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Research article

Embodiment of underweight and normal-weight avatars affects bodily self-representations in anorexia nervosa

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A R T I C L E I N F O

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A B S T R A C T

Body image distortion (BID) is a crucial aspect of anorexia nervosa (AN), leading to body overestimation, dissatisfaction, and low self-esteem. BID significantly influences the onset, maintenance, and relapse of the pathology. We assessed whether a Full Body Illusion (FBI) using under and normal-weight avatars' bodies affects perceptual body image and body schema estimations in both individuals with anorexia nervosa (AN) and healthy controls (HC). After each embodiment procedure, we asked participants to estimate the width of their hips (Perceptual Body Image Task) and the minimum aperture width of a virtual door necessary to pass through it (Body Schema Task). Additionally, we asked participants to rate the avatars in terms of self-similarity, attractiveness, and implicit disgust (i.e., pleasant/unpleasant body odour). Whereas participants with AN ($N = 26$) showed changes in body schema estimations after embodying the normal-weight avatar, no changes were found in HC ($N = 25$), highlighting increased bodily self-plasticity in AN. Notably, individuals with AN rated the normal weight avatar as the most similar to their real body, which was also considered the least attractive and the most repulsive. These ratings correlated with BID severity. Furthermore, at the explicit level, all participants reported feeling thinner than usual after embodying the underweight avatar. Overall, our findings suggest that BID in AN engages multiple sensory channels (from visual to olfactory) and components (from perceptual to affective), offering potential targets for innovative non-invasive treatments aimed at modifying flexible aspects of body representation.

1. Introduction

Anorexia nervosa (AN) is a severe psychiatric disorder distinguished by three primary symptoms: i) severe reduction of food intake leading to an extremely low body weight; ii) intense fear of gaining weight; and iii) distorted perception of one's own body weight and shape [1]. Body image distortion (BID) affects all aspects of body representation, including the perceptual, affective, and cognitive dimensions, resulting in body overestimation, body dissatisfaction due to the discrepancies between perceived and ideal body [2–4],

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body preoccupations, and ultimately, low self-esteem (e.g. Refs. [2–5]). BID is pivotal in the initiation, perpetuation, and recurrence of AN pathology [6,7]. Specifically, research indicates that while low body mass index (BMI) is the strongest predictor of AN onset, body dissatisfaction further amplifies this relationship [8]. Moreover, weight/shape overestimation (e.g. Ref. [9]) and body dissatisfaction (e.g. Ref. [10]) are risk factors for the maintenance of AN symptoms, whereas a greater reduction in weight and shape concerns from admission to discharge is associated with a lower risk of relapse (e.g. Ref. [11]). Therefore, addressing BID is an important treatment goal in the therapeutic process.

Recently, attempts have been made to reduce body image distortion (BID) using experimental paradigms based on Interpersonal Multisensory Stimulation (IMS). These paradigms induce an illusion of owning a body different from one's own and have the potential to alter various aspects of self-representation, including the perceptual, affective, and social dimensions [12–14]. In IMS experiments, individuals commonly undergo tactile stimulations on their own body that coincide with observed touches administered to a corresponding body part of another individual or virtual body (referred to as synchronous IMS). Crucially, the position in the space of the observed other (or virtual) body is compatible with the participant's body schema (e.g. Refs. [15,16]). Thus, the touch felt on one's body is spatially and temporally synchronous with the touch observed on the other (or virtual) body. This multisensory congruence typically induces the illusion of feeling the observed body as ours. However, a conflict arises when synchronous IMS is applied to a body whose appearance does not match the stored representation of one's own body (i.e., one's own offline bodily self-representation). To resolve this conflict, the brain updates the bodily self-representation to incorporate features of the synchronously stimulated observed body [4,17]. This process results in a change in bodily self-representation and the illusory sensation of owning, controlling, and being located in another body/a virtual body, known as the Embodiment illusion. Embodiment illusions tend to be stronger in individuals with lower awareness of their visceral bodily signals [18–22], especially when interoceptive signals are incorporated into IMS paradigms. This can be achieved via synchronous cardio-visual feedback [19,23] or real-time mapping of the participant's respiratory patterns onto the virtual body [21,24]. In support of the relationship between the awareness of interoceptive bodily signals and the strength of the embodiment illusion, individuals with AN appear to have a heightened susceptibility to bodily illusions [25]. This finding aligns with the fact that they generally exhibit altered interoceptive abilities [26,27]. Therefore, recent studies have utilised IMS paradigms and immersive virtual reality in an attempt to modify body representation in healthy controls and decrease BID in individuals with AN.

Initial findings in healthy participants have demonstrated that embodying avatars with different body weights (and BMI) can induce illusory feelings of body ownership over the virtual avatar, leading to body size estimation changes of one's own body according to the embodied avatar's size [28–30] as well as changes in body (dis)satisfaction [30,31]. However, the results from studies conducted on patients with AN have been less conclusive. When IMS was applied to a normal-weight hand, it reduced hand size overestimation in individuals with AN in both synchronous (experimental) and asynchronous (control) conditions [32]. Similarly, synchronous and asynchronous IMS applied to a healthy weight avatar viewed from a first-person perspective (1-PP) decreased the overestimation of shoulders, abdomen, and hips in patients with AN [25]. Therefore, in both cases, the observed effect, i.e., the reduction of overestimation in individuals with anorexia, may be attributed to the mere exposure to virtual bodies or body parts of different weights and sizes rather than be the result of the embodiment illusion itself.

Findings from our prior investigation [33], tailored to discern between the impact of mere exposure to virtual bodies of varying weights and the influence of the embodiment illusion on individuals' body image, indicated no alteration in BID subsequent to the embodiment of three virtual bodies exhibiting distinct BMIs. These virtual bodies comprised one closely resembling participants' perceived body dimensions, alongside two others featuring increased and decreased weight. To assess BID, we employed a depictive method of body size estimation [2,6,34], wherein individuals were tasked with choosing the avatar that most closely resembled their perceived or ideal body from a spectrum spanning from −30 % to +50 % of their actual body dimensions. Interestingly, a recent review [5] suggested that metric methods of body size estimation might be more suitable than depictive ones in capturing body size overestimation in AN, as the latter relies on an explicit representation of the bodily self [6,34,35]. Additionally, in our previous study, the application of IMS occurred over avatars viewed from a first-person perspective (1-PP), while the body size estimation task was performed on the avatars observed from a third-person perspective (3-PP). Therefore, it is possible that we did not observe any effects on BID due to the fact that individuals with anorexia nervosa appear to be unable to update their offline representation of the body (stored in a third-person perspective) with new content derived from online, real-time perception-driven inputs (experienced from a first-person perspective). Evidence suggests that our spatial perception, including bodily experiences, results from the combination of diverse sensory inputs within two distinct frames of reference: egocentric, where the body serves as the reference for first-person experience, and allocentric, where the body is perceived as an object within the physical environment.

The Allocentric Lock Theory suggests that individuals with eating disorders are locked to an allocentric negative representation of their body and are unable to modify it even after significant body changes [36]. Thus, the question regarding the efficacy of the embodiment as a tool for affecting and ultimately reducing body image distortion in anorexia nervosa remains controversial.

In the present study, our first aim was to investigate the effects of the embodiment of an underweight and a normal-weight virtual body on implicit measures of the self-body dimension. Specifically, we aimed to investigate two components of body representation known to be distorted in individuals with anorexia nervosa: 1) perceptual body image, which encompasses one's body shape and positioning based on the integration of somato-perceptive signals [37], and 2) body schema, which pertains to the dynamic sensorimotor representation of the body that initiates and directs actions, irrespective of whether those actions are anticipated, executed, or just imagined [38,39].

To achieve this, we employed two specific tasks: 1) a metric body size estimation task, in which participants were asked to estimate the width of their hips without visual access to their own body (similar to Ref. [30]), and 2) an immersive virtual reality version of the door's aperture task (similar to Ref. [29]) which was adapted from a real-world version involving door apertures projected on the wall

[40,41]. In the door's aperture task, participants were tasked with estimating the minimum door aperture's width required for them to walk through without twisting their bodies by freely adjusting the distance between two virtual pillars. Both of these tasks are designed to measure the aforementioned components of body representation that are known to be distorted in individuals with anorexia nervosa. Furthermore, in accordance with the Allocentric Lock Theory [36], both the size estimation tasks and the embodiment illusion were conducted from an egocentric frame of reference. This ensured that participants experienced both the body size estimation tasks and the embodiment illusion from their own first-person perspective, enhancing the relevance of the findings to their personal bodily experiences.

We expected that individuals with AN, compared to healthy controls (HC), would exhibit BID, as indicated by body size overestimation in both perceptual body image and body schema measures. We also expected that individuals with AN would exhibit reduced perception of their bodily signals (i.e. low interoception [42]), which would be associated with the severity of their clinical condition. Furthermore, based on previous research [25,32], we expected that, especially in individuals with anorexia nervosa, the embodiment of underweight and normal-weight avatars would change the perceived self-body dimension (as assessed by perceptual body image and body schema tasks). Specifically, we predicted a decrease in overestimation in both perceptual body image and body schema tasks following the embodiment of the underweight avatar, whereas we anticipated an increase (or no change) in perceived self-body dimension when embodying the normal weight avatar. Given their heightened bodily plasticity [43], we also hypothesised that these changes would be more pronounced in individuals with anorexia compared to the control group.

The second objective of the study was to explore whether the illusory ownership of avatars with desired or undesired body weights (e.g., underweight and normal-weight bodies) could also influence explicit subjective perception of the self-body dimension and the associated emotional reactions, as suggested by our previous study [33]. Furthermore, we asked participants to report their subjective feeling of being thinner or fatter than usual after each IMS condition. We expected that the subjective feelings of being thinner/fatter than usual would depend on participants' perceived self-body dimension. Hence, we could expect that all participants would experience a sensation of being thinner than usual during the illusory experience of having an underweight body, which is thinner than the actual body of HC and similar to the real body of AN. On the contrary, we would expect no changes in the subjective feeling of being fatter than usual after embodying the normal-weight body, which is similar to the actual body of HC and to the perceived body of AN. Additionally, we anticipated that individuals with AN would report more negative emotions following the embodiment of the normal-weight avatars, while we did not expect to find any significant difference in the emotions experienced by control participants in regard to the size of the embodied avatars [33].

Finally, the third aim of the present study was to explore whether perceptual and emotional distortions of the self-body image would also affect how individuals with AN perceive the bodies of underweight and normal-weight avatars, as well as the strength of their embodiment. To investigate this, participants were requested to evaluate both the underweight and normal-weight avatars regarding their similarity to their own body, overall attractiveness, and implicit disgust (i.e., how pleasant or unpleasant the avatar's body odour would be). We expected that individuals with AN would rate the normal-weight avatar as the most similar to their own real body. However, we also expected them to rate the normal-weight avatar as the most unattractive and disgusting compared to HC and that these ratings would be positively associated with the extent of their BID.

2. Materials and methods

2.1. Participants

The study included 26 female individuals diagnosed with anorexia nervosa [(mean ± s.e.) (age = 20.61 ± 3.60, BMI = 16.90 ± 0.76)], along with 25 age-matched female healthy controls (HC) (age = 22.00 ± 2.58, BMI = 20.09 ± 1.57). Patients were recruited from the Eating Disorder Centre of ASL 1 Rome and met the diagnostic criteria for Anorexia Nervosa (restricting type) according to the DSM-5. Healthy controls were screened for any history of eating disorders or other psychiatric conditions, serving as exclusion criteria. Sample size calculation utilised G*Power 3.1.9.2, employing a 2 x 2 x 2 mixed repeated measures ANOVA. The effect size (f) was derived from a previous study investigating changes in body size estimation among anorexic patients following the induction of the embodiment illusion over an avatar observed from the first-person perspective [25]. To achieve a power of 0.80, with alpha set at 0.05 and f at 0.33, a total sample of 50 participants (25 per group) was required.

2.2. Stimulus preparation: virtual scenario and Avatar creation

The virtual setting was designed to reproduce a room with various furnishings, such as a deck chair, a sliding door, and a desk. These elements were meticulously crafted to heighten the immersive experience for participants (as in Ref. [44]) while ensuring that they remained focused on the experimental tasks.

Inside the virtual environment, participants found themselves in a room resembling their physical surroundings, with their avatar reclined on a deck chair similar to the one they were seated in for the entirety of the experiment. The virtual door used for the Body Schema Task (see 2.7.2) was situated precisely 3 m away from the participant's perspective [29]. Autodesk 3ds Max 2017 was used to realise all the 3D modelling and texturing of the virtual environment.

To represent different body types, an underweight avatar (BMI = 15) and a normal-weight avatar (BMI = 19) were created using the MakeHuman software. These avatars mirrored the bodies of a control participant and a person with anoressia nervosa recruited during a previous study, both having an average height of 168 cm. Detailed skin, clothing, and material textures for both avatars were generated using Adobe Photoshop 7.0. All experimental tasks were programmed in C# and integrated into Unity 2017.3.1f1 for implementation.

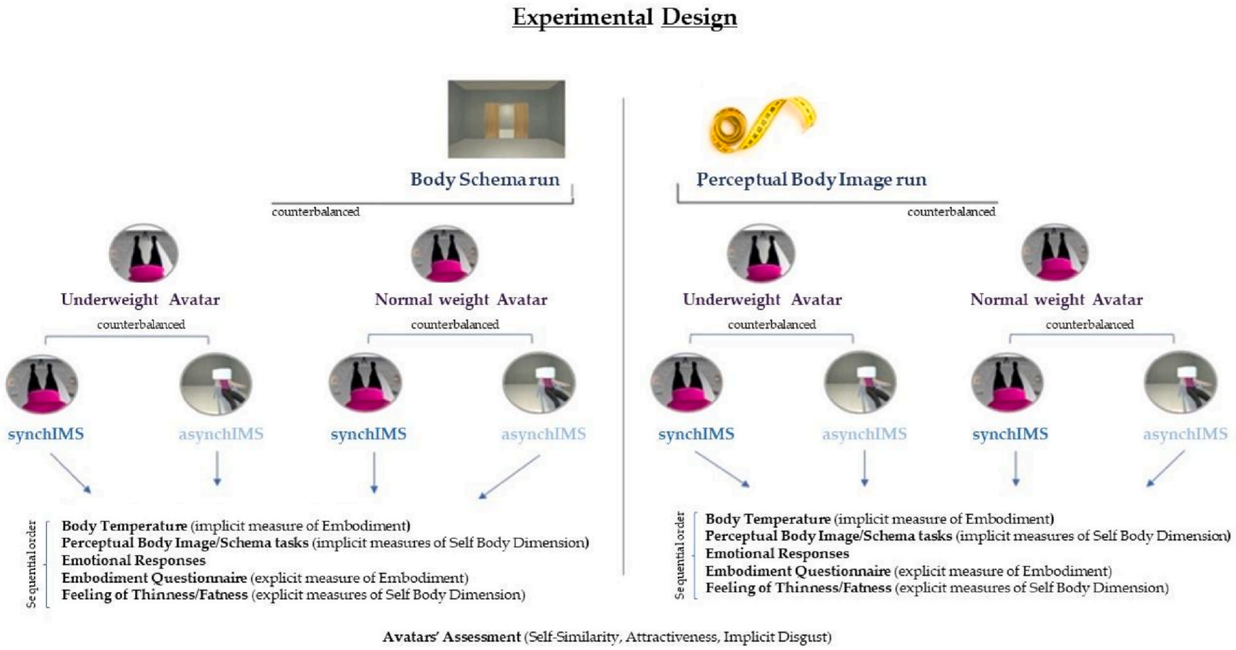


Fig. 1. General Procedure. Participants underwent a Body Schema and a Perceptual Body Image run. Within each run, they received the embodiment procedure with a normal and an underweight avatar's body in separate blocks. For each experimental block, participants experienced synchronous congruent and asynchronous incongruent interpersonal multisensory stimulations (IMS) in separate trials. Following each IMS trial, participants completed both explicit and implicit measures to assess the embodiment illusion. Implicit measures of self-body dimension, including Perceptual Body Image and Body Schema tasks, were administered, along with explicit measures to gauge feelings of thinness/fatness and emotions experienced during IMS. At the conclusion of the experimental procedure, participants provided ratings from a first-person perspective on the similarity of normal and underweight BMI avatars to their own bodies, as well as assessments of attractiveness and implicit disgust rating (the latter expressed in terms of pleasant body odour).

2.3. Pre-experimental session: self-report questionnaires of eating disorder severity and interoceptive awareness

Following verbal instructions and before the experimental procedure, participants were tasked with completing a series of questionnaires aimed at assessing body dissatisfaction and the severity of eating disorder symptoms. The questionnaires administered were: 1) the Eating Disorder Inventory - 2 (EDI-2) [35]; 2) the Body Shape Questionnaire (BSQ) [45]; and 3) the Body Uneasiness Test (BUT) [46]. Detailed descriptions of all the questionnaires employed are provided in section 2.3.3. Additionally, to measure participants' awareness of their internal bodily signals, they were asked to complete the Italian version of the Multidimensional Assessment of Interoceptive Awareness, Version 2 [47]. Participants with AN completed the questionnaires in ambulatory care, assisted by the medical staff of the Eating Disorder Centre of ASL 1 Rome, whereas healthy controls completed the questionnaires at the Social and Cognitive Neuroscience Laboratory within the Department of Psychology at Sapienza University of Rome.

2.4. General procedure

Fig. 1 illustrates an overview of the procedure.

Before starting the general procedure, participants were given standardised attire, consisting of a pink t-shirt and a pair of black leggings, which they were instructed to wear to match the virtual avatar's clothing. Once they were ready, participants reclined on a deck chair and donned the VR head-mounted display (HMD, Oculus Rift) for the whole duration of the procedure.

First, participants were instructed to provide a measure of their self-body image, which was assessed using the Perceptual Body Image Task (please see 2.7.1) and the Body Schema Task (2.7.2). Subsequently, participants experienced the Embodiment procedure (please see 2.5) in two runs, administered in a counterbalanced order. During each run, either the Body Schema or Perceptual Body Image task was employed to evaluate the impact of incongruent and congruent asynchronous/synchronous IMS on implicit assessments of perceived self-body dimensions. Each run consisted of two blocks that differed in avatar size. During one block, participants were presented with an avatar exhibiting a BMI within the underweight range (BMI = 15), while in the other block, they experienced an avatar representing the normal-weight range (BMI = 19). The blocks were administered in a counterbalanced order across participants. Each block comprised two IMS trials. In one trial, the participant was exposed to synchronous congruent IMS, and in the other trial, to asynchronous incongruent IMS. The presentation order of IMS trials was also counterbalanced.

Following each IMS trial, we gathered several measures: 1) implicit and explicit measures of the strength of the embodiment illusion (see 2.6.1 & 2.6.2); 2) implicit and explicit measures of self-body dimensions [i.e., Perceptual Body Image/Body Schema task

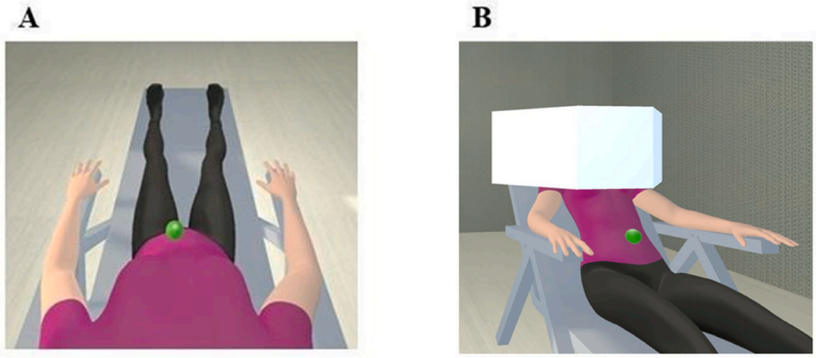


Fig. 2. Embodiment Procedure. Throughout the embodiment procedure, participants observed a virtual green ball interacting with the avatar's belly in three different modalities: single touches, double touches, and stroking movements. **(A)** In the synchronous congruent condition, participants viewed an avatar from a first-person perspective (1-PP) and received tactile stimulation on their own real body that perfectly synchronised in time and location with the virtual touches observed on the avatar. This synchronisation created a congruency between the participants' real body and the virtual body they observed, integrating visual, tactile, and proprioceptive cues. **(B)** In contrast, during the asynchronous incongruent condition, participants observed an avatar positioned slightly to their right from a third-person perspective (3-PP) to prevent direct alignment with the observed avatar. The tactile stimulation they experienced on their own real body did not correspond in time or location with the virtual touches observed on the avatar, leading to a complete discrepancy between the participants' real body and the observed virtual body across visual, tactile, and proprioceptive modalities.

(see 2.7.1 & 2.7.2) and feelings of thinness and fatness triggered by the embodiment of avatars with different body weights (see 2.8)]; and 3) participants' emotional state after experiencing the embodiment illusion (2.9). At the conclusion of the experimental session, participants were presented again with the underweight and normal-weight BMI avatars from a first-person perspective and were asked to rate them based on their perceived similarity, attractiveness, and implicit disgust (section 2.10).

2.5. Embodiment illusion procedure

At the start of the Embodiment runs, we calibrated the position of the virtual camera in order to ensure accurate alignment between the participant's actual body and the body of the virtual avatar. Participants were asked to focus on the avatar's belly and indicate to the experimenter if the observed touch on the avatar matched the location of the touch felt on their own body. Once calibration was completed, each condition of the Full Body Illusion (FBI) was induced.

During synchronous congruent IMS sessions, participants viewed tactile stimulations administered to an avatar from a first-person perspective (1-PP), resulting in a complete alignment of visual, tactile, and proprioceptive feedback between the participants' actual body and the observed virtual body. Consequently, the tactile stimuli experienced by participants on their own real bodies precisely matched the timing and location of the touches observed on the virtual body (as depicted in Fig. 2A). To differentiate the effects of the embodiment illusion from the mere observation of an avatar from a first-person perspective, we also implemented an asynchronous incongruent condition. During this condition, the avatar was presented from a third-person perspective (3-PP), and the touches were delivered asynchronously to deliberately maximise both the visuo-proprioceptive and visuo-tactile discrepancies between the participants' real body and the avatar's virtual body. As a result, tactile stimuli administered to the participants' bodies were asynchronous both in timing and location compared to the observed touches (as illustrated in Fig. 2B). To ensure there was no spatial alignment between the participant's body and the observed avatar, the avatar was positioned in front of the participants, slightly to the right of their midline. We opted for implementing a "double asynchronous" paradigm, introducing temporal and spatial disparities in the visuo-tactile stimulation, to mitigate the likelihood of eliciting the embodiment illusion during the incongruent (asynchronous) condition. This precaution was grounded in empirical findings suggesting that even when visuo-tactile cues are incongruent, observing a virtual body from a first-person perspective (1-PP) can still trigger the embodiment illusion [48]. Lastly, all touches were administered by a trained female experimenter, and the synchronicity between the real and virtual touches was aided by the implementation of audio cues signalling each touch location and timing.

2.6. Implicit and explicit measures of embodiment strength

2.6.1. Implicit measures

Participants' body temperature was registered before and immediately after each IMS block as an implicit measure of the strength of the embodiment illusion. Temperature readings were taken beneath the participants' right armpit, employing the same method outlined in our previous study [33], utilising an infrared thermometer (IFR 100, microlife, precision: ±0.2 °C, range: 32.0–42.2 °C). To assess changes in body temperature after embodiment, we calculated the difference between the temperature values collected after exposure to the avatars and the baseline values.

2.6.2. Explicit measures

As an explicit measure of the embodiment illusion strength, we used a self-reported questionnaire [33] evaluating three core facets of the embodiment illusion: Ownership (the sensation of possessing the virtual body), Agency (the feeling of controlling the virtual body), and Referral of Touch (perception of being touched by a virtual object). Additionally, control items were integrated to divert participants' focus from the study's hypothesis and to account for response biases (refer to Table 1 for the complete inventory of questionnaire items). Administered within the virtual reality setting, the questionnaire was displayed on a whiteboard positioned in front of the participants, with the items presented in a randomised sequence. Notably, no avatar was present in the virtual environment during the questionnaire session. Participants provided their ratings on a Visual Analogue Scale (VAS), ranging from 0 ("I do not agree at all") to 100 ("I completely agree").

Table 1
Questionnaire items assessing subjective feelings during the a/synchronous IMS on four subscales.

Embodiment questionnaire	
Items	**Subscales**
I felt I was looking at my own body	Ownership
I felt the virtual body was my own body	Ownership
I felt I could control the virtual body	Agency
I felt I could move the virtual body	Agency
I felt the virtual body obeyed or could obey my will	Agency
I felt that the touch I received was caused by the ball moving on the virtual body	Referral of Touch
I felt I was receiving the touch where the ball was touching the virtual body	Referral of Touch
I felt I had more than one body	Control
I felt I did not own a body anymore	Control

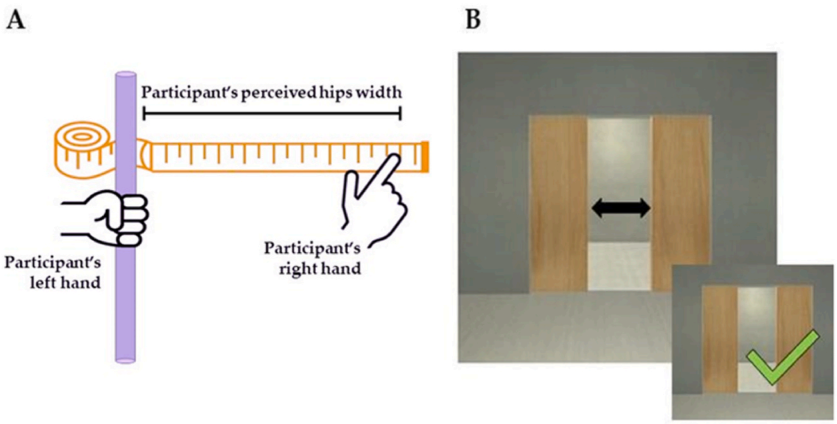


Fig. 3. Perceptual Body Image Task (A) - Participants' vision was occluded during the whole procedure. They were asked to hold a metal handle with the left hand, with their arm stretched out. The hand holding the handle was positioned on the medial line of the participant's body. Using the thumb and index of the right hand to hold the ruler, the participant had to slide across the ruler attached to the handle and estimate the perceived width of their hips. **Body Schema Task (B) -** The task comprised four trials, each commencing with a different aperture for the door (0.30 m, 0.60 m, 0.90 m, and 1.20 m). Participants had the capability to finely adjust the width of the door's aperture, increasing or decreasing it by 1 mm increments until reaching their desired setting. Randomisation for the sequence of these four trials was performed independently for each participant.

Table 2
Questionnaire items assessing participants' explicit perception of Self-Body Dimension.

Questionnaire Items	
Items	**Subscales**
I felt like my body was thinner than usual	Feelings of Thinness
I felt like my body was fatter than usual	Feelings of Fatness

2.7. Implicit measures of self-body dimension (perceptual body image and body schema tasks)

2.7.1. Perceptual body image task

The Perceptual Body Image Task was performed with participants laying down on a deck chair while wearing the Head-mounted Display (HMD). They were asked to estimate the width of their own hips by relying exclusively on non-visual perception of their body. Following the methodology employed by Preston and colleagues [30], participants completed four estimation trials. Throughout this task, participants wore the HMD with the screens deactivated, thus blocking the view of their own bodies. Participants held a ruler in front of them and used the index finger and thumb of their right hand to slide across the ruler, adjusting the distance between their hands in accordance with the estimation of their hip's width. To prevent participants from aligning their hands with their perceived hip width, one of the experimenters held in place the left hand of participants along the median line of their body while they conducted the estimation, allowing only the right hand to move freely (refer to Fig. 3, panel A).

2.7.2. Body schema task

For the Body Schema Task, participants were directed to envision themselves walking through the opening of the virtual sliding door that was presented in front of them inside the virtual scenario and to determine the minimum width of the aperture needed for them to pass through without contorting their body (refer to Fig. 3, panel B). Using a joypad (Belkin Nostromo Speedpad n52) positioned on the deck chair's right armrest, participants could adjust the width of the door's aperture by either expanding or reducing it. Participants were able to manipulate the aperture width with precision, adjusting it in increments of 1 mm by pressing the left and right arrows on the joypad until achieving the desired aperture width, which ranged from a minimum of 0 m to a maximum of 1.50 m. Consistent with prior research [29], the task comprised four trials, each commencing with a distinct initial aperture width (0.30 m, 0.60 m, 0.90 m, and 1.20 m). The sequence of these trials was randomised independently for each participant.

2.8. Explicit measures of the self-body dimension (feelings of thinness/fatness)

To evaluate the subjective perception of feeling either "thinner" or "fatter" than usual, akin to the methodology described in Ref. [31], we introduced two supplementary items ("I felt like my body was thinner/fatter than usual"), as outlined in Table 2. Participants provided their ratings on a VAS, with scores ranging from 0 ("I do not agree at all") to 100 ("I completely agree"). Subsequently, an aggregate measure of Body Feeling was computed by subtracting the score for the "feeling thinner" item from the score for the "feeling fatter" item.

2.9. Measure of the emotional response induced by embodiment

The valence and intensity of emotional responses elicited by observing synchronous or asynchronous congruent/incongruent IMS with underweight and normal-weight BMI avatars were assessed. Participants rated their emotional experience using a VAS, ranging from zero ("Very negative") to 100 ("Very positive"), following each IMS block. The VAS was displayed on a whiteboard within the virtual reality environment, and no avatar was present during this task.

2.10. Avatars' assessment: self-similarity, attractiveness and implicit disgust ratings

At the conclusion of the experiment, participants were prompted to rate the underweight and normal-weight BMI avatars across three dimensions: similarity to their own body (Self-Similarity), physical attractiveness (Attractiveness), and the perceived pleasantness or unpleasantness of the avatar's body odour (Implicit Disgust). For Self-Similarity ratings, participants utilised a VAS ranging from 0 ("Not similar at all") to 100 ("Completely similar"). Attractiveness ratings were provided on a VAS ranging from 0 ("Not attractive at all") to 100 ("Maximally attractive"). To measure Implicit Disgust, participants imagined the body odour of the observed avatars and rated it on a VAS ranging from 0 ("Maximally unpleasant") to 100 ("Maximally pleasant").

During this final evaluation, the avatars were presented from a 1-PP while participants remained reclined on the deck chair, ensuring spatial congruence between the participants' real body and the virtual body under assessment. The sequence of avatar presentation was counterbalanced among participants, and the order of the three rating questions was randomised.

3. Results

Statistica 8.1 software (Statsoft Inc., Tulsa, OK, 2007) and JASP (jasp-stats.org) were used to conduct all the statistical analyses. Significance was set at $p < 0.05$ or corrected following FDR correction methods when required to deal with multiple comparisons. Post-hoc comparisons were conducted using the Duncan test whenever required.

3.1. Sample characterisation: eating disorders severity, self-body measures and interoceptive awareness

Independent samples t-tests were employed to compare the AN and HC groups across all pertinent demographic variables, presence of eating disorders pathology (BMI, EDI, BSQ, BUT), interoceptive awareness (MAIA), and self-body dimension (Perceptual Body Image and Body Schema tasks conducted at baseline). Refer to Table 3 for the outcomes.

Table 3
Means (M) and Standard Deviations (SD) of measures assessing the severity of eating disorders, perceived self-body dimensions, and interoceptive awareness are presented separately for two distinct groups: healthy controls (HC) and individuals diagnosed with anorexia nervosa (AN). Perceived self-body dimensions are quantified as a percentage of the actual width of participants' hips (Perceptual Body Image) and shoulders (Body Schema), with 100 representing the true width of the body part. BMI = Body Mass Index; EDI = Eating Disorder Inventory; BSQ = Body Shape Questionnaire; BUT GSI = Body Uneasiness Test, General Symptom Index subscale, MAIA = Multidimensional Assessment of Interoceptive Awareness.

Demographic and Eating Disorder Variables							
	HC (N = 25)		AN (N = 26)				
	M	SD	M	SD	T	df	*p*
Age	22.00	2,58	20.61	3.60	1.57	49	0.122
BMI	20.08	1.57	16.90	0.67	9.27	49	<0.001
EDI - drive for thinness	3.84	5.70	14.42	7.52	−5.56	49	<0.001
EDI - bulimia	1.88	3.58	1.04	3.53	0.96	49	0.340
EDI – body dissatisfaction	8.08	6.82	15.33	8.09	−3.40	49	0.001
BSQ	85.72	32.43	121.12	37.26	−3.58	49	<0.001
BUT GSI	1.40	0.87	2.78	0.96	−5.34	49	<0.001
MAIA Noticing	3.62	0.69	2.91	0.96	2.93	49	0.005
MAIA Not Distracting	2.46	0.73	2.37	0.90	0.38	49	0.706
MAIA Not Worrying	2.25	0.85	2.07	0.86	0.72	49	0.472
MAIA Attention Regulation	2.86	0.97	2.46	1.00	1.42	49	0.161
MAIA Self-Regulation	2.52	1.22	1.40	0.99	3.50	49	0.001
MAIA Emotional Awareness	3.30	0.65	3.00	1.01	1.23	49	0.226
MAIA Body Listening	2.85	0.90	1.77	1.06	3.78	49	<0.001
MAIA Trusting	3.12	1.25	1.25	1.16	5.33	49	<0.001
Perceptual Body Image Task	85.80	16.83	107.60	26.34	−6.34	49	<0.001
Body Schema Task	142.37	26.68	175.50	49.44	−9.44	49	0.004

As expected, individuals with AN presented significantly lower BMI compared to HC participants. Moreover, the results from the self-reported questionnaires show that, with respect to controls, patients reported higher drive for thinness (EDI), higher body dissatisfaction (EDI), a marked concern with their body shape (BSQ) and higher body uneasiness (BUT). As all our participants had a diagnosis of AN-restricting type, it is important that no difference between patients and controls was found in the bulimia symptoms severity (EDI). Compared to healthy participants, patients with AN also showed, as indexed by the MAIA questionnaire, to be less aware of their bodily sensations (Noticing scale), to have a reduced ability to soothe emotional distress by focusing on bodily sensations (Self-Regulation scale), to listen less to their own body for insight (Body Listening scale) and to be less able of experiencing their own body as safe and trustworthy (Trusting scale).

Individuals diagnosed with anorexia significantly overestimated the width of their hips (Perceptual Body Image Task) and the door's minimum aperture width needed to walk it without contorting their body (Body Schema Task) in comparison to the healthy controls (seeTable 3), before any kind of embodiment illusion was at play.

3.2. *Explicit and implicit measures of embodiment*

Separate 2 × 2 × 2 ANOVAs were conducted for each measure of the embodiment illusion (explicit measures: Ownership, Agency, and Referral of touch; implicit measures: participants' body temperature), with Group serving as the between-subjects factor, and Avatar's size and type of IMS as within-subjects factors.

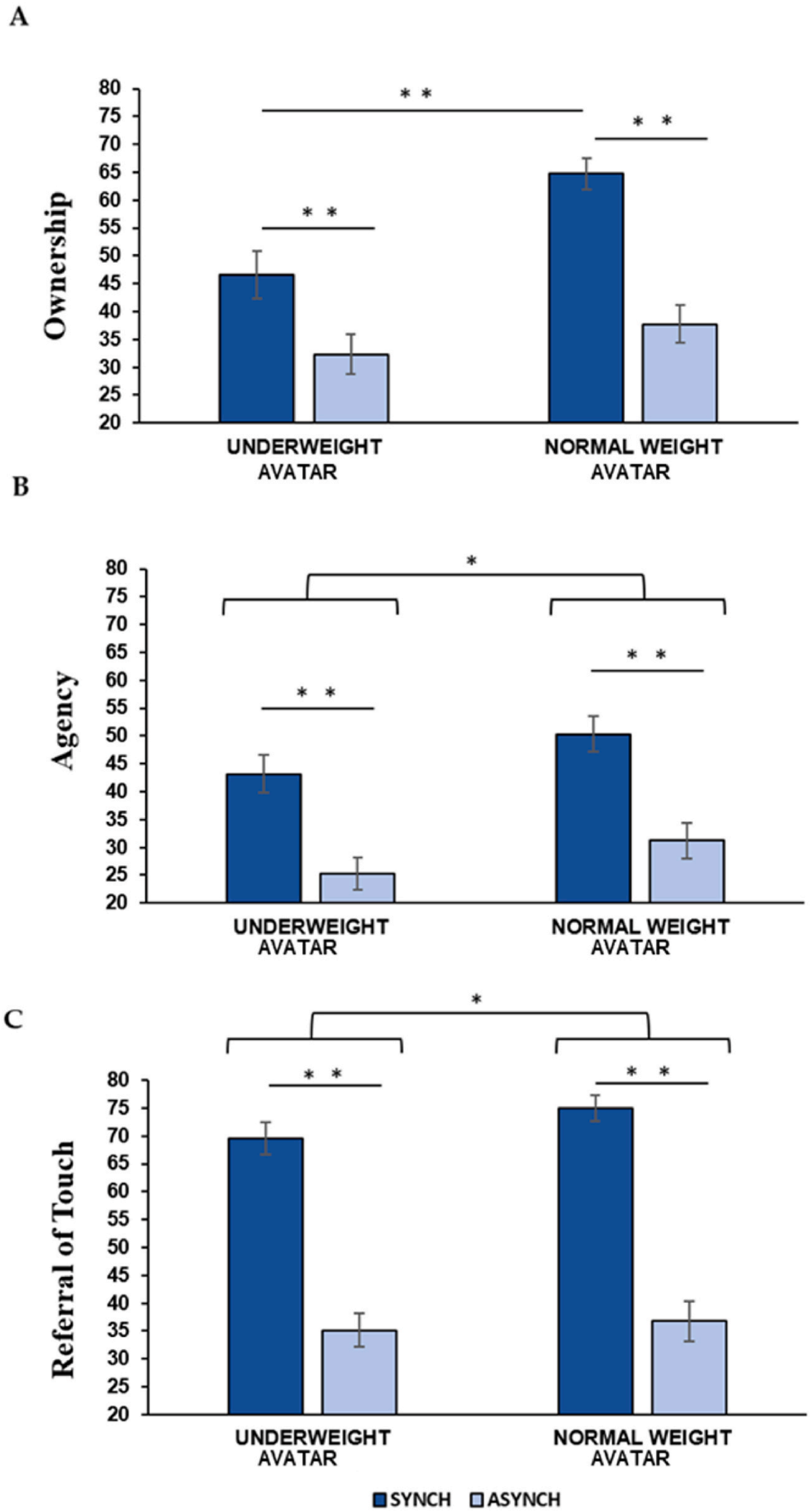
3.2.1. *Explicit measures of embodiment: ownership, agency and referral of touch*

The analysis uncovered a significant main effect of IMS across all components of the embodiment illusion, with stronger ratings for Ownership, Agency, and Referral of Touch observed after synchronous congruent IMS compared to asynchronous congruent IMS (all Fs > 43.12; all ps < 0.000; all ηsˆ2 > 0.468; see Fig. 4, panels A, B, and C, respectively). Additionally, a significant main effect of the Avatar's size was found for all components of the embodiment illusion, with higher ratings recorded for the normal-weight BMI avatar in comparison to the underweight BMI avatar, irrespective of IMS and Group (all Fs > 4.23; all ps < 0.045; all ηsˆ2 > 0.080).

Only for the Ownership component, there was a significant interaction between IMS and Avatar [F (1,49) = 5.42, p = 0.024, η2 = 0.100; please see Fig. 4A]. Regardless of Group, participants experienced an embodiment illusion with both avatars (Normal-weight Avatar: Synch (64.75 ± 2.83) vs. Async (37.75 ± 3.41), p = 0.000; Underweight Avatar: Synch (46,63 ± 4.23) vs. Async (32.34 ± 3.52), p = 0.001). However, illusory ownership was stronger for the normal-weight avatar in comparison to the underweight one when the Synch IMS was applied (Synch-IMS: Normal-weight vs. Underweight Avatar, p = 0.0001).

Moreover, for the Ownership ratings, we found a significant interaction between IMS and Group [F (1,49) = 5.65, *p* = 0.021, η2 = 0.104]. Post-hoc analysis revealed a significant difference between the synchronous and asynchronous congruent/incongruent conditions both in HC and AN (all ps < 0.05), with higher values in the synchronous conditions with respect to the asynchronous one. However, neither the Synch nor the Asynch IMS conditions differed between the groups.

There was also a significant Avatar * Group interaction [F (1,49) = 4.73, *p* = 0.034, η2 = 0.088]. Post-hoc analysis revealed that in the HC group, there was a significant difference between the two body size avatars, as the normal BMI avatar received a higher



(caption on next page)

Fig. 4. Explicit measures of the Embodiment illusion: Subjective feelings of Ownership (A), Agency (B), and Referral of Touch (C) during a/synchronous in/congruent IMS. (A) Main effect of IMS and Avatar's size for the Ownership component of the embodiment illusion. Additionally, a significant interaction effect between IMS (Synchronous vs Asynchronous) and Avatar (Underweight vs Normal-weight) demonstrates higher ownership values for the normal weight synchronous condition compared to the underweight synchronous condition. **(B)** Main effect of the IMS and Avatar's size for the Agency component of the embodiment illusion. **(C)** Main effect of the IMS and Avatar's size for the Referral of Touch component of the embodiment illusion. Error bars represent standard error of the mean. * = $p < 0.05$, ** = $p < 0.001$.

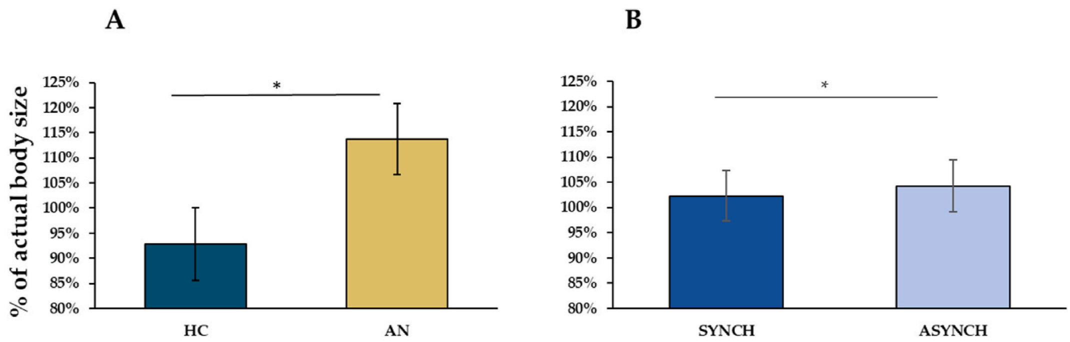


Fig. 5. Perceptual Body Image Task estimations after IMS. (A) Panel illustrating the main effect of group (healthy controls—HC; patients with anorexia nervosa—AN) on the perceptual body image task estimations (estimations are presented as a % of the participants' hips width, 100 % represent participants' actual hips with). **(B)** Panel illustrating the main effect of the IMS (synchronous congruent vs asynchronous incongruent IMS) on participants' hips with estimations. Error bars indicate standard error of the mean. * = $p < 0.05$.

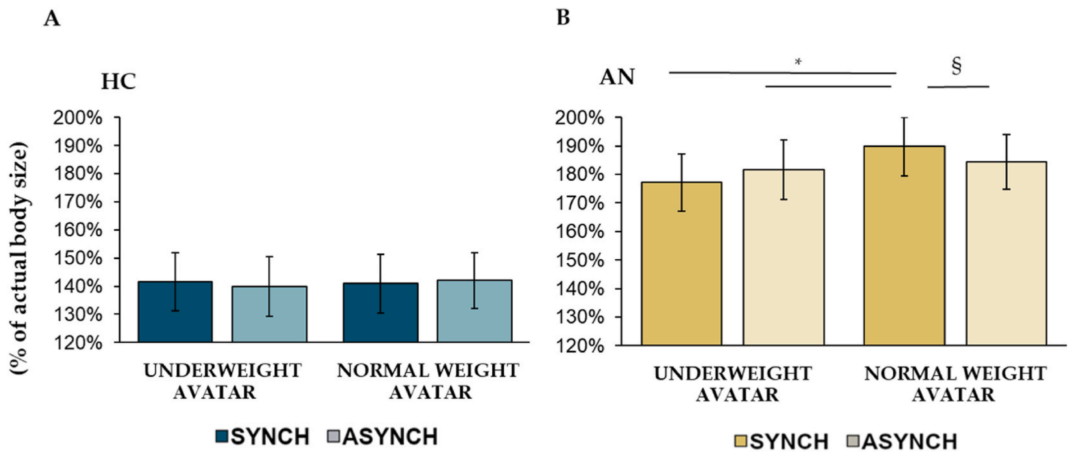


Fig. 6. Body Schema Task estimations after IMS. Graph illustrating the effect of the triple interaction among Group (healthy controls—HC, **Panel A**; patients with anorexia nervosa—AN, **Panel B**), Avatar's size (underweight vs normal-weight avatar), and IMS (synchronous congruent vs asynchronous incongruent IMS) on the body schema task estimations (estimations are presented as a % of the participants' hips width, 100 % represent participants' actual hips with). Error bars denote standard error of the mean. * = $p < 0.05$, § = $p = 0.056$.

ownership rating [underweight avatar 35.48 ± 4.71 vs. normal weight avatar 53.26 ± 3.46, $p < 0.001$]. However, the ownership ratings attributed to the two body size avatars by patients with AN did not differ significantly [underweight avatar 43.48 ± 4.62 vs normal weight avatar 4.24 ± 3.40, $p = 0.146$]. The remaining main and interaction effects were not significant (all $F < 2.57$; all ps > 0.11).

3.2.2. Implicit measures of embodiment: body temperature

The same 2 × 2 × 2 ANOVA revealed only a significant main effect of the IMS condition [$F(1,49) = 4.11$, $p = 0.048$, $\eta 2 = 0.077$], with lower body temperature in the synchronous congruent IMS (−0.10 ± 0.02) vs. asynchronous incongruent IMS (-0.05 ± 0.02) regardless of the Group and of the Avatar.

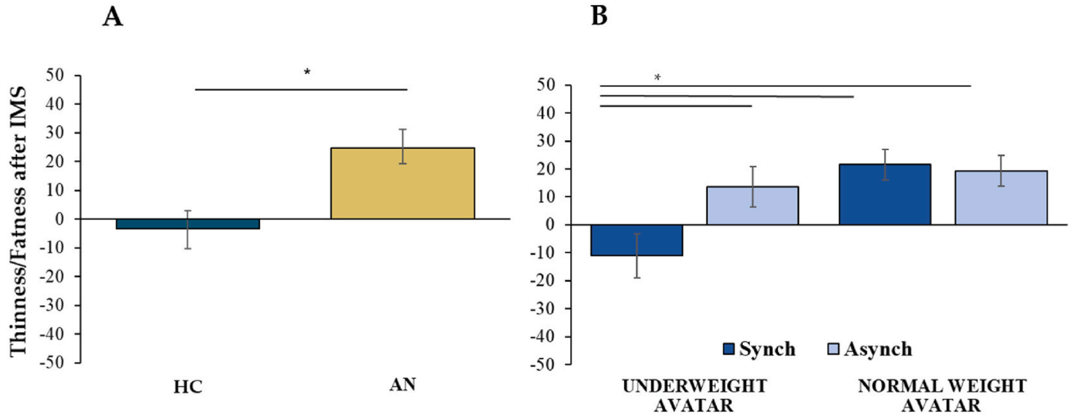


Fig. 7. Explicit measures of the Self-Body Dimension: Feelings of Thinness/Fatness after IMS. (A) Panel illustrating the main effect of Group. **(B)** Panel illustrating the interaction effect between IMS (synchronous congruent vs asynchronous incongruent) and Avatar's size (underweight vs normal-weight avatar). Feeling fatter than usual is indicated by positive values, while feeling thinner than usual is indicated by negative values. Error bars denote standard error of the mean. * = $p < 0.05$.

3.3. The effect of the embodiment over implicit and explicit measures of self- body dimension

3.3.1. Implicit measures of the self-body dimension: body perceptual body image and body schema tasks

Separate 2 × 2 × 2 ANOVAs were conducted with Group as the between-subjects factor and Avatar's size and IMS as within-subjects factors for Perceptual Body Image and Body Schema estimations following embodiment.

3.3.2. Perceptual body image task

The analysis revealed that, regardless of the size of the avatars and IMS condition, individuals with anorexia reported a larger hip width compared to HC participants in the Perceptual Body Image Task [main effect of Group: $F(1,49) = 4.30$, $p = 0.043$, $\eta\hat{}2 = 0.080$; AN (113 % ± 07 %) vs. HC (93 % ± 07 %), Fig. 5, panel A]. Additionally, all participants reported a smaller hip width after the synchronous congruent IMS (102 % ± 05 %) in comparison to the asynchronous incongruent IMS (104 % ± 05 %) condition [main effect of IMS: $F(1,49) = 4.04$, $p = 0.050$, $\eta\hat{}2 = 0.076$], (see Fig. 5, panel B). All the remaining main effects and interactions were not significant (all Fs < 3.64; all ps > 0.062).

3.3.3. Body schema task

The analysis revealed that individuals with anorexia reported overall higher body estimations, i.e., wider doors' apertures, compared to HC participants (141 % ± 09 %), independently of the IMS and size of the avatars [main effect of the Group [$F(1,49) = 9.06$, $p = 0.004$, $\eta2 = 0.153$]. Additionally, there was a significant triple interaction among Group, Avatar's size, and IMS [$F(1,49) = 5.47$, $p = 0.023$, $\eta2 = 0.10$; Fig. 6]. Post-hoc tests indicated that individuals with anorexia reported a larger estimation of the door's aperture width after the normal-weight Avatar synchronous congruent IMS condition (190 % ± 10 %) compared to the underweight Avatar synchronous congruent condition (177 % ± 10 %; $p < 0.001$). With respect to the comparison with the asynchronous normal-weight avatar (184 % ± 10 %), although the p-value of the post-hoc was 0.056, further evidence should be provided to support this possible difference. Regarding HC participants' body estimations, results show that estimation of the door aperture did not differ as a function of IMS type or Avatar size (all ps > 0.703).

The remaining main effects and interactions were not significant (all Fs < 3.21; all ps > 0.079).

3.3.4. Explicit measures of the self-body dimension: feelings of thinness/fatness after the embodiment

A 2 × 2 × 2 ANOVA was conducted, with Group as the between-subjects factor and Avatar's size and IMS as within-subjects factors, using Feelings of Thinness/Fatness after embodiment as the dependent variable. Positive values denoted feeling fatter than usual, while negative values indicated feeling thinner than usual.

Results revealed overall higher ratings of feeling fatter than usual in patients with anorexia (24.87 ± 6.13) with respect to healthy controls (−3.16 ± 6.25), [main effect of the Group: $F(1,49) = 10.25$, $p = 0.002$, $\eta2 = 0.173$, see, Fig. 7 panel A]. There was also a significant main effect of Avatar [$F(1,41) = 10.04$, $p = 0.003$, $\eta2 = 0.170$] and IMS [$F(1,49) = 4.13$, $p = 0.047$, $\eta2 = 0.078$], further explained by a significant interaction between the two conditions [$F(1,49) = 6.18$, $p = 0.016$, $\eta2 = 0.112$] (See Fig. 7 panel B). Post-hoc analysis performed to explore the double interaction showed that all participants reported feeling thinner than usual after the synchronous congruent with respect to asynchronous IMS incongruent with the underweight BMI avatar (−11. ± 7.87) and to the other conditions, namely the normal-weight avatar during both the synchronous congruent and the asynchronous incongruent IMS (all ps < 0.002). All the other interaction effects were not significant (all Fs < 3.50; all ps > 0.067).

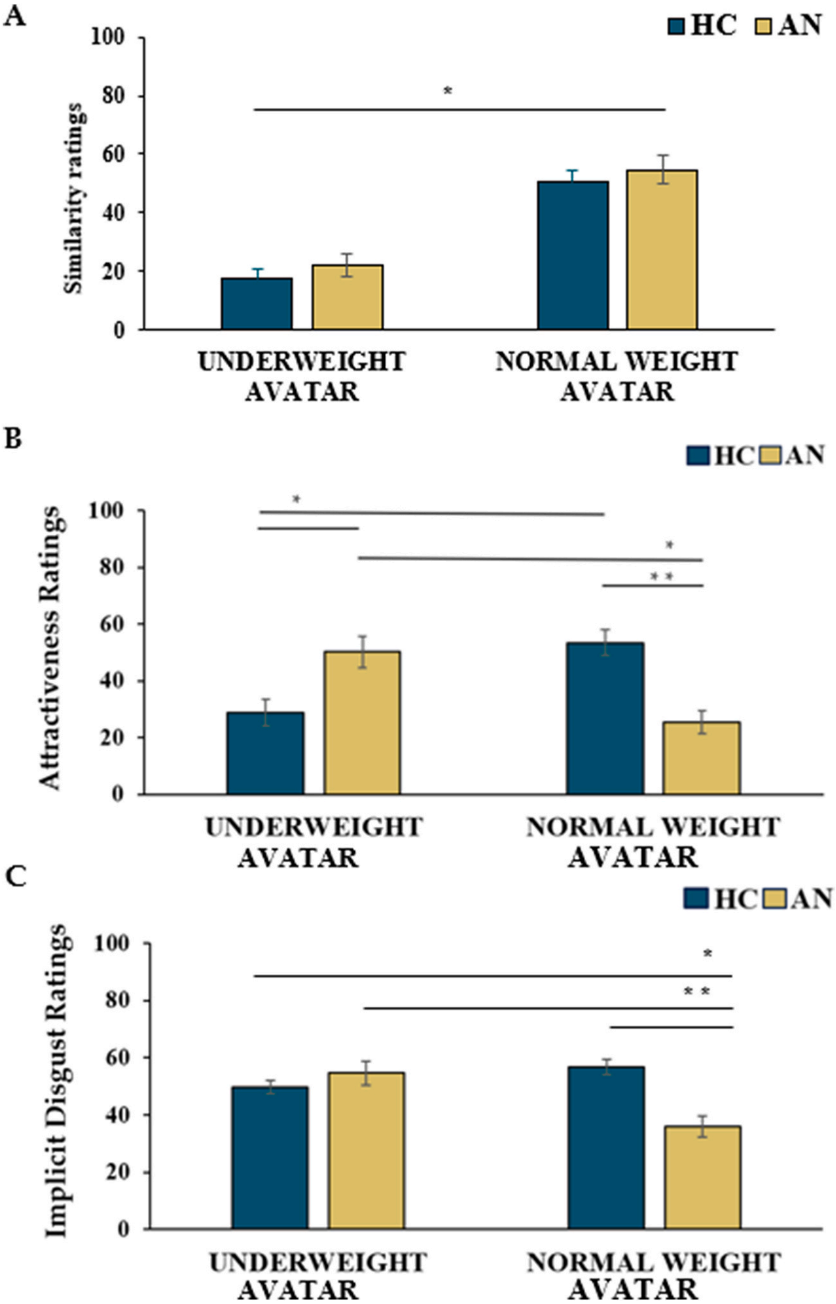


Fig. 8. Participants' assessment of under/normal-weight Avatars (observed with a 1-PP). (A) Panel illustrating the main effect of Avatar's size on similarity ratings. **(B)** Panel illustrating the effect of the interaction between Avatar's size and Group on attractiveness ratings. **(C)** Panel illustrating the effect of the interaction between Avatar's size and Group on ratings of implicit disgust, indexed by the attribution of body odour pleasantness. The lower the value on the y-axis, the less pleasant the estimated body odour. Error bars represent standard error of the mean. * = $p < 0.05$, **$p < 0.001$.

3.4. Emotional response after the embodiment

A $2 \times 2 \times 2$ ANOVA was conducted, with Group as the between-subjects factor and Avatar's size and IMS as within-subjects factors, using emotional ratings after embodiment as the dependent variable. A significant main effect of the Group was observed [$F(1,49) = 7.93$, $p = 0.007$, $\eta 2 = 0.139$], with more negative emotions reported by individuals with anorexia (37.95 ± 3.28) compared to healthy controls (51.13 ± 3.34), regardless of avatar size and the type of IMS applied. All the remaining main effects and interactions were not significant (all Fs < 2.26; all ps > 0.139).

3.5. Correlations between eating disorders severity, interoceptive awareness and embodiment-induced changes to the perceived self-body dimension

We checked whether the severity of clinical symptoms and interoceptive awareness in AN would be related to embodiment-induced changes to the perceived dimension of one's own body (i.e., body schema task estimations). To this aim, we correlated participants' scores in the EDI, BUT, BSQ, and MAIA subscales (namely the questionnaires/subscales where AN differed significantly from HCs) with an index of the synchronous IMS-induced changes to body schema. This index was calculated for each participant as the difference between the aperture value obtained after the embodiment of the normal-weight avatar (triggered by the synchronous congruent IMS with the normal-weight avatar) and the averaged values obtained in the remaining three conditions (namely the asynchronous congruent IMS with the normal-weight avatar and the a/synchronous congruent IMS with the underweight avatar). This decision was supported by the results of the post-hoc analysis showing that there are no significant differences between these three aforementioned conditions, while all three were different from the estimations following the congruent IMS in association with the normal-weight avatar.

Results showed that all the correlations were above the threshold corrected for multiple comparisons in both AN and HC. Therefore, the strength of the effect triggered by the embodiment of the normal weight Avatar did not vary with the severity of clinical symptoms and ratings of interoceptive awareness.

3.6. Under/normal-weight Avatar's assessment: self-similarity, attractiveness and implicit disgust ratings

Three separate 2x2 ANOVAs were conducted, with Group as the between-subjects factor and Avatar's size as the within-subjects factor, using judgments of Self-similarity, Attractiveness, and Implicit disgust as dependent variables.

Self-Similarity - the normal-weight avatar is perceived as the most similar to the self in AN and HC.

A significant main effect of the Avatar's size was found, indicating that all participants perceived the normal-weight BMI avatar as more similar to their actual body compared to the underweight BMI avatar [$F\ (1,49) = 50.73$, $p < 0.001$, $\eta 2 = 0.509$]; Normal-weight: (52.60 ± 3.01); Underweight BMI: (19.74 ± 2.65); as illustrated in Fig. 8, panel A]. All the other effects were not significant (all $Fs < 1.73$; all $ps > 0.193$).

To confirm the lack of interaction between the Group and the Avatar's Size on self-similarity ratings, a Bayesian repeated measure-ANOVA was also performed. The results confirm that the data on participants' self-similarity ratings are more likely in a model that does not include the main effect of Group (BFexclusion = 2.878) nor the interaction effect between Group and Avatar's Size (BFexclusion = 3.469).

Attractiveness - the normal-weight avatar is the most unattractive for AN, the most attractive for HC.

Results revealed a significant Group * Avatar's size interaction [$F\ (1,49) = 20.21$, $p < 0.001$, $\eta 2 = 0.292$]. Post hoc tests showed that individuals with anorexia considered the normal weight avatar as significantly less attractive with respect to the underweight BMI avatar [Normal weight BMI avatar (25.44 ± 4.19) vs. Underweight BMI (50.27 ± 5.00), $p = 0.003$; Fig. 8, panel B]. HC showed the opposite trend, as the normal weight BMI avatar received higher attractiveness ratings in comparison to the underweight BMI avatar [Normal weight BMI avatar (53.44 ± 4.47) vs. Underweight BMI (28.96 ± 5.30), $p = 0.004$; Fig. 8, panel B]. Additionally, we found that AN evaluated the underweight avatar as the most attractive, whereas HC evaluated the normal-weight avatar as the most attractive (all $ps < 0.05$). All the other effects were not significant (all $Fs < 0.84$; all $ps > 0.364$).

Implicit Disgust - AN rated the normal-weight avatar as the least pleasant odour.

Results revealed a significant main effect of Group and a significant Group * Avatar's size interaction [main effect for the Group: $F\ (1,49) = 7.34$, $p = 0.009$, $\eta 2 = 0.130$; Group * Avatar's size: $F\ (1,49) = 13.40$, $p < 0.001$, $\eta 2 = 0.214$]. Regardless of the Avatar, we found that HC provided more positive scores than AN. Post-hoc comparisons performed to explore the Group × Avatar interaction instead showed that individuals with AN perceived the normal-weight avatar as the most disgusting one (measured in terms of body odour pleasantness). Specifically, individuals with anorexia nervosa attributed to it a less pleasant odour compared the one attributed to underweight avatar and to the odour attributed by control participants to both avatars [AN normal-weight avatar (36.08 ± 3.14) vs AN underweight avatar (54.71 ± 3.29, $p < 0.001$), HC normal-weight avatar (56.96 ± 3.20, $p = < 0.001$), HC underweight avatar (48.84 ± 3.36, $p = 0.004$), Fig. 8 panel C]. Avatar's size main effect was not significant [$F\ (1,49) = 2.68$, $p = 0.108$, $\eta 2 = 0.052$].

3.7. Correlations between eating disorders severity, interoceptive awareness and assessment of under/normal-weight avatars

To better characterise the relationship between the severity of AN pathology and perception of underweight and normal-weight avatars, we separately correlated scores obtained in the EDI, MAIA, BUT, and BSQ scales (where we found a difference between AN and HC) with indices of the ratings of implicit disgust and attractiveness and assigned to the avatars (where we found significant Avatar × Group interactions) in both groups. To control for multiple comparisons, we corrected the significance threshold of p values for the number of correlations performed with the same variable ($N = 8$) by using the FDR correction [49].

Firstly, we created attractiveness and implicit disgust indices, such that the higher the index, the more participants rated 1) the underweight avatar as attractive (compared to the normal-weight one) and 2) the normal-weight avatar as disgusting (compared to the underweight one). The attractiveness index was obtained for each participant by subtracting attractiveness ratings given to the underweight avatar from those given to the normal-weight avatar. Similarly, for each participant, we subtracted ratings of body odour pleasantness attributed to the underweight avatar from those attributed to the normal weight one.

Table 4
Correlations between the attractiveness ratings (Att. Index) and implicit disgust ratings (Dis. Index) and clinical measures of eating disorder severity (EDI – drive for thinness, EDI – body dissatisfaction, BSQ, BUT-GSI) A and self-reported measures of interoception (MAIA subscales). Both the attractiveness and implicit disgust indexes were calculated as differences between the underweight and normal-weight avatar ratings such that the higher the index, the more participants rated 1) the underweight avatar as attractive (compared to the normal-weight one) and 2) the normal-weight avatar as disgusting (compared to the underweight one). * = **p <.006,** § = p > ,009

Correlations between Eating Disorders severity, Interoceptive awareness and Attractiveness/Implicit Disgust of Under/Normal-weight avatars

	HC		AN	
	Attractiveness Index	Implicit Disgust Index	Attractiveness Index	Implicit Disgust Index
EDI - drive for thinness	0.52§	0.25	0.64*	0.57*
EDI - Body Dissatisfaction	0.70*	0.41	0.79*	0.70*
BSQ	0.61*	0.13	0.65*	0.47§
BUT GSI	0.41	<0.01	0.60*	0.47§
MAIA Noticing	−0.23	−0.24	0.22	<0.01
MAIA Self-Regulation	0.28	0.15	−0.72*	−0.53*
MAIA Body Listening	−0.18	−0.06	−0.42	−0.51*
MAIA Trusting	−0.01	0.02	−0.44	−0.41

We found that, only in AN, the more the participants were dissatisfied with their body (EDI - body dissatisfaction), desired to be thinner than they were (EDI - drive for thinness), were concerned about their body shape (BSQ), presented negative body image (BUT-GSI), and focused less on their internal signals to regulate their distress (MAIA - Self Regulation), the more: a) the underweight avatar was attractive compared to the normal one; b) the normal-weight avatar was disgusting in respect to the underweight one. Furthermore, the less AN listened to their visceral signals (MAIA - Body Listening), the more the normal-weight avatar was disgusting in comparison to the underweight one. Results, r, and p values are reported in detail in Table 4.

4. Discussion

The primary objective of this study was to delve deeper into and, notably, decrease Body Image Distortion (BID) among individuals with anorexia nervosa (AN). As highlighted in the introduction, BID holds significant sway across all phases of the disorder, spanning from its inception to its persistence and even relapse (as discussed in a recent review [50]).

In order to pursue this objective, we collected both subjective and objective measures of BID and investigated whether BID also influences the perception of avatars' bodies during an embodiment illusion. In particular, to reduce BID in AN, we implemented an Interpersonal Multisensory Stimulation (IMS) protocol known to induce the embodiment illusion, which refers to the illusory feeling of owning an avatar's body, as well as changes in bodily self-perception. Specifically, we investigated the effects of embodying avatars with desired (underweight) and undesired (normal weight) bodies on the perceived dimension of the self-body, the explicit sensation of feeling thinner or fatter than usual, and the associated emotional experiences.

Consistent with previous findings [32,39,51,52], we replicated evidence supporting the alteration of the perceptual, cognitive, and affective dimensions of body representation in the AN group, as demonstrated by the results of our body estimation tasks and self-report questionnaires. In particular, individuals diagnosed with AN demonstrated an overestimation of their hip width (assessed through the perceptual body image task) and the minimum aperture width needed to pass through a door without body contortion (evaluated via the body schema task) [51,53]. Thus, contrary to our previous study, where we adopted a depictive measure of body size estimation and found no body size overestimation in individuals with anorexia [33], the findings of the current study, in which we utilised metric methods of body size estimation and found overestimation in AN, provide further support to the increasing body of evidence indicating that metric methods of body size estimation are more adept at measuring body size overestimation in AN [5].

According to the theoretical framework proposed by Longo [54], these findings can be due to the fact that body representation is composed of multiple components distributed across two primary dimensions: perceptual versus conceptual and implicit versus explicit. In this framework [54], body schema and perceptual body image are both located in the perceptual dimension of body representation (somatoperception), suggesting a potential reliance on the same representation of body size (see Ref. [55] for a theoretical account). However, they differ on the other dimension. In fact, metric methods rely more on these implicit representations of the body, as they depend on automatic somatosensory and motor representations, which are severely impaired in AN and less controllable [52,56,57]. In contrast, depictive methods primarily rely on visual perception, thoughts, and feelings towards the body, thus addressing more explicit and conscious representations of body image, i.e. what participants think their body looks like, and therefore can be more under the control of the patients [5].

Moreover, the AN group reported higher levels of body dissatisfaction and drive for thinness (assessed by the Eating Disorder Inventory questionnaire), increased body concerns (measured by the Body Shape Questionnaire), a more negative body image (evaluated using the Body Uneasiness Test questionnaire), and lower interoceptive sensitivity (measured by the Multidimensional Assessment of Interoceptive Awareness questionnaire) compared to the control group.

Additionally, AN patients showed a distinct evaluation of normal and underweight body avatars, which aligned with their BID. On the one hand, and similarly to control participants, AN rated the normal-weight BMI avatar as the most similar to their real body, despite the high discrepancy between their own body and the avatar's BMI. On the other hand, and contrary to control participants, AN rated the normal-weight avatar's body as significantly less attractive and more disgusting than the underweight avatar. Interestingly, the severity of body image distortion (as indexed by perceptual body image/schema tasks and self-reported questionnaires) correlated with the extent to which AN rated the normal-weight avatar's body as unattractive and disgusting (compared to the underweight one). Thus, these findings illustrate the discrepancy between the undesired healthy BMI body (as it is considered the most similar) and the desired underweight BMI body (as it is considered the most attractive), which characterise individuals with AN. These results also provide new evidence about how a healthy BMI body is perceived by individuals with AN, as our patients imagined it to have a bad odour, which is a measure of implicit disgust.

Concerning the embodiment illusion, despite the difference observed in the avatars' evaluation between the two groups, our results showed that the synchronous congruent IMS procedure successfully induced the embodiment illusion over avatars of different body weights in both AN and HC participants. The results on the implicit measure of the embodiment illusion showed a decrease in participants' body temperature in the synchronous congruent compared to asynchronous incongruent conditions, regardless of the weight of the avatar presented. This suggests that, at the implicit level, both groups embodied the normal and the underweight avatars in the same way. These results replicate our previous findings [33] and provide further evidence in favour of using temperature as an implicit measure of embodiment. Nevertheless, when interpreting these results, it's crucial to note that while body temperature has been validated as a measure of body ownership in numerous studies [58,59], its reliability has been contested by several others [60–63]. More sophisticated technologies, such as those used to measure inner body temperature in a more reliable and continuous way (e.g., Ref. [64,76]), might help to shed light on the reliability of the body temperature as a marker of the embodiment illusion.

In terms of the explicit measure of the embodiment illusion through self-report questionnaires, the analysis indicated that synchronous congruent IMS elicited a significantly stronger embodiment illusion compared to asynchronous incongruent IMS. Additionally, across all assessed embodiment illusion components—ownership, agency, and referral of touch—the normal-weight avatar consistently garnered higher ratings compared to the underweight avatar. Our experimental manipulation also seems to affect the ownership component of the embodiment illusion more than the other components. Certainly, both groups exhibited notably heightened illusory ownership subsequent to synchronous congruent IMS in comparison to asynchronous incongruent IMS. However, the ownership illusion was more pronounced following synchronous congruent IMS with the normal-weight avatar in contrast to the underweight one. This finding takes on added significance when examining the ratings of self-similarity, attractiveness, and implicit disgust (i.e., body odour pleasantness) assigned by both HC and AN participants to the underweight and normal-weight avatars. Both groups perceived the normal weight avatar as the most similar to themselves. However, while healthy controls rated this avatar positively in terms of attractiveness and body odour pleasantness, individuals with AN rated it as the least attractive and most unpleasant in terms of body odour. Hence, we speculate that the experience of embodying a normal weight avatar may reflect the everyday life experience of individuals with AN with their own real body. The heightened sense of body ownership and perceived self-similarity with the normal weight avatar might resemble the experience of individuals with anorexia nervosa who overestimate their real body, which is also considered as non-attractive and repulsive.

Regarding the perceptual body image task, we found that individuals with AN presented a higher overestimation of the size of their hips compared to controls, regardless of the type of IMS and the size of the avatar presented. This reflects the general tendency of individuals with AN to overestimate their body size at the perceptual level. Additionally, the main effect of IMS revealed a lower overestimation in both groups and for both avatars after experiencing the synchronous congruent condition compared to the asynchronous incongruent condition. While this result might suggest an effect of IMS in decreasing body overestimation, it needs to be interpreted with caution, taking into account the rest of our findings, i.e. the increase in overestimation in body schema estimations after the synchronous congruent condition with the normal-weight avatar.

Related to this latter point, the most interesting findings of the current study arise from the impact of embodiment on body schema estimations. Although the embodiment of underweight and normal weight avatars did not alter HC participants' estimations of the minimum door aperture width needed for passage, individuals with AN reported larger door aperture widths after embodying the normal weight avatar compared to when they were embodying the underweight avatar. Importantly, the effect of embodiment on door aperture width estimation occurred only in AN patients and was specific to the congruent IMS condition, ruling out the possibility that the effect might be attributable to mere exposure to a normal-weight body.

To the best of our knowledge, this study represents the first instance of a specific change in patients' body schema due to a congruent/synchronous full-body illusion, i.e., embodiment. Previous studies [29,30] have reported a reduced estimation of one's own body size in neurotypical individuals following exposure to a slender virtual body. Similarly, another study observed a decrease in body size estimation among both AN and HC participants [25]. However, in all the aforementioned studies, these effects occurred following both synchronous and asynchronous IMS, complicating the delineation of the genuine impact of the full-body illusion from mere exposure to a desired thin body. The only exception is represented by a single case report study by Serino and colleagues [12], which described one patient with AN showing a qualitative reduction in abdomen size estimation (a perceptual body image task) after the synchronous IMS of a young and thin healthy-weight avatar. Despite being extremely interesting, such results might be taken with caution, as the study is only descriptive, lacks statistical analyses and a proper control sample, and the findings were not replicated over the course of a multidimensional treatment protocol (that included psychotherapy and medical drugs) and at one-year follow-up.

Furthermore, the observation that we detected an effect solely in AN indivisuals lends credence to the notion of heightened bodily self-plasticity in people with eating disorders relative to healthy controls [43]. However, this plasticity might be asymmetric, suggesting that it is easier to enlarge AN body schema than to reduce it. Thus, while our findings indicate the potential for modulating BID in AN by harnessing the multisensory integrative processes through which the brain identifies the body as one's own, we cannot conclusively assert that we have attained a reduction in BID in individuals with anorexia, particularly when implicit measures of perceptual body image and body schema are considered.

However, when considering the subjective reports of the self-body dimension, our results show a different picture. The embodiment of an underweight avatar induced the sensation of being thinner than usual, both in HCs and in people with AN. This means that every participant reported feeling thinner than usual following synchronous congruent IMS with the underweight BMI avatar in contrast to asynchronous incongruent IMS (as well as to all other conditions). This discrepancy in the effect of IMS and avatar weight on subjective and objective measures of self-body image perception can be interpreted in light of predictive coding accounts of self-recognition and embodiment illusion, also taking into consideration the features of the perceptual and affective/cognitive components of Body Image Distortion in anorexia nervosa. In line with the predictive coding theory [65,66], the spatial-temporal alignment between the two touches initially elicits surprise because participants are directed not to move, preventing them from confirming whether the observed body part truly belongs to them [67]. Furthermore, the observed body does not align with the stored visual representation of the self-body [16,17]. Consequently, the brain may seek to alleviate this conflict by integrating the body characteristics of the observed body into the representation of the bodily self.

Therefore, on the one hand, considering that patients with AN often perceive their bodies as larger than they are and, in our study, they identified the normal weight avatar as the most similar to themselves, they might have encountered reduced conflict during synchronous congruent IMS with the normal weight avatar. This is because the observed virtual avatar matched their internal representation of their body in terms of weight and shape. Consequently, the detection of this multisensory congruency might have signalled to the brain that the observed body was its own. As a result, the IMS-driven online perceptual representation of the self-body dimension was consistent with the offline representation stored in memory. The lack of such a discrepancy might have resulted in higher illusory ownership ratings and consequently affected the BID. Indeed, our findings suggest that applying synchronous congruent IMS to a normal-weight body, which mirrors BID found in individuals with AN, could reinforce the mistaken belief of owning a body larger than their real (and desired) body.

On the other hand, when patients with AN were experiencing synchronous congruent IMS with an underweight virtual body, the detection of visuo-tactile multisensory signals might have convinced the brain that the observed body must also belong to the self. However, in this case, there was a discrepancy between the IMS-driven online (underweight) and the offline (overweight) bodily self-representations. Such mismatch might have resulted in a lower, yet still significant, illusory ownership of the underweight virtual body without altering the offline perceptual representation of the self-body (as indexed by body schema estimation). Therefore, it appears that to accommodate changes to the stored representation of the bodily self, IMS protocols must consider a minimal discrepancy between participants' perceived self-body dimensions and the avatar's body weight.

It is also worth noting that the cognitive/affective dimension of body image appears to be much less influenced by the aforementioned perceptual discrepancy between online and offline body representations. Both individuals with AN and HCs reported feeling thinner than usual after embodying the underweight virtual body, which patients rated as minimally similar to the self but maximally attractive and pleasant. Striving to obtain an underweight body is a characteristic of AN individuals. Previous research on healthy individuals has shown that perceived attractiveness of the synchronously stimulated other body might increase the extent to which participants incorporate other's facial/body features into their self-representation [67,68]. Interestingly, a recent single case report study [69] demonstrated the possibility of decreasing the fear of gaining weight, body-related anxiety, body image disturbances, and body-related attentional bias by systematically and hierarchically exposing an embodied avatar to an individual with AN. The avatar depicted a virtual representation of the patient's own silhouette, and its body mass index progressively increased in subsequent sessions. Although the perceptual component of BID was not measured in the mentioned study, we might speculate that by repeatedly exposing the patient to a gradually enlarged embodied avatar, it could be possible to progressively reduce the discrepancy between online and offline body representations, ultimately leading to a reduction in AN's critical symptom of body size overestimation.

5. Conclusions

In conclusion, the findings of the present study suggest that it may be possible to use bodily illusions to modify body image distortion in individuals with anorexia nervosa, as the embodiment of a normal-weight avatar was successful in changing their body schema estimations, although not in the desired direction, i.e., we observed only an increase of the body size overestimation following the embodiment of the normal-weight avatar. Moreover, our findings underscore the distortion of both cognitive and emotional facets of body image as pivotal elements of anorexia nervosa. Patients rated the normal-weight avatar as the most similar to themselves yet simultaneously deemed it the least attractive and the most repulsive. While the current experimental protocol may not be able to directly reduce body size overestimation, it identified potential targets for developing novel non-invasive treatments aimed at modifying the more flexible components of body representation, specifically the body schema. Finally, our results suggest that body image disturbance in individuals with anorexia nervosa extends through all sensory channels (from visual to olfactory) and components (from perceptual to affective), highlighting the requirement of different multiple interventions to address it effectively.

6. Limitations

In the synchronous congruent IMS condition, we presented the avatar from a first-person perspective and applied synchronous visuo-tactile stimulation on the participants' bellies. However, while this procedure was successful in inducing a sense of embodiment in our participants, and virtual touches can have beneficial effects on individuals (e.g., Ref. [70]), literature shows that patients with AN exhibit a multisensory impairment of body perception that involves both tactile and proprioceptive sensory components [57].

Moreover, individuals with AN appear to process touch as less pleasant compared to healthy controls [71,72]. Therefore, to minimise possible confounding effects derived by touch, it is our opinion that future studies should preferably rely on the visual motor congruency between the participant's actual body and observed virtual body to induce the embodiment illusion.

In addition to this, when interpreting the effect of the synchronous multi-sensory stimulation on body schema changes, it is important to point out that a debate exists on the actual contribution of embodiment in altering body schema [55], and more studies might be required to investigate further the relationship between the mechanisms updating body representations and those responsible for the sense of embodiment. Finally, while our focus was on investigating the impact of embodying avatars of varying body sizes on implicit measures of body size overestimation, namely through the doors' aperture and the ruler task, we acknowledge the possibility that more explicit variables, such as participants' beliefs, thoughts, and emotions about their body size, as well as compliance, may have influenced their body size estimations [73]. Future studies could seek to mitigate these response biases either by controlling the allowed response time for body size estimation tasks (e.g., Ref. [74]) or by manipulating task instructions in order to obfuscate the expected outcome (e.g., Ref. [75]).

Ethics and consent statement

The study received approval from the Ethical Committees of the IRCCS Santa Lucia Foundation in Rome (Prot. CEIPROG.535) and was conducted adhering to the Ethical standards outlined in the 2013 Declaration of Helsinki. Prior to participation, all individuals read and signed an informed consent form. For participants under the age of 18, parental consent was mandatory, and assent was additionally obtained from the minors themselves. Monetary compensation was provided to participants as remuneration for their involvement in the study.

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Additional information

The present work partially refers to L.P.'s doctoral dissertation, which provides a preliminary account of this study. The dissertation is freely accessible on the IRIS website, the online repository of Sapienza University of Rome, at the following link.

Data availability statement

Data is not publicly available. Data will be made available on request to the CA author (email: luca.provenzano@iit.it)

CRediT authorship contribution statement

Luca Provenzano: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sofia Ciccarone:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Giuseppina Porciello:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Manuel Petrucci:** Resources, Investigation, Data curation. **Barbara Cozzani:** Supervision, Resources. **Armando Cotugno:** Supervision, Resources, Project administration. **Ilaria Bufalari:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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