert and Ehrsson (Kalckert & Henrik Ehrsson, 2012), wherein participants were seated in front of a table and placed their right arm and hand into a box, so that the right hand was covered from their view. A rubber hand was positioned above the box, aligned to the participants' right shoulder.

Prior to each experimental procedures, participants underwent a *proprioceptive judgement task*, in which they were blindfolded and they had to estimate the perceived position of their right index finger. To this aim, participants were instructed to rapidly and accurately point with their left index finger toward a measuring tape in centimeters located on the side of the box to reach the perceived position of their right index finger for six times. For each pointing participants were asked to perform the pointing movement starting from the *baseline position* (i.e., left hand on the left knee).

In the *visuo-tactile RHI* protocol, the classical version of the visuo-tactile RHI was exploited (Botvinick & Cohen, 1998; Bruno et al., 2022; Fossataro et al., 2018; Galigani et al., 2021; Rossi Sebastiano et al., 2021; Rossi Sebastiano et al., 2024). The experimenter stroked the rubber hand and the participant's hand in either a *synchronous* or an *asynchronous* fashion.

In the *Active visuo-motor RHI* (VM-Active) protocol (Kalckert & Ehrsson, 2012), the participants and the rubber hand's index finger were tied to two sticks that can be either connected to each other or not. Participants were instructed to move their right index finger performing a tapping. In the *synchronous* condition, the sticks were linked together, thus when participants lift their finger, the rubber hand's finger simultaneously moved. In the *asynchronous* condition, the sticks were untied, thus the stick of the fake finger was manually moved by the experimenter introducing a delay with respect to the participant's movement, so that artificial finger appeared to be moving in opposite phases.

Table 1 – Participants' demographic information.

Group label	N	Age	Educational level	Body Mass Index	Pharmacological treatment	
		M ± SD	M ± SD	M±SD	Frequency	(type of drugs, Frequency)
HC	31	26.03 ± 4.59	17.35 ± 2.03	20.45 ± 2.42[a]	–	
AN-R	20	22.55 ± 7.32	13.15 ± 1.98	14.31 ± 1.96	14	AD = 12 BDZ = 9 AP = 4 STAB = 1
AN-BP/BN	16/4	23.10 ± 4.98	13.50 ± 2.46	16.40 ± 2.05	17	AD = 11 BDZ = 13 AP = 12 STAB = 3

Abbreviations: HC = Healthy controls; AN-R = Anorexia Nervosa Restrictive; AN-BP/BN = Anorexia Nervosa Binge/Purging and Bulimia Nervosa; AD = Antidepressant; BDZ = Benzodiazepines; AP = Antipsychotics; STAB = Mood stabilizers.

[a] BMI of 11 participants of the HC groups is missing.

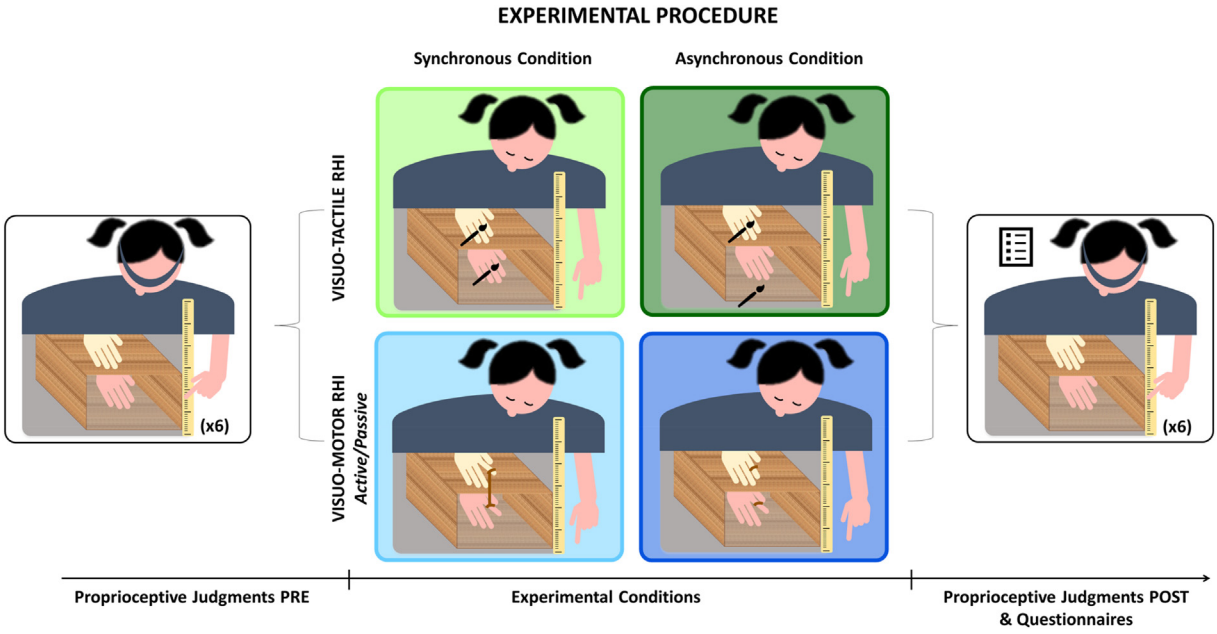

Fig. 1 – Experimental procedure: the figure represents the three RHI protocols (visuo-tactile, visuo-motor active and passive) in both conditions (synchronous and asynchronous). All the RHI protocols begin with six proprioceptive judgements, during which participants have to indicate where they feel their index finger by pointing on the ruler. The proprioceptive judgments are followed by the illusion procedure, which can be either synchronous or asynchronous, according to the condition. Then, six proprioceptive judgements and the subjective questionnaires are collected.

In the *Passive visuo-motor RHI* (VM-Passive) protocol (Kalckert & Ehrsson, 2012), the participants and the rubber hand's index finger were tied to two sticks as in the active one, but participants were instructed to be relaxed while the experimenter moved the two fingers by means of the two sticks either simultaneously (*synchronous* condition) or not (*asynchronous* condition).

In each protocol, the stimulation procedure, either synchronous or asynchronous, lasted 90 s. The order of the three RHI protocols was randomized between subjects, as well as the order of conditions (i.e., synchronous, asynchronous) that was counterbalanced between subjects and RHI types.

Immediately after the RHI stimulation phase, in both the synchronous and the asynchronous conditions, the *proprioceptive judgement* task was repeated to derive the *proprioceptive drift* on the vertical plane, by subtracting the pre-stimulation by the post-stimulation rates: positive values represent a shift toward the position of the rubber hand.

Following the post-stimulation pointing task, participants were administered with the *body ownership* and the *sense of agency* questionnaires (Kalckert & Ehrsson, 2014b), investigating the sense of ownership and agency toward the rubber hand. Both questionnaires are composed of three items presented in randomized order (See Table 2). Subjects were asked to express their agreement/disagreement regarding each item of the questionnaires on a 7-points Likert Scale, going from −3 to +3, where 0 represents neutrality.

2.3. *Self-report questionnaires*

Participants completed a set of self-report questionnaires allowing to collect different measures on several psychological dimensions. Some of these questionnaires were specifically focused on eating behaviours, i.e., IDEA and EDI 2, while other psychiatric symptoms were assessed through further questionnaires. It follows a brief and introductive description for each test.

- *Identity and Eating Disorders*—IDEA (Stanghellini et al., 2012) provides a clinical assessment of abnormalities about identity's perception and experience of the perception of one's own body. The questionnaire explores how different variables such as the gaze of others, the dietary restriction and objective features (e.g., weight) can alter and impact the life and inner perception of participants' body. Moreover the tool investigates the sense of alienation from the body, commonly reported by patients with eating disorders.

Table 2 – Statements employed to measure the sense of body ownership and agency during the experiment.

Body ownership items	1) I felt as if I was looking at my own hand 2) I felt as if the rubber hand was part of my body 3) I felt as if the rubber hand was my hand
Agency items	1) I felt as if I could cause movements of the rubber hand 2) I felt as if I could control movements of the rubber hand 3) The rubber hand was obeying my will and I can make it move just like I want it

- *Eating Disorder Inventory 2*—EDI 2 (Garner, 1991) assesses psychological features associated with eating disorders. It comprises eleven sub-scales, which include: drive for thinness, bulimia, body dissatisfaction, perfectionism, interpersonal distrust, interoceptive awareness, maturity fears, ineffectiveness, asceticism, impulsiveness and social insecurity.
- *Body Shape Questionnaire*—BSQ (Cooper et al., 1987; Marzola et al., 2022) evaluates the levels of body dissatisfaction investigating in particular the feelings towards body shape and the perception of being fat, typically reported by patients with EDs as a core concern. The tool has 34 items and focuses on the previous four weeks; a higher global score indicates a more marked body dissatisfaction.
- *Body Checking Questionnaire*—BCQ (Reas et al., 2002) assesses, with 23 items, the frequency of body checking behaviours, such as check the diameter of the wrist or pinching cheeks to check the fatness. It considers the current level of involvement in these conducts that could transform into compulsions or worsen body dissatisfaction.
- *Body Image Avoidance Questionnaire*—BIAQ (Rosen et al., 1991) estimates the levels of body image avoidance with 19 items organized in four factors: *clothing* (i.e., wearing large and/or covering clothes), social activities (i.e., the avoidance of contest in which the attention of others could be on food or weight), eating restrain (i.e., restriction of caloric intake), grooming and weighing (i.e., behaviors that involve the confrontation with the body).
- *Beck Depression Inventory*—BDI (Beck et al., 1961) measures the incidence and severity of depressive symptoms, investigating both the cognitive-affective component and the somatic one. The questionnaire is composed by 21 items based on how he/she felt in the previous two weeks about specific areas of daily life: sadness, pessimism, sense of failure, loss of pleasure, guilt, feelings of punishment, self-esteem, self-criticalness, suicidal thoughts, crying, agitation, loss of interest, indecision, sense of worthlessness, loss of energy, changes in sleeping, irritability, changes in appetite, concentration, fatigue, and loss of libido.
- *State-Trait Anxiety Inventory*—STAI-Y (Spielberger & Sydeman, 1994) assesses in individual anxiety trough two sub-scales. The Y1 investigates state anxiety (i.e., how the individual feels in the specific moment of the administration of the questionnaire, and describes his/her current moods), while the Y2 evaluates trait anxiety (i.e., the participants' usual mood, their stable and persistent emotional state). Both scales contain 20 items, and the score is assigned on a 4-point Likert's scale in which 1 corresponds to "not at all" and 4 to "very much".

2.4. *Data analysis*

Firstly, to assess whether different susceptibilities to the illusion emerged within each group of participants based on the types of RHI, we conducted a 3*2 repeated-measures ANOVA separately for each dependent variable (i.e., sense of body ownership questionnaire; sense of agency questionnaire; proprioceptive drift) and for each group (HC; AN-R; AN-BP/BN). The within-subject factors were "Type of RHI" (3 levels: visuo-tactile; visuo-motor active; visuo-motor passive) and "Condition" (2 levels: synchronous; asynchronous). Correction for multiple comparison were performed by applying Bonferroni post-hoc tests.

Then, to compare the illusion effect induced by each type of RHI between groups, we calculated a *RHI index*, by subtracting the asynchronous condition by the synchronous one, so that the greater the RHI index the greater the illusion effect. Thus, the obtained index for each measure (i.e., sense of body ownership questionnaire; sense of agency questionnaire; proprioceptive drift), representing the pure effect of the RHI susceptibility, were analysed separately for each type of RHI by means of a one-way ANOVA with "Group" (3 levels: HC, AN-R, AN-BP/BN) as between-subject factor. Correction for multiple comparison were performed by applying Bonferroni post-hoc tests.

Finally, to explore any possible relation between clinical symptoms of ED and the RHI susceptibility, the obtained RHI indexes (i.e., body ownership and sense of agency questionnaires, and proprioceptive drift) and body-image related self-report questionnaires scores were correlated by means of Spearman correlation tests and p-values were FDR corrected for multiple comparisons. Specifically, the RHI indexes were correlated with three subscales of the EDI-2 commonly adopted to highlight the core symptoms of EDs (i.e., Drive for Thinness; Bulimia; Body Dissatisfaction), and the questionnaires specifically assessing body image disturbance, namely the BSQ, the BCQ and the BIAQ scores in the two groups of patients (i.e., AN-R: AN-BP/BN). Furthermore, we have also performed a Spearman correlation between RHI indexes and BMI.

Statistical analyses were performed by means of Statistica Software release 7 and IBM SPSS Statistics Software release 29.0.1.0.

3. Results

3.1. *Rubber hand illusion*

For the within-group analyses, each dependent variable was entered in a 3*2 repeated measures ANOVA with "Type of RHI" (3 levels: visuo-tactile; visuo-motor active; visuo-motor passive) and "Condition" (2 levels: synchronous; asynchronous) as within-subject factors, separately for each group.

For the between-group analyses, the RHI indexes obtained in each type of RHI were entered in three one-way ANOVAs with "Group" (3 levels: HC, AN-R, AN-BP/BN) as between-subject factor, one for each RHI version (i.e., visuo-tactile; visuo-motor active; visuo-motor passive).

3.1.1. *Body ownership questionnaire*

3.1.1.1. Within-group results. For all groups, we found a main effect of condition, with significantly higher ratings in synchronous compared to asynchronous stimulation (HC: $F_{1,30} = 133.21$, $p < .001$; partial $\eta^2 = .82$; AN-R: $F_{1,19} = 47.56$, $p < .001$; partial $\eta^2 = .71$; AN-BP/BN: $F_{1,19} = 42.0$, $p < .001$; partial $\eta^2 = .69$).

3.1.1.2. Between-groups results. In any of the RHI versions, the one-way ANOVAs over the body ownership questionnaire

showed no differences between groups (visuo-tactile: $F_{2,68} = 1.76$, $p = .18$, partial $\eta^2 = .05$; visuo-motor active: $F_{2,68} = 3.01$, $p = .06$, partial $\eta^2 = .08$; visuo-motor passive: $F_{2,68} = .92$, $p = .41$, partial $\eta^2 = .03$). See Fig. 2.

3.1.2. *Sense of agency questionnaire*

3.1.2.1. WITHIN-GROUP RESULTS. In the HC group, the ANOVA showed a significant Type of RHI*Condition interaction ($F_{2,60} = 38.85$, $p < .001$; partial $\eta^2 = .56$), suggesting that participants gave significantly higher ratings in synchronous compared to asynchronous only in the visuo-motor active

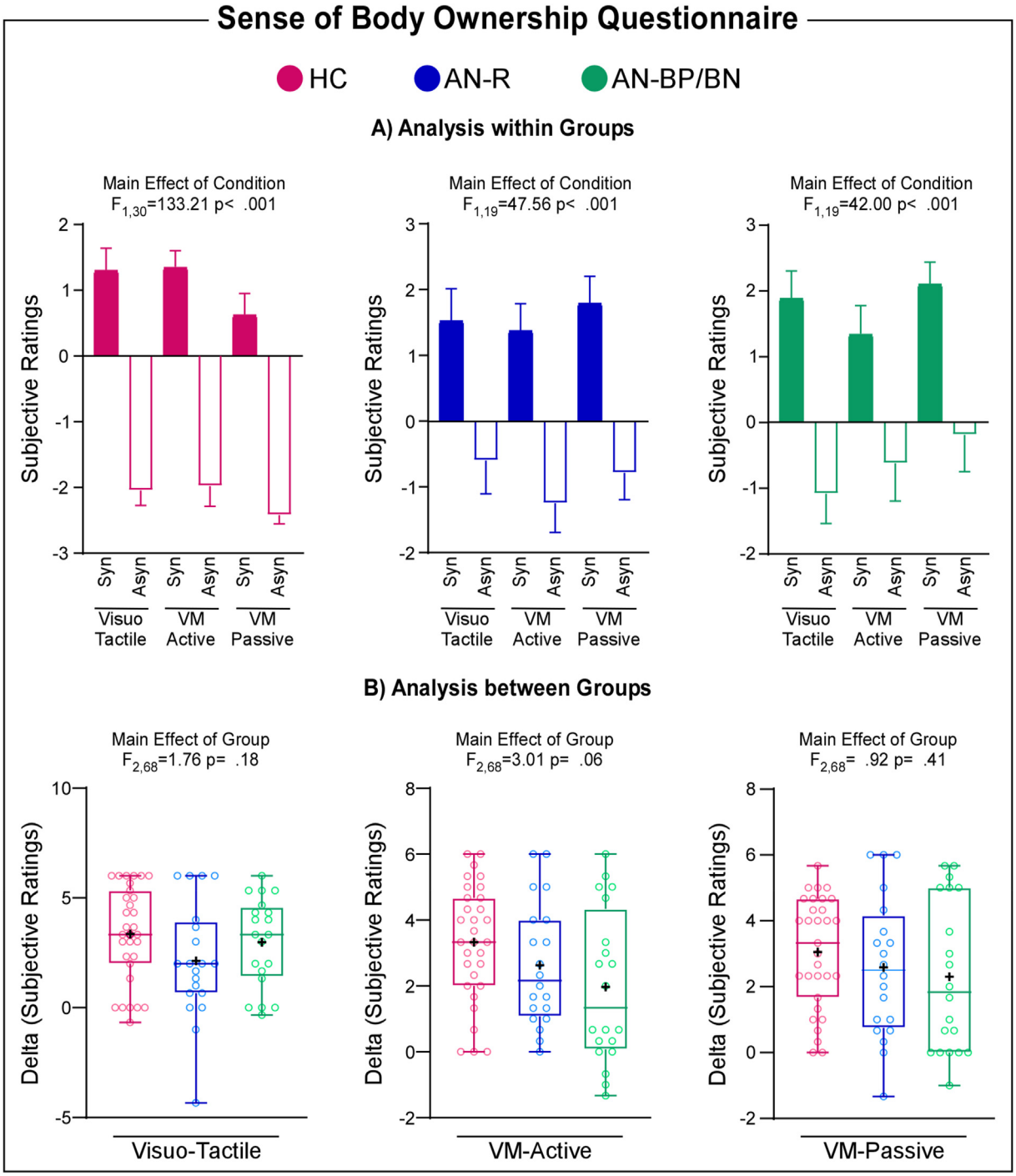

Fig. 2 – Ownership questionnaire results. A) Subjective ratings at the Body Ownership questionnaire in the three RHI types (Visuo-Tactile, VM-Active, VM-Passive) for Controls (in magenta), AN-R patients (in blue) and AN-BP/BN patients (in green). B) RHI index in each type of RHI among groups. In the boxplot, whiskers represent the minimum and the maximum value, the limits of the box represent the first and the third quartile, the median is depicted by the line that divides the box into two parts, the cross represents the mean value and the circles represent single-subjects' values. *$p < .05$. **$p < .005$

($p < .001$) and passive ($p < .001$) RHI, and not in the visuo-tactile ($p = .52$). Further, ratings given in the synchronous condition of the visuo-motor active RHI are significantly greater than those of all the other conditions (p_s always <.001). In the AN-R group as for the HCs, the ANOVA showed a significant Type of RHI*Condition interaction ($F_{2,38} = 9.46$, $p < .001$; partial $\eta^2 = .33$), suggesting that patients gave significantly higher ratings in synchronous compared to asynchronous only in the visuo-motor active ($p < .001$) and passive ($p = .002$) RHI, and not in the visuo-tactile RHI ($p = .27$). Moreover, AN-R patients reported higher ratings in the synchronous condition of the visuo-motor active than in all the other conditions (p_s always <.001). In the AN-BP/BN group, we found a significant Type of RHI*Condition interaction ($F_{2,38} = 7.61$, $p = .002$; partial $\eta^2 = .29$). Indeed, despite ratings given in the synchronous condition of the visuo-motor active are significantly higher than those given in all the other conditions (p_s always <.001) as in HC and AN-R groups, in the AN-BP/BN group a significant RHI effects (with higher ratings in synchronous compared to asynchronous) is present in all the types of RHI, including the visuo-tactile RHI (visuo-tactile: $p < .001$; visuo-motor active: $p < .001$; visuo-motor passive: $p = .02$).

3.1.2.2. Between-groups results. In the visuo-tactile RHI, the one-way ANOVA over the sense of agency questionnaire showed a main effect of Group ($F_{2,68} = 3.93$, $p = .02$, partial $\eta^2 = .10$), suggesting that AN-BP/BN patients demonstrated a stronger illusory agency over the rubber hand compared to HC ($p = .02$), but not against AN-R patients (.17). No difference emerged when comparing HC and AN-R ($p = 1$). Neither in the active nor in the passive visuo-motor RHI, any significant effect of groups was observed (visuo-motor active: $F_{2,68} = 2.31$, $p = .11$, partial $\eta^2 = .06$; visuo-motor passive: $F_{2,68} = .13$, $p = .88$, partial $\eta^2 = .004$). See Fig. 3.

3.1.3. *Proprioceptive drift*

3.1.3.1. Within-group results. In the HC group, the ANOVA showed a main effect of condition ($F_{1,30} = 26.93$, $p < .001$; partial $\eta^2 = .47$), suggesting that independently from the type of RHI, the shift of the perceived position of the own hand was significantly greater in the synchronous than asynchronous condition. In the AN-R group, the ANOVA showed a significant Type of RHI*Condition interaction ($F_{2,38} = 4.54$, $p = .02$; partial $\eta^2 = .19$), suggesting that the shift of the perceived position of the own hand was significantly greater in the synchronous than asynchronous only in the visuo-tactile ($p = .002$) and visuo-motor passive ($p = .001$) RHI, and not in the visuo-motor active ($p = .1$). In the AN-BP/BN group, we found a significant main effect of Condition ($F_{1,19} = 4.51$, $p = .047$; partial $\eta^2 = .19$), suggesting that independently from the type of RHI, the shift of the perceived position of the own hand was significantly greater in the synchronous than asynchronous condition.

3.1.3.2. Between-groups results. In the visuo-tactile RHI, the one-way ANOVA over the proprioceptive drift showed no differences among groups ($F_{2,68} = .18$, $p = .84$, partial $\eta^2 = .005$). In the visuo-motor active RHI, we found a significant main effect of Group ($F_{2,68} = 5.60$, $p = .006$, partial $\eta^2 = .14$), with a smaller proprioceptive drift compared to HC in AN-R patients ($p = .008$) and marginally significant in AN-BP/BN ($p = .07$). In the visuo-motor passive RHI, a significant main effect of Group ($F_{2,68} = 4.84$, $p = .01$, partial $\eta^2 = .12$) was observed, as AN-BP/BN demonstrated a weaker proprioceptive drift compared to HC ($p = .009$). See Fig. 4.

3.2. *Self report questionnaire*

Results of self-report questionnaires are resumed in Table 3. Note that BSQ, BCQ and BIAQ have been completed only by patients and not by controls.

3.3. *Correlations*

For what concerns correlation between RHI effect and ED symptoms, Spearman Correlation tests revealed a statistically significant positive correlation between body ownership questionnaire scores following the visuo-tactile RHI and Body Dissatisfaction ($r_s = .382$, $p_{corr} = .046$) subscale of the EDI-2. Whereas, only a trend approaching the significant level has been observed for the Drive for Thinness of the EDI-2 ($r_s = .408$, $p_{corr} = .06$) and the Eating Restraint subscale of the BIAQ ($r_s = .424$, $p_{corr} = .09$). See Fig. 5, panel A), B) and C). Conversely, no significant correlations emerged between RHI measure and BMI.

4. Discussion

The present study aimed at independently testing the sense of body ownership and the sense of agency in AN, by exploiting the visuo-tactile RHI, the passive visuo-motor RHI, and active visuo-motor RHI.

As far as the sense of body ownership is concerned, overall we observed no differences in the strength of the illusory ownership between patients with AN and healthy controls. Indeed, irrespective of the type of RHI, all groups reported higher sense of body ownership over the fake hand in synchronous than in asynchronous condition. This evidence is apparently in contrast with previous findings (Eshkevari et al., 2012; Keizer et al., 2014) describing an altered sense of body ownership in AN patients, that exhibit a more plastic representation of the own body, as depicted by the greater disposition to incorporate the rubber hand. Nonetheless, despite our results suggests that patients with AN do not show such altered multisensory integration mechanism, exhibiting a normal susceptibility to the illusion as that one experienced by healthy controls, correlation results highlight that the susceptibility to the illusion is guided by the severity of ED symptoms. Specifically, Body Dissatisfaction subscale of EDI-2 is related to the amount of illusory body ownership reported in the visuo-tactile RHI. This suggests that a higher level of body dissatisfaction is linked to a more malleable body representation which is highly sensible to visual capture. Thus, we may speculate that a negative affective disposition toward one's own body appearance affects the perceptual component of the body, leading to a higher malleability of body representation. This, in turn, makes patients more susceptible to physical ideals promoted by society. This is especially relevant in AN patients in which a strong drive for thinness representing the core of the psychopathology is positively

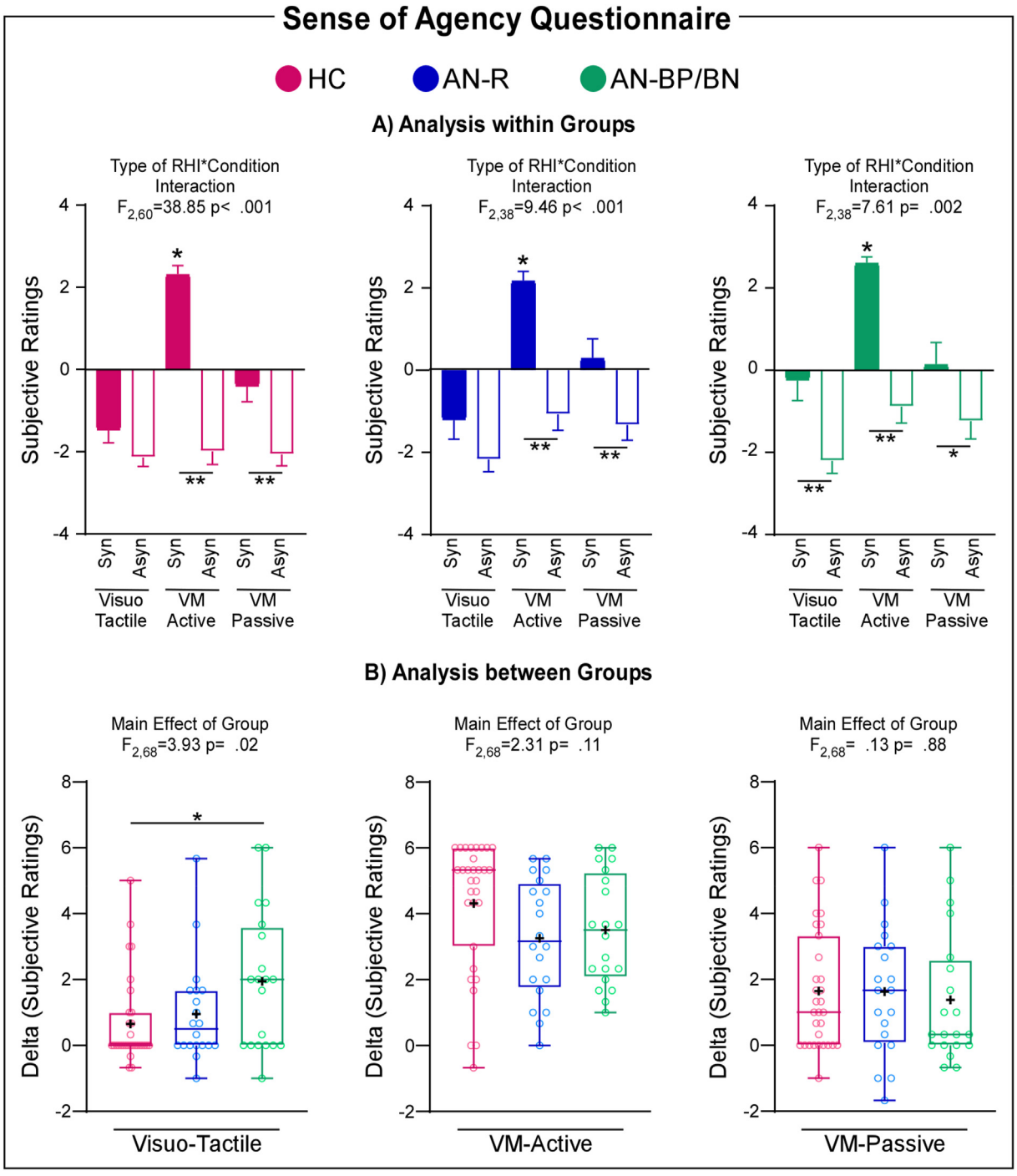

Fig. 3 – Sense of agency questionnaire results. A) Subjective ratings at the Sense of Agency questionnaire in the three RHI types (Visuo-Tactile, VM-Active, VM-Passive) for Controls (in magenta), AN-R patients (in blue) and AN-BP/BN patients (in green). B) RHI index in each type of RHI among groups. In the boxplot, whiskers represent the minimum and the maximum value, the limits of the box represent the first and the third quartile, the median is depicted by the line that divides the box into two parts, the cross represents the mean value and the circles represent single-subjects' values. *$p < .05$. **$p < .005$

reinforced by the 'thinspiration' driven by media websites (Griffiths et al., 2018), thus increasing the dissatisfaction towards the body (Salvato, Romano, et al., 2020). The persistent drive for thinness reinforced by media, alongside a rigidly perceived body image in anorexia nervosa (AN), contributes to maintaining the disorder. This phenomenon aligns with the allocentric lock hypothesis proposed by Riva (2012), suggesting that individuals with AN remain "locked" into a distorted body memory that does not update in response to changes in their actual appearance or physical condition. This rigid body image results from an inability to accurately integrate new sensory information about one's own body (such as weight gain/loss) into an updated self-representation. The allocentric lock hypothesis postulates that this distortion

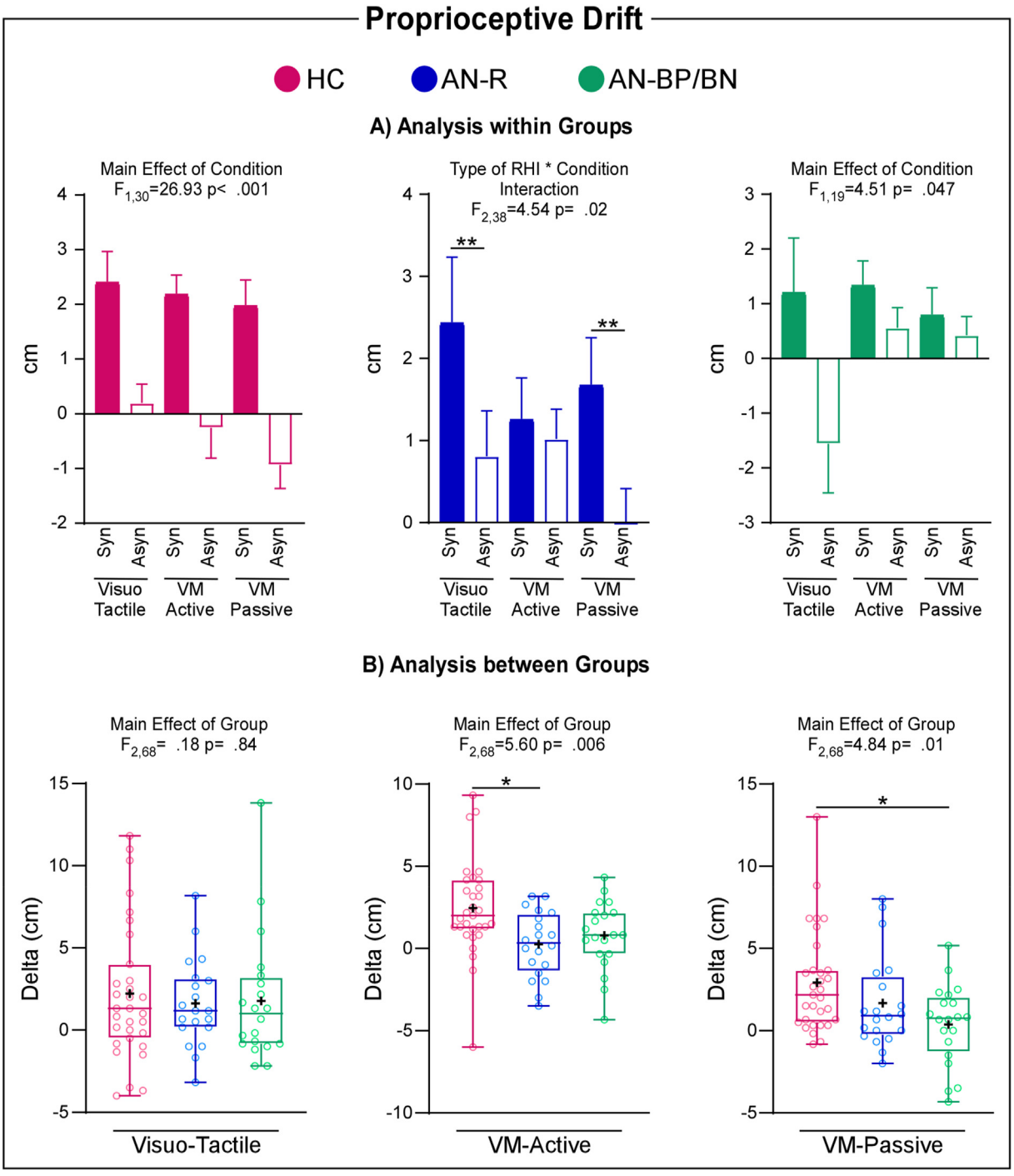

Fig. 4 – Proprioceptive drift scores results. A) Subjective ratings at the Proprioceptive drift in the three RHI types (Visuo-Tactile, VM-Active, VM-Passive) for Controls (in magenta), AN-R patients (in blue) and AN-BP/BN patients (in green). B) RHI index in each type of RHI among groups. In the boxplot, whiskers represent the minimum and the maximum value, the limits of the box represent the first and the third quartile, the median is depicted by the line that divides the box into two parts, the cross represents the mean value and the circles represent single-subjects' values. *$p < .05$. **$p < .005$

arises from an allocentric (externally anchored) perspective, where individuals rely on an outdated memory of their body rather than real-time, egocentric (self-centred) sensory inputs. In this vein, media messages glorifying thinness exacerbate such mismatch between perception and reality, thus reinforcing an idealized body image that individuals with AN may strive to attain despite health risks.

Concerning the sense of agency, in line with a previous study by Carey & Preston (2019), our data show that patients with AN exhibited a spared sense of agency in the visuo-motor active and passive RHI types compared to healthy controls. Typically the sense of agency is not addressed in the classic visuo-tactile RHI, which has been explored here because this study is focused on the comparison among the three types of

Table 3 – Means, standard deviations and comparisons for all self-report questionnaires.

Self-report Questionnaire	AN-R (*N*), *M* ± *SD*	AN-BP/BN (*N*), *M* ± *SD*	HC (*N*), *M* ± *SD*	McDonald/ Cronbach coefficients	Statistics*	Post-hoc comparisons
IDEA	(17), 2.12 ± 0.70	(18), 2.34 ± 0.98	(31), 0.648 ± 0.396	$\omega = 0.96$	$F_{(2,63)} = 45.66^{a}$ $p < 0.001$	AN-R vs HC ($p < 0.001$) AN-BP/BN vs HC ($p < 0.001$) AN-R vs AN-BP/BN ($p = 1$)
EDI 2	(20), 102.6 ± 48.19	(20), 126.7 ± 50.03	(31), 39.903 ± 45.949	$\omega = 0.95$	$\chi^2_{(2)} = 30.06^{b}$ $p < 0.001$	AN-R vs HC ($p < 0.001$) AN-BP/BN vs HC ($p < 0.001$) AN-R vs AN-BP/BN ($p = 0.742$)
BDI-II	(20), 17.58 ± 8.87	(20), 22.28 ± 8.03	(31), 7.58 ± 8.75	$\omega = 0.97$	$\chi^2_{(2)} = 24.62^{b}$ $p < 0.001$	AN-R vs HC ($p = 0.002$) AN-BP/BN vs HC ($p < 0.001$) AN-R vs AN-BP/BN ($p = 0.58$)
STAI-Y						
State	(20), 57.65 ± 12.71	(20), 63.95 ± 8.88	(31), 35.84 ± 12.53	$\alpha = 0.95$	$F_{(2,68)} = 41.33^{a}$ $p < 0.001$	AN-R vs HC ($p < 0.001$) AN-BP/BN vs HC ($p < 0.001$) AN-R vs AN-BP/BN ($p = 0.28$)
Trait	(20), 61.65 ± 9.62	(20), 68.15 ± 7.79	(31), 42.19 ± 11.87	$\alpha = 0.89$	$F_{(2,68)} = 44.89^{a}$ $p < 0.001$	AN-R vs HC ($p < 0.001$) AN-BP/BN vs HC ($p < 0.001$) AN-R vs AN-BP/BN ($p = 0.15$)
BSQ	(15), 120.67 ± 45.28	(11), 135.09 ± 48.04	-	$\alpha = 0.96$	-	AN-R vs AN-BP/BN ($p = 0.44$) [c]
BCQ	(14), 63.21 ± 24.66	(13), 61.08 ± 36.35	-	$\alpha = 0.97$	-	AN-R vs AN-BP/BN ($p = 0.86$) [c]
BIAQ	(14), 45.14 ± 16.81	(12), 45.92 ± 18.76	-	$\alpha = 0.78$	-	AN-R vs AN-BP/BN ($p = 0.91$) [c]

Abbreviations: IDEA: Identity and Eating Disorders; EDI-2: Eating Disorder Inventory, version 2; BDI-II: Beck Depression Inventory II; STAI-Y: State-Trait Anxiety Inventory; DERS: Difficulties in Emotion Regulation Scale; BSQ: Body Shape Questionnaire; BCQ: Body Checking Questionnaire; BIAQ: Body Image Avoidance Questionnaire.
* = Different statistics were used following the assumptions for the distribution of each self-report test; a = One-way ANOVA and Bonferroni post-hoc test; b = Kruskal-Wallis test and Dunn's post-hoc test; c = paired t-test.

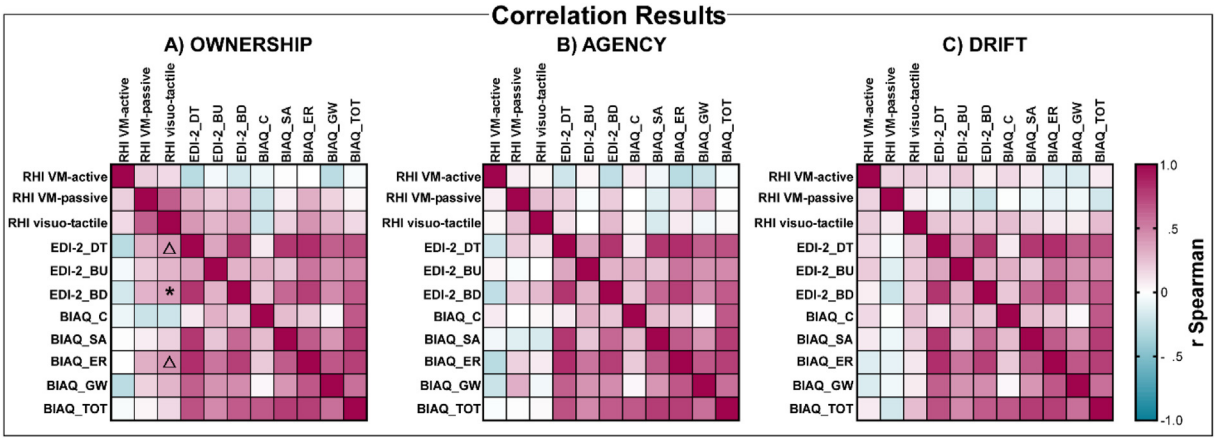

Fig. 5 – Correlations results. The figure depicts the correlation between clinical symptoms of EDs and RHI susceptibility for the sense of body ownership questionnaire (panel A), the sense of agency questionnaire (panel B), and the proprioceptive drift (panel C). The colour bar represents the correlation coefficient (Spearman r), *$p < .05$; △ $.06 < p < .09$. EDI-2 DT (Drive for Thinnes); EDI-2 BU (Bulimia); EDI-2 BD (Body Dissatisfaction); BIAQ C (Clothing); BIAQ ER (Eating Restraint); BIAQ SA (Social Activity); BIAQ GW (Grooming and weighing).

RHI. Interestingly, as novel finding we demonstrated that AN-BP/BN patients showed an abnormal illusory agency in the visuo-tactile RHI, wherein no active movements are performed. Indeed, no illusory agency should be observed in this type of RHI and, actually, healthy controls and AN-R patients did not report agency in both synchronous and asynchronous conditions, whereas AN-BP/BN patients showed higher ratings of agency in the synchronous than asynchronous condition. As stated in the introduction, sense of body ownership and agency jointly contribute to build a coherent bodily-self representation (Fossataro et al., 2020; Pyasik et al., 2021; Tsakiris et al., 2010). However, while the sense of body ownership is ever present the sense of agency depends on the presence of voluntary actions. Indeed, it has been proposed that self-awareness is fed by two sources, the "acting self," that owns the efferent information and the consequent bodily sensations, and the "sensory self" that solely owns bodily sensations not intentionally generated, but only passively experienced (Tsakiris & Haggard, 2005). We may speculate that the higher disposition in feeling agency toward a static fake hand observed in AN-BP/BN patients can be ascribed to their overreliance on the "acting self" to generate the illusory body ownership as if the passively experienced sensations were not enough to attribute a body parts to their own body. Thus, we may argue that AN-BP/BN patients build self awareness on the interplay between the "sensory self" and the "acting self" more extensively than controls and AN-R patients. Relatedly, Stanghellini et al. (2012), proposed a conceptualization of EDs as a specific disorder of the "lived body" (i.e., the one's own experience of directly live the body from within, in first person). Thus patients with EDs, living their body as "alien", could be prone to exhibit different patterns of illusions compared to healthy subjects. Interestingly, this data is intertwined with the need for compulsive exercise that patients often develop with the aim, not only of reducing weight, but also of having a feeling of control and well-being correlated with active proprioception and body awareness (Casper, 2022).

As far as the proprioceptive drift, from the between group comparison, no differences emerged in the visuo-tactile RHI, thus suggesting that all groups showed a similar shift toward the fake hand position. Interestingly, in the visuo-motor active RHI, both AN-R and AN-BP/BN patients showed a significantly lower RHI index compared to controls. This can be explained by the fact that AN patients shifted the perceived position of the own hand toward the fake hand in both synchronous and asynchronous stimulations, thus suggesting a stronger susceptibility to the visual-capture of proprioception even when the movements of the own and the rubber hand are out of phase. Moreover, in the visuo-motor passive RHI a similar pattern is observed only in the AN-BP/BN group, thus suggesting that the absence of voluntary movements bring AN-R patients back to correctly perceive the own hand location. Our results are in line with the data on proprioceptive drift in visuo-motor active RHI by Carey and Preston (Carey & Preston, 2019) who found in AN patients a proprioceptive drift in both illusion and control conditions even though not significant. Based on this result, we may argue that, despite AN patients explicitly reported a normal illusory body ownership and agency over the fake hand in the visuo-motor RHI, they implicitly revealed an enhanced susceptibility to the visual-capture of proprioception.

Overall, the results of our study may corroborate the "interactive" model of sense of agency and body ownership proposed by Seghezzi and collaborators (Seghezzi et al., 2019). Such neurocognitive model describes a neurofunctional overlap between sense of agency and body ownership, which can be reflected in the strong interplay between "sensory self" and "acting self" shown by AN patients to give rise to a cohesive sense of self. Hence, given the behavioral evidence that the interconnection between agency and ownership in AN patients is particularly enhanced, they may represent a

valuable model to deepen in future studies the neurofunctional interplay between these constructs.

Despite the novel findings of the study, some limitations deserve attention and must be taken into account in interpreting the results and their implication. First of all, we acknowledge that the sample enrolled in the study is relatively small. Furthermore, in our sample of EDs, we included the AN-BP and BN variants in the same group, which mainly consisted of AN-BP patients and only a few BN patients. This grouping method has been adopted because participants diagnosed with a bulimic variant of EDs (i.e., AN-BP and BN) show a similar behavioural pattern in relation to the binge purging behaviours of the disorders (Cuthbert & Kozak, 2013; Sagiv et al., 2019). However, future experiments relying on a more significant number of EDs patients would allow better exploring alterations of bodily-self representation in the EDs spectrum. Further research addressing EDs categories in different phases of the illness, comparing individuals in the acute phase with those in the recovery phase, would be informative on the role of body ownership/agency interplay in the course of the illness.

5. Conclusion

Overall our results indicate that in EDs different components contribute to the alteration of bodily experience. It is therefore confirmed how the alteration of body image and shape is a complex and multidimensional construct (Prnjak et al., 2022). Our findings provide evidence for a tight link between the sense of body ownership and the sense of agency in driving bodily-self awareness (Seghezzi et al., 2019). Indeed, our data support the idea that individuals with AN-BP/BN must simultaneously rely on both the "acting self" and the "sensory self" to attribute a body parts to their own body. Interestingly, despite EDs patients experienced the RHI similar to controls at the explicit level, when the RHI effect is assessed by implicit measures the susceptibility to the illusion resulted abnormal in the visuo-motor RHI. Hence, such dissociation between explicit and implicit RHI measures demonstrates a more plastic bodily-self representation when the RHI enlists hand movements, leading to a stronger visual-capture of proprioception. Finally, as suggested by correlations between body image related questionnaire and the RHI effect, our findings emphasize the intricate link between the perceptual and cognitive-affective aspects of body representation. Further research is necessary to uncover the pathological conditions in which emotional bodily experiences are linked to perceptual changes in body representation, deepening the complexity of this relationship. This may pave the way for possible therapeutic interventions aimed at improving body image perception through virtual reality-based treatments targeting body ownership. By enhancing the sense of ownership over one's own body, these interventions could help alleviate body dissatisfaction in clinical populations.

This study contributes to highlight how the body-related impairment is pervasive and complex, going beyond the most known body image disturbance and showing different facets in the diagnostic variants of EDs. Lastly, future studies could investigate how therapeutic motor activities can be useful in recovering correct body perception.

CRediT authorship contribution statement

Marcella Romeo: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Livia Colle:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Dize Hilviu:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Paola Longo:** Writing – review & editing, Resources. **Emiliano Ricciardi:** Writing – review & editing, Supervision. **Giovanni Abbate-Daga:** Writing – review & editing, Supervision, Resources. **Francesca Garbarini:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Carlotta Fossataro:** Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.

Scientific transparency statement

DATA: Some raw and processed data supporting this research are publicly available, while some are subject to restrictions: https://osf.io/t83wf/

CODE: This research did not make use of any analysis code.

MATERIALS: No study materials supporting this research are publicly available.

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Funding

This work has been funded by Università degli Studi di Torino–Fondi di ricerca locale (grant number COLL_-RILO_20_01) to L.C.

Acknowledgements

The authors are grateful to all of the patients and participants involved in the study.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.02.011.

REFERENCES

Ambrosecchia, M., Ardizzi, M., Russo, E. C., Ditaranto, F., Speciale, M., Vinai, P., Todisco, P., Maestro, S., & Gallese, V. (2023). Bodily self-recognition and body size overestimation in restrictive anorexia nervosa: Implicit and explicit mechanisms. *Frontiers in Psychology, 14*, Article 1197319. https://doi.org/10.3389/FPSYG.2023.1197319/BIBTEX

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders – fifth edition (DSM-5)*. Arlington, VA: American Psychiatric Association.

Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An inventory for measuring depression. *Archives Of General Psychiatry, 4*, 561–571. https://doi.org/10.1001/archpsyc.1961.01710120031004

Bellard, A., Urgesi, C., & Cazzato, V. (2022). Self-body recognition and attitudes towards body image in younger and older women. *Archives of Women's Mental Health, 25*(1), 107–119. https://doi.org/10.1007/s00737-021-01164-x

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience, 13*(8), 556–571. https://doi.org/10.1038/nrn3292

Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron, 88*(1), 145–166. https://doi.org/10.1016/j.neuron.2015.09.029

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature, 391*(6669), 756. https://doi.org/10.1038/35784, 756.

Bruch, H. (1974). *Eating disorders. Obesity, anorexia nervosa, and the person within*. London, UK: Routledge & Kegan Paul.

Bruno, V., Sarasso, P., Fossataro, C., Ronga, I., Neppi-Modona, M., & Garbarini, F. (2022). The rubber hand illusion in microgravity and water immersion. *Npj Microgravity, 8*(1). https://doi.org/10.1038/s41526-022-00198-4

Caglar-Nazali, H. P., Corfield, F., Cardi, V., Ambwani, S., Leppanen, J., Olabintan, O., Deriziotis, S., Hadjimichalis, A., Scognamiglio, P., Eshkevari, E., Micali, N., & Treasure, J. (2014). A systematic review and meta-analysis of 'Systems for Social Processes' in eating disorders. *Neuroscience and Biobehavioral Reviews, 42*, 55–92. https://doi.org/10.1016/j.neubiorev.2013.12.002

Campione, G. C., Mansi, G., Fumagalli, A., Fumagalli, B., Sottocornola, S., Molteni, M., & Micali, N. (2017). Motor-based bodily self is selectively impaired in eating disorders. *Plos One, 12*(11), Article e0187342. https://doi.org/10.1371/JOURNAL.PONE.0187342

Carey, M., & Preston, C. (2019). Investigating the components of body image disturbance within eating disorders. *Frontiers in Psychiatry, 10*, 1–15. https://doi.org/10.3389/fpsyt.2019.00635

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L., & Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: Delayed influence of combined tactile and visual input on proprioception. *Autism : The International Journal of Research and Practice, 16*(4), 406–419. https://doi.org/10.1177/1362361311430404

Case, L. K., Wilson, R. C., & Ramachandran, V. S. (2012). Diminished size–weight illusion in anorexia nervosa: Evidence for visuo-proprioceptive integration deficit. *Experimental Brain Research, 217*(1), 79–87. https://doi.org/10.1007/s00221-011-2974-7

Casper, R. C. (2022). Restlessness and an increased urge to move (drive for activity) in anorexia nervosa may strengthen personal motivation to maintain caloric restriction and may augment body awareness and proprioception: A lesson from leptin administration in anorexia nervosa. *Frontiers in Psychology, 13*, Article 885274. https://doi.org/10.3389/FPSYG.2022.885274/BIBTEX

Colle, L., Hilviu, D., Boggio, M., Toso, A., Longo, P., Abbate-Daga, G., Garbarini, F., & Fossataro, C. (2023). Abnormal sense of agency in eating disorders. *Scientific Reports 2023, 13*(1), 1–11. https://doi.org/10.1038/s41598-023-41345-5, 13(1).

Cooper, Z., Fairburn, C. G., Cooper, P. J., Psych, D., & Taylor, M. J. (1987). The development and validation of the body shape questionnaire. *International Journal of Eating Disorders, 6*(4), 485–494.

Crucianelli, L., Cardi, V., Treasure, J., Jenkinson, P. M., & Fotopoulou, A. (2016). The perception of affective touch in anorexia nervosa. *Psychiatry Research, 239*, 72–78. https://doi.org/10.1016/j.psychres.2016.01.078

Crucianelli, L., Cascio, C. J., Salomon, R., & Salvato, G. (2022). Editorial: When the body feels like mine: Constructing and deconstructing the sense of body ownership through the lifespan. In *Frontiers in human neuroscience, 16*Frontiers Media S.A. https://doi.org/10.3389/fnhum.2022.854135.

Crucianelli, L., Reader, A. T., & Ehrsson, H. H. (2024). Subcortical contributions to the sense of body ownership. *Brain: a Journal of Neurology, 147*(2), 390–405. https://doi.org/10.1093/BRAIN/AWAD359

Cuthbert, B. N., & Kozak, M. J. (2013). Constructing constructs for psychopathology: The NIMH research domain criteria. *Journal of Abnormal Psychology, 122*(3), 928–937. https://doi.org/10.1037/a0034028

Errante, A., Rossi Sebastiano, A., Ziccarelli, S., Bruno, V., Rozzi, S., Pia, L., Fogassi, L., & Garbarini, F. (2022). Structural connectivity associated with the sense of body ownership: A diffusion tensor imaging and disconnection study in patients with bodily awareness disorder. *Brain Communications, 4*(1). https://doi.org/10.1093/braincomms/fcac032

Eshkevari, E., Rieger, E., Longo, M. R., Haggard, P., & Treasure, J. (2012). Increased plasticity of the bodily self in eating disorders. *Psychological Medicine, 42*(4), 819–828. https://doi.org/10.1017/S0033291711002091

Eshkevari, E., Rieger, E., Longo, M. R., Haggard, P., & Treasure, J. (2013). Persistent body image disturbance following recovery from eating disorders. *International Journal of Eating Disorders*. https://doi.org/10.1002/eat.22219. n/a–n/a.

Eshkevari, E., Rieger, E., Musiat, P., & Treasure, J. (2014). An investigation of interoceptive sensitivity in eating disorders using a heartbeat detection task and a self-report measure. *European Eating Disorders Review, 22*(5), 383–388. https://doi.org/10.1002/erv.2305

Fairburn, C. G., Cooper, Z., & Shafran, R. (2003). Cognitive behaviour therapy for eating disorders: A "transdiagnostic" theory and treatment. *Behaviour Research and Therapy, 41*(5), 509–528. https://doi.org/10.1016/S0005-7967(02)00088-8

Ferroni, F., Rabellino, D., Mazzeschi, C., & Ardizzi, M. (2024). Editorial: The bodily self and its alterations: Psychopathological, neural and theoretical aspects. *Frontiers in Psychology, 15*, Article 1447443. https://doi.org/10.3389/FPSYG.2024.1447443/BIBTEX

Floris, M., & Panero, M. (2024). "I'm not hungry:" bodily representations and bodily experiences in anorexia nervosa. *Review of Philosophy and Psychology*, 1–23. https://doi.org/10.1007/S13164-024-00735-Y, 2024.

Fossataro, C., Bruno, V., Giurgola, S., Bolognini, N., & Garbarini, F. (2018). Losing my hand. Body ownership attenuation after virtual lesion of the primary motor cortex. *European Journal of Neuroscience, 48*(6), 2272–2287. https://doi.org/10.1111/ejn.14116

Fossataro, C., Burin, D., Ronga, I., Galigani, M., Rossi Sebastiano, A., Pia, L., & Garbarini, F. (2020). Agent-dependent modulation of corticospinal excitability during painful transcutaneous electrical stimulation. *Neuroimage, 217*. https://doi.org/10.1016/j.neuroimage.2020.116897

Gadsby, S., & Williams, D. (2018). Action, affordances, and anorexia: Body representation and basic cognition. *Synthese, 195*(12), 5297–5317. https://doi.org/10.1007/S11229-018-1843-3/METRICS

Galigani, M., Fossataro, C., Gindri, P., Conson, M., & Garbarini, F. (2021). Monochannel preference in autism spectrum conditions revealed by a non-visual variant of rubber hand illusion. *Journal of Autism and Developmental Disorders*. https://doi.org/10.1007/s10803-021-05299-9

Gandola, M., Invernizzi, P., Sedda, A., Ferrè, E. R., Sterzi, R., Sberna, M., Paulesu, E., & Bottini, G. (2012). An anatomical account of somatoparaphrenia. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior, 48*(9), 1165–1178. https://doi.org/10.1016/j.cortex.2011.06.012

Garbarini, F., Fossataro, C., Pia, L., & Berti, A. (2020). What pathological embodiment/disembodiment tell us about body representations. *Neuropsychologia*. , Article 107666. https://doi.org/10.1016/j.neuropsychologia.2020.107666

Garner, D. M. (1991). *Eating disorder inventory-2; professional manual*. Odessa, FL: Psychological Assessment Resources, Inc.

Glashouwer, K. A., van der Veer, R. M. L., Adipatria, F., de Jong, P. J., & Vocks, S. (2019). The role of body image disturbance in the onset, maintenance, and relapse of anorexia nervosa: A systematic review. *Clinical Psychology Review, 74*, Article 101771. https://doi.org/10.1016/J.CPR.2019.101771

Graham-Schmidt, K. T., Martin-Iverson, M. T., Holmes, N. P., & Waters, F. (2016). Body representations in schizophrenia: An alteration of body structural description is common to people with schizophrenia while alterations of body image worsen with passivity symptoms. *Cognitive Neuropsychiatry, 21*(4), 354–368. https://doi.org/10.1080/13546805.2016.1231111

Griffiths, S., Castle, D., Cunningham, M., Murray, S. B., Bastian, B., & Barlow, F. K. (2018). How does exposure to thinspiration and fitspiration relate to symptom severity among individuals with eating disorders? Evaluation of a proposed model. *Body Image, 27*, 187–195. https://doi.org/10.1016/J.BODYIM.2018.10.002

Grivaz, P., Blanke, O., & Serino, A. (2017). Common and distinct brain regions processing multisensory bodily signals for peripersonal space and body ownership. *Neuroimage, 147*, 602–618. https://doi.org/10.1016/j.neuroimage.2016.12.052

Izydorczyk, B. (2022). *Body image in eating disorders clinical diagnosis and integrative approach to psychological treatment*. Routledge.

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience, 6*, 40. https://doi.org/10.3389/fnhum.2012.00040

Kalckert, A., & Ehrsson, H. H. (2014a). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition, 26*, 117–132. https://doi.org/10.1016/j.concog.2014.02.003

Kalckert, A., & Ehrsson, H. H. (2014b). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition, 26*(1), 117–132. https://doi.org/10.1016/j.concog.2014.02.003

Kalckert, A., & Henrik Ehrsson, H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience, 6*, 1–14. https://doi.org/10.3389/fnhum.2012.00040. MARCH 2012.

Keizer, A., Smeets, M. A. M., Postma, A., van Elburg, A., & Dijkerman, H. C. (2014). Does the experience of ownership over a rubber hand change body size perception in anorexia nervosa patients? *Neuropsychologia, 62*, 26–37. https://doi.org/10.1016/j.neuropsychologia.2014.07.003

Lee, H.-S., Hong, S.-J. J., Baxter, T., Scott, J., Shenoy, S., Buck, L., Bodenheimer, B., & Park, S. (2021). Altered peripersonal space and the bodily self in schizophrenia: A virtual reality study. *Schizophrenia Bulletin, 47*(4), 927–937. https://doi.org/10.1093/schbul/sbab024

Longo, P., Scaliti, E., Panero, M., Toppino, F., Brustolin, A., Salis, B., Lacidogna, M. C., Abbate-Daga, G., & Martini, M. (2024). A quantitative study on peripersonal space in anorexia nervosa and healthy subjects: Role of social variables and association with psychopathology. *International Journal of Clinical and Health Psychology, 24*(3), Article 100476. https://doi.org/10.1016/J.IJCHP.2024.100476

Martini, M., Longo, P., Delsedime, N., Abbate-Daga, G., & Panero, M. (2023). Increased general, eating, and body-related psychopathology in inpatients in a specialized eating disorders unit after the beginning of the COVID-19 pandemic: A retrospective comparison with the pre-pandemic period. *Journal of Clinical Medicine, 12*(2), 573. https://doi.org/10.3390/JCM12020573/S1

Martini, M., Marzola, E., Brustolin, A., & Abbate-Daga, G. (2021). Feeling imperfect and imperfectly feeling: A network analysis on perfectionism, interoceptive sensibility, and eating symptomatology in anorexia nervosa. *European Eating Disorders Review, 29*(6), 893–909. https://doi.org/10.1002/ERV.2863

Marzola, E., Martini, M., Longo, P., Toppino, F., Bevione, F., Delsedime, N., Abbate-Daga, G., & Preti, A. (2022). Psychometric properties of the Italian body shape questionnaire: An investigation of its reliability, factorial, concurrent, and criterion validity. *Eating and Weight Disorders: EWD, 27*(8), 3637–3648. https://doi.org/10.1007/S40519-022-01503-6/FIGURES/2

Marzola, E., Panero, M., Cavallo, F., Delsedime, N., & Abbate-Daga, G. (2020). Body shape in inpatients with severe anorexia nervosa. *European Psychiatry, 63*(1). https://doi.org/10.1192/j.eurpsy.2019.5

McLean, S. A., & Paxton, S. J. (2019). Body image in the context of eating disorders. *The Psychiatric Clinics of North America, 42*(1), 145–156. https://doi.org/10.1016/J.PSC.2018.10.006

Neustadter, E. S., Fineberg, S. K., Leavitt, J., Carr, M. M., & Corlett, P. R. (2019). Induced illusory body ownership in borderline personality disorder. *Neuroscience of Consciousness, 2019*(1). https://doi.org/10.1093/nc/niz017

Noordenbos, G., & Lammers, M. (2018). Psychische achtergronden. In G. Noordenbos, & A. van Elburg (Eds.), *Handboek Eetstoornissen* (pp. 99–108). De Tijdsstroom Uitgeverij.

Panero, M., Longo, P., De Bacco, C., Abbate-Daga, G., & Martini, M. (2022). Shame, guilt, and self-consciousness in anorexia nervosa. *Journal of Clinical Medicine, 11*(6683), 6683. https://doi.org/10.3390/JCM11226683, 2022 11(22).

Pia, L., Fossataro, C., Burin, D., Bruno, V., Spinazzola, L., Gindri, P., Fotopoulou, K., Berti, A., & Garbarini, F. (2020). The anatomo-clinical picture of the pathological embodiment over someone else's body part after stroke. *Cortex; a Journal Devoted To the Study of the Nervous System and Behavior, 130*, 203–219. https://doi.org/10.1016/j.cortex.2020.05.002

Prnjak, K., Jukic, I., Mitchison, D., Griffiths, S., & Hay, P. (2022). Body image as a multidimensional concept: A systematic review of body image facets in eating disorders and muscle dysmorphia. *Body Image, 42*, 347–360. https://doi.org/10.1016/J.BODYIM.2022.07.006

Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force. *Physiological Reviews, 92*(4), 1651–1697. https://doi.org/10.1152/PHYSREV.00048.2011/ASSET/IMAGES/LARGE/Z9J0041226360016.JPEG

Pyasik, M., Ronga, I., Burin, D., Salatino, A., Sarasso, P., Garbarini, F., Ricci, R., & Pia, L. (2021). I'm a believer: Illusory self-generated touch elicits sensory attenuation and somatosensory evoked potentials similar to the real self-

touch. *Neuroimage*. , Article 117727. https://doi.org/10.1016/j.neuroimage.2021.117727

Reas, D. L., Whisenhunt, B. L., Netemeyer, R., & Williamson, D. A. (2002). Development of the body checking questionnaire: A self-report measure of body checking behaviors. *International Journal of Eating Disorders, 31*(3), 324–333. https://doi.org/10.1002/EAT.10012

Riva, G. (2012). Neuroscience and eating disorders: The allocentric lock hypothesis. *Medical Hypotheses, 78*(2), 254–257. https://doi.org/10.1016/J.MEHY.2011.10.039

Romano, D., Gandola, M., Bottini, G., & Maravita, A. (2014). Arousal responses to noxious stimuli in somatoparaphrenia and anosognosia: Clues to body awareness. *Brain : A Journal of Neurology, 137*(Pt 4), 1213–1223. https://doi.org/10.1093/brain/awu009

Romano, D., & Maravita, A. (2019). The dynamic nature of the sense of ownership after brain injury. Clues from asomatognosia and somatoparaphrenia. *Neuropsychologia, 132*. https://doi.org/10.1016/j.neuropsychologia.2019.107119

Rosen, J. C., Srebnik, D., Saltzberg, E., & Wendt, S. (1991). Development of a body image avoidance questionnaire. *Psychological Assessment, 3*(1), 32–37. https://doi.org/10.1037/1040-3590.3.1.32

Rossi Sebastiano, A., Bruno, V., Ronga, I., Fossataro, C., Galigani, M., Neppi-Modona, M., & Garbarini, F. (2021). Diametrical modulation of tactile and visual perceptual thresholds during the rubber hand illusion: A predictive coding account. *Psychological Research, 1*, 1–17. https://doi.org/10.1007/s00426-021-01608-0

Rossi Sebastiano, A., Poles, K., Gualtiero, S., Romeo, M., Galigani, M., Bruno, V., … Garbarini, F. (2024). Balancing the senses: electrophysiological responses reveal the interplay between somatosensory and visual processing during body-related multisensory conflict. *Journal of Neuroscience, 44*(19). https://doi.org/10.1523/JNEUROSCI.1397-23.2024

Sagiv, E., Hadlaczky, G., Sheetrit, N., Gur, E., Horesh, N., & Gvion, Y. (2019). The fear of losing—nonsuicidal self-injury as a protective mechanism in eating disorders. *Frontiers in Psychiatry, 10*, 825. https://doi.org/10.3389/fpsyt.2019.00825

Salvato, G., Crivelli, D., Gandola, M., & Bottini, G. (2023). Self-touch facilitates the recognition of the dis-owned left hand in somatoparaphrenia: A single case study. *Neurocase, 29*(5), 133–140. https://doi.org/10.1080/13554794.2024.2345405

Salvato, G., Gandola, M., Veronelli, L., Agostoni, E. C., Sberna, M., Corbo, M., & Bottini, G. (2016). The spatial side of somatoparaphrenia: A case study. *Neurocase, 22*(2), 154–160. https://doi.org/10.1080/13554794.2015.1077257

Salvato, G., Gandola, M., Veronelli, L., Berlingeri, M., Corbo, M., & Bottini, G. (2018). The vestibular system, body temperature and sense of body ownership: A potential link? Insights from a single case study. *Physiology & Behavior, 194*, 522–526. https://doi.org/10.1016/j.physbeh.2018.07.008

Salvato, G., Richter, F., Sedeño, L., Bottini, G., & Paulesu, E. (2020a). Building the bodily self-awareness: Evidence for the convergence between interoceptive and exteroceptive information in a multilevel kernel density analysis study. *Human Brain Mapping, 41*(2), 401–418. https://doi.org/10.1002/HBM.24810

Salvato, G., Romano, D., De Maio, G., & Bottini, G. (2020b). Implicit mechanisms of body image alterations: The covert attention exposure effect. *Attention, Perception, and Psychophysics, 82*(4), 1808–1817. https://doi.org/10.3758/S13414-019-01921-2/TABLES/2

Seghezzi, S., Giannini, G., & Zapparoli, L. (2019). Neurofunctional correlates of body-ownership and sense of agency: A meta-analytical account of self-consciousness. *Cortex; a Journal Devoted To the Study of the Nervous System and Behavior, 121*, 169–178. https://doi.org/10.1016/j.cortex.2019.08.018

Spielberger, C. D., & Sydeman, S. J. (1994). State-trait anxiety inventory and state-trait anger expression inventory. In M. E. Maruish (Ed.), *The use of psychological testing for treatment planning and outcome assessment* (pp. 292–321). Hillsdale, NJ, USA: L. Erlbaum Associates. https://doi.org/10.1002/9780470479216.corpsy0943.

Stanghellini, G., Castellini, G., Brogna, P., Faravelli, C., & Ricca, V. (2012). Identity and eating disorders (idea): A questionnaire evaluating identity and embodiment in eating disorder patients. *Psychopathology, 45*(3), 147–158. https://doi.org/10.1159/000330258

Troscianko, E. T., & Leon, M. (2020). Treating eating: A dynamical systems model of eating disorders. *Frontiers in Psychology, 11*, Article 545301. https://doi.org/10.3389/FPSYG.2020.01801/BIBTEX

Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia, 48*(3), 703–712. https://doi.org/10.1016/j.neuropsychologia.2009.09.034

Tsakiris, M., & Haggard, P. (2005). Experimenting with the acting self. *Cognitive Neuropsychology, 22*(3–4), 387–407. https://doi.org/10.1080/02643290442000158

Tsakiris, M., Longo, M. R., & Haggard, P. (2010). Having a body versus moving your body: Neural signatures of agency and body-ownership. *Neuropsychologia, 48*(9), 2740–2749. https://doi.org/10.1016/j.neuropsychologia.2010.05.021

Urgesi, C., Fornasari, L., Canalaz, F., Perini, L., Cremaschi, S., Faleschini, L., Thyrion, E. Z., Zuliani, M., Balestrieri, M., Fabbro, F., & Brambilla, P. (2014). Impaired configural body processing in anorexia nervosa: Evidence from the body inversion effect. *British Journal of Psychology, 105*(4), 486–508. https://doi.org/10.1111/bjop.12057

Urgesi, C., Fornasari, L., De Faccio, S., Perini, L., Mattiussi, E., Ciano, R., Balestrieri, M., Fabbro, F., & Brambilla, P. (2011). Body schema and self-representation in patients with bulimia nervosa. *International Journal of Eating Disorders, 44*(3), 238–248. https://doi.org/10.1002/eat.20816

Urgesi, C., Fornasari, L., Perini, L., Canalaz, F., Cremaschi, S., Faleschini, L., Balestrieri, M., Fabbro, F., Aglioti, S. M., & Brambilla, P. (2012). Visual body perception in anorexia nervosa. *International Journal of Eating Disorders, 45*(4), 501–511. https://doi.org/10.1002/eat.20982

Zopf, R., Contini, E., Fowler, C., Mondraty, N., & Williams, M. A. (2016). Body distortions in Anorexia Nervosa: Evidence for changed processing of multisensory bodily signals. *Psychiatry Research, 245*, 473–481. https://doi.org/10.1016/j.psychres.2016.09.003