Self-perception in anorexia nervosa: When the body becomes an object

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Authors:

Scarpina Federica 1,2, Bastoni Ilaria 3,4, Villa Valentina 3,4, Mendolicchio Leonardo 4, Castelnuovo Gianluca 4,5, Mauro Alessandro 1,2, Sedda Anna 6,7.

1. "Rita Levi Montalcini" Department of Neurosciences, University of Turin, Italy.

2. I.R.C.C.S. Istituto Auxologico Italiano, U.O. di Neurologia e Neuroriabilitazione, Ospedale San Giuseppe, Piancavallo (VCO), Italy.

3 I.R.C.C.S. Istituto Auxologico Italiano, U.O. dei Disturbi del Comportamento Alimentare, Ospedale San Giuseppe, Piancavallo (VCO), Italy.

4 I.R.C.C.S. Istituto Auxologico Italiano, Laboratorio di Psicologia, Ospedale San Giuseppe, Piancavallo (VCO), Italy.

5. Psychology Department, Università Cattolica del Sacro Cuore, Milan, Italy.

6 Psychology Department, School of Social Sciences, Heriot-Watt University, Edinburgh, UK.

7. Centre for Applied Behavioural Sciences, School of Social Sciences, Heriot-Watt University.

* Corresponding Author

Scarpina Federica. "Rita Levi Montalcini" Department of Neurosciences, University of Turin, Via Cherasco, 15, 10126, Turin, Italy. Email: federica.scarpina@unito.it Istituto Auxologico Italiano – IRCCS Ospedale S. Giuseppe. Via Cadorna 90 – 28824 Piancavallo (Oggebbio – VCO), Italy. Phone: +39-0323514353. Fax: +39-0323514338. Email: f.scarpina@auxologico.it

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Highlights

- Women with Anorexia Nervosa act as if they have a larger body than their physical one.
- We explored bodily actions based on a self-frame of reference through motor imagery in affected women.
- They showed altered imagery/motor strategy in the experimental tasks.
- Affected participants adopted a third-person, rather than a first-person perspective.
- Affected participants tended to objectify body parts.

Abstract.

Objective. Women with anorexia nervosa (AN) act as if they have a larger body, as evidenced in obstacle avoidance tasks, where an allocentric perspective is adopted. This alteration emerges not only when they perform, but also when they imagine movements. However, no previous study has investigated own body centered tasks. As such, in this study we aim at documenting if women with AN show an altered behaviour also when the task requires a first-person perspective.

Method. We explored the performance of eleven woman affected by AN compared to eighteen matched controls, in two motor imagery tasks based on a self-frame of reference, the Hand Laterality Task and the Mental Motor Chronometry Task. Moreover, two control tasks relative to visual imagery were administered.

Results. In the Hand Laterality Task, affected participants did not adopt a motor strategy to judge hands laterality (i.e. no biomechanical constraints effect). Crucially, they also showed an altered behavior in the control task. Similarly, they did not show the expected isochrony in the Mental Motor Chronometry Task, when actions pertained the left (but not the right) hand, in absence of any difference in the control task.

Conclusions. Our findings reveal altered imagery processes in AN. Specifically, affected participants adopt a third-person, rather than a first-person perspective, even when the task requires to imagine their own body in an internal frame of reference. In other words, participants with AN objectify body stimuli. Different mechanisms (i.e., checking behaviour; mirror self-reflection; altered multisensory integration) can explain such an altered imagery in AN.

Keywords: anorexia nervosa; body in action; mental imagery; motor imagery.

Introduction.

When we perceive our body in relation to the space surrounding us, we can assume two different perspectives. Imagine to be sitting at the short side of a table, at the center of which there is an apple that you want to grab. You can imagine the action accordingly to your body perspective: you move your arm towards the apple, which is in front of you, you grab it an bring it to your mouth. This first perspective is called body-centered, first-person, or egocentric perspective, and it is dependent on the position of our body and body parts relative to the environment (De Lange et al., 2006; Burgess, 2006). Alternatively, we can assume a third person, allocentric perspective, based on the knowledge of what a movement or posture should look like when watching it from the outside, in other words from an external observer' view (De Lange et al., 2006; Burgess, 2006). In this case, you would observe your sister, sitting next to you at the table, grabbing the apple and eating it. In such case, your brain processes the position of the apple in relation to the other person's body position. Assuming the egocentric rather than the allocentric perspective shapes spatial cognition, actions in space, and social interactions (Vogeley et al., 2004). Moreover, experiencing space as centered upon our own body enhances the perception of ourselves as agents in our environment (Vogeley et al., 2004). Crucially, there is neuropsychological evidence suggesting an altered self-perception in different clinical conditions where the body is involved, such as movement disorders (Fiori et al., 2013,2014; Scarpina et al., 2019a), pain (Schwoebel et al. 2001; Coslett et al. 2010), and congenital absence of body parts (Funk and Brugger, 2008). For other conditions however evidence is still scarce. This is the case of Anorexia nervosa (AN), that impacts severely not only body physical appearance, but also bodily perception (Gadsby, 2017). Its effect on the body is so pervasive that perceptual alterations emerge in the case of real (Keizer et al., 2011; Guardia et al., 2010, 2012; Metral et al., 2014) as well as imagined actions (Guardia et al., 2010, 2012; Metral et al., 2014; Beckmann et al., 2021). When women affected by AN walk through door-like openings, they rotate their shoulders more than their physical dimensions should require. This behaviour suggests that they act as if they have a larger body than the actual physical dimensions, consistently with the overestimation of body dimension judgments (Keizer et al., 2011). Interestingly, this behavior is observed also when affected women imagine themselves walking through the aperture (Guardia et al., 2010, 2012; Metral et al., 2014; Beckmann et al., 2021). Crucially, the misjudgment seems to pertain only to their own body, and not others' body (Guardia et al., 2012). The fact that real and imagined actions are distorted in AN is not surprising if we consider that both actions rely on the same cognitive body representation, influenced not only by peripheral sensations and perceptions, but also memories, feelings, and cognitions about one's own and others' anatomy (Sirigu et al. 1996; Parsons, 1987; Schwoebel et al. 2001; Coslett et al. 2010).

Previous evidence in the field (Guardia et al., 2010, 2012, Keizer et al., 2011; Metral et al., 2014; Beckmann et al., 2021) pertains to body-centered actions (i.e., walking) in relation to an external obstacle (i.e., door-like openings) to be avoided. In such a case, the brain computes online the position and the movement of the body in relation to the object that needs to be avoided (Holmes and Spence, 2004). However, it still needs to be clarified if body action differences emerge also in the absence of any external objects, when an internal body-centered frame of reference is engaged. In this case, the cognitive computations necessary to perform an action are only based on the position and characteristics of our own body, in a more egocentric reference, compared with the allocentric processes that occur when external frames are involved in actions. As such, knowledge about how, and more crucially, in what perspective individuals affected by AN perceived themselves in their own environment has implications not only in terms of theories of the pathology, but can also inform more broadly about relevant issues which individuals might face in other domains of their life, and ultimately help developing more comprehensive therapeutical approaches.

With the aim of testing whether behavioural alterations appear in AN also when actions are processed accordingly to an internal body-centered frame of reference, we used a set of tasks

(Scarpina et al., 2019, 2022; Brusa et al., 2020). This set includes the Hand Laterality Task (Parsons, 1987), in which individuals judge if a visual stimulus represents a left or a right hand (i.e., laterality judgement) independently from its spatial rotation (i.e. the hand is shown without any rotation or rotated 180°) and view (i.e. the palm or the dorsum of the hand is shown), and the Mental Motor Chronometry Task (Schwoebel and Coslett, 2005), in which individuals are asked to imagine performing movements with their limbs. Both tasks are based on *motor imagery*, the active process of internally representing a motor act, without an overt movement (Parsons, 1987; Rumiati et al., 2010), but they differ in terms of level of awareness required to solve the task (Schwoebel and Coslett, 2005; McAvinue and Robertson, 2008): indeed, the Hand Laterality Task individuals adopt a process that is more implicit when compared with the Mental Motor Chronometry Task, as instructions do not directly ask the participant to use motor imagery.

Our hypothesis grounded on the previous evidence relative to the obstacle-avoidance task (Keizer et al., 2011; Guardia et al., 2010, 2012; Metral et al., 2014; Beckmann et al., 2021). Indeed, the work of Keizer and colleagues (2011), in which participants were asked to walk through different apertures while performing an interference task, hence assessing a more *implicit* bodily action, and by others (Guardia et al., 2010, 2012; Metral et al., 2014; Beckmann et al., 2021), in which participants were *explicitly* invited to think of their body dimensions when imaging bodily actions, suggest that the altered behavior in AN globally emerges independently from the level of awareness. As such, we can predict that in both the (more implicit) Hand Laterality Task and the (more explicit) Mental Motor Chronometry Task, we should be able to observe dysfunctions. However, De Lange and colleagues (2008) suggest that increased self-monitoring evoked by explicit motor imagery can have profound consequences in some psychopathological conditions. In AN, higher attentional bias to body shape-related information (Rieger et al., 1998; Shafran et al., 2007; Smeets et al., 2009; Urgesi et al., 2012) as well compulsive monitoring of body appearance (Steinfeld et al., 2017) are described. Thus, it could also be hypothesized that dysfunctions are evident in the case of the more explicit task.

As done previously (Scarpina et al., 2019, 2022; Brusa et al., 2020), we also included two control tasks, in which objects, instead of hands, were used as experimental targets. These control tasks allow to test any confounding effect of mental imagery, the set of cognitive processes consisting in retrieving, constructing and manipulating the mental representation of objects and/or events (Kosslyn et al., 1995). As motor imagery is related to the ability to successfully conduct mental simulations (Pelgrims et al., 2009), if visual imagery is compromised, an alteration in motor imagery not due to motor components but rather to perceptual ones could be expected too.

Methods

Participants. The study was approved by the Ethical Committee of the IRCCS Istituto Auxologico Italiano (Milan, Italy). We performed the experiment in accordance with the Helsinki Declaration. Participants gave informed written consent before taking part in the experiment and were volunteers. They were free to withdraw at any point during the study and were naïve to the rationale of the experiment.

Only right-handed women have been included in the study, as an influence of handedness in motor imagery emerged in other studies (such as, Choisdealbha et al., 2011; Jongsma et al., 2013). Participants were consecutively recruited at admission to the hospital, where they were receiving eating disorder treatment at the time of the experiment. They were included in this study if they satisfied the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2013)'s criteria for Anorexia Nervosa, that are: *i)* restriction of food intake leading to weight loss or a failure to gain weight resulting in a "significantly low body weight" of what would be expected for someone's age, sex, and height; ii) fear of becoming fat or gaining weight; iii) have a distorted view of themselves and of their condition. Both "restricting type" and "binge-eating/purging type" (American Psychiatric Association, 2013) were included in this study We performed a clinical assessment of the eating style through the traditional the Eating Disorder

Inventory™–3 (EDI-3) (Garner, 2004), which focuses on the symptomatology associated with eating disorders, and the Binge Eating Scale (Gormally et al., 1982) to assess the presence of binge eating behavior. We administered The Symptom Checklist-90 (SCL90; Derogatis, 1990), which allows to evaluate the self-reported severity of psychopathological symptoms, and the Italian version (Grossi et al., 2006) of the Psychological General Well Being Index (PGWBI) (Dupuy, 1984), which measures anxiety, depressed mood, positive well-being, self-control, general health and vitality.

In the present study, we included a group of female right-handed participants selected from previously published papers (Scarpina et al., 2019, 2022), as controls. All these participants have a healthy weight and do not report an eating disorder.

Anthropomorphic measures. We measured the body Mass Index (BMI) expressed as body mass (kg)/height(m)^2; weight and height were measured to the nearest 0.1 kg and 0.1 cm, respectively. Moreover, we collected anthropomorphic measures of our participants' hands (which were the target of our experimental tasks) to ensure behavioral differences are not related to this physical factor in AN, the physical dimension of the body can be altered (i.e., Keizer et al., 2011). Hand width was quantified as the distance between the knuckles of the index and little fingers, and hand length as the length (knuckle-to-tip) of the middle finger. The hand shape index (SI), which reflects the overall aspect ratio of the hand, is computed according to the formula: SI=100×(width/length) (Longo and Haggard, 2012). Larger values indicate a wide hand, smaller values a slender hand. All the measurements were performed using a standard caliper, on both hands.

Body Uneasiness Test. Participants with AN and controls were required to fill out the Body Uneasiness Test (Cuzzolaro et al., 2006), which assesses body image characteristics. We measured body image as it represents a crucial feature of the disorder (Carter et al., 2004; Stice and Shaw, 2002; American Psychiatric Association, 2013; Gadsby, 2017) and the negative effects of AN on body image could influence performance in other body related tasks. This self-rating scale explores various areas of body-related psychopathology, that are: dissatisfaction regarding the body and its weight; avoiding and compulsive control behavior; experience of separation and foreignness regarding the body; specific worries for certain body parts, characteristics or functions. BUT scoring consists of the total score of the test (Global Severity Index, BUT GSI), the number of the parts of their body that the individual dislikes (Positive Symptoms Total, BUT PST) and the mean intensity of all disliked body parts (Positive Symptom Distress Index, BUT PSDI); higher scores for both parts indicate greater body uneasiness. This questionnaire has been validated in individuals with a body mass index lower than 25, showing a good internal consistency (Cronbach's alpha coefficients range between 0.69 and 0.90.>0.7) (Cuzzolaro et al., 2006).

Experimental Tasks. In this work, we adopted the same experimental methods described in Scarpina and colleagues (2019, 2022) and Brusa and colleagues (2020). This experiment consists of two main experimental tasks in which the motor imagery process is tested at different levels of awareness and in which body parts are prompted. Specifically, in the Hand Laterality Task, that is the more implicit task, pictures of right and left hands are showed in different orientation (0°, 90°, 180°, and 270°) and view (palm vs dorsum). Participants are required to perform a laterality judgment, or if a right or a left hand is shown, independently from the orientation and view. *Reaction Time* in millisecond and *Accuracy* are collected. The other task is the Mental Motor Chronometry Task, which tests a more explicit imagery process. Participants are required to imagine performing and to perform movements with the right and the left hands. The time in second required by participants to imagine and to perform movements is collected. The experiment consists also of two control tasks. In the Mental Letter Discrimination Task, which refers to the more implicit imagery process, participants judge if a visual stimulus represents an alphabetical letter shown in canonical or in mirror view, independently from the visual orientation (0°, 90°, 180°, and

270°). *Reaction Time* in millisecond and *Accuracy* are collected. In the Mental Bar Movement Task, which refers to more explicit imagery process, participants are required to imagine the movements of bars. The time in second required by participants to imagine the bars movement is collected. Details about these tasks are reported in the Supplementary Materials (S1).

Data Analyses.

Demographic and bodily description. An independent sample t-test was used to check for differences between the two groups in terms of all the demographic features (*Age* and *Years of Education, Body Mass Index, Hand Width; Hand Length, Hand Shape Index*).

Body Uneasiness Test. A non-parametric Mann-Whitney U test was used to compare groups at the Body Uneasiness Test (Cuzzolaro et al., 2006).

Experimental Task. Preliminary we performed a preprocessing of the data (Scarpina et al., 2019, 2022; Brusa et al., 2020). Focusing on the Hand Laterality Task and the Mental Letter Discrimination Task, we removed from the experiment participants who showed a level of accuracy below the threshold of 50% of accuracy for stimuli displayed at 0° (the easiest stimuli, for which one should not expect errors), which might suggest that the participant was randomly guessing his/her responses (Schwoebel et al. 2001; Coslett et al. 2010; Funk and Brugger, 2008; Fiori et al., 2013,2014; Scarpina et al., 2019, 2022; Brusa et al., 2020).

Hand Laterality Task. For Reaction Time, trials in which participants gave a wrong response were discarded from the analyses, and outliers were removed using a cut-off of two standard deviations above and below the individual participant mean (Scarpina et al., 2019, 2022; Brusa et al., 2020). Reaction time and Accuracy were computed for each orientation (0°; 90°; 180°; 270°), for the right and left hand separately, for each participant. We investigated two main experimental effects: the effect of *stimulus orientation* and the effect of *biomechanical constraints* (Parsons, 1987; Fiori et al., 2013; 2014, Scarpina et al., 2019, 2022; Brusa et al., 2020), the latter one being an index of motor imagery, while the first being more related to visual imagery. The effect of stimulus orientation was investigated through a mixed ANOVA, with *Orientation* (0° vs 180°) as within subjects factors and *Group* (participants with AN vs controls) as between subjects factor. A significantly higher level of accuracy and faster reaction time for stimuli at 0° than those at 180° should be expected if the effect is present. The effect of biomechanical constraints was explored through a mixed ANOVA with *Posture* (comfortable vs awkward) as within subjects factors and *Group* (participants with AN vs controls) as between subjects factor. A significantly higher level of accuracy and a faster reaction time for stimuli showing hands in a comfortable position rather than in an awkward position should be expected, if the effect is present. Post hoc comparisons were carried out using estimated marginal means Bonferroni corrected for multiple comparisons, in case of a significant interaction. For both the experimental effects, we also analyzed the speed-accuracy trade-off, computing the inverse efficiency score (IES) (the average of correct RTs divided by the proportion of correct responses, Townsend & Ashby, 1983) When instructions require to be as fast as possible, as in our case, responding can become more error-prone if individuals are biased towards acting fast. IES allow to control for this trade off, and ensure relevant effects found are not explained by it. As such, we submitted IES transformed data to a mixed ANOVA with *Orientation* (0° vs 108°) within-subjects factor and *Group* (participants with AN vs controls) as between-subjects factor. Post hoc comparisons were carried out using estimated marginal means Bonferroni corrected for multiple comparisons, in case of significant interactions. The same analysis was performed introducing *Posture* (comfortable vs awkward) as within-subjects factor for the biomechanical constraints effect.

Mental Motor Chronometry Task. For each group, the relationship between the time required to imagine movements and the time required to execute movements, which is an index of motor imagery, was investigated through Spearman's correlation, run independently for the right hand and the left hand. According to previous evidence (Schwoebel and Coslett, 2005; Scarpina et al., 2019, 2022; Brusa et al., 2020), we should expect this relationship to be significant. In case of statistically significant results in Spearman's correlation, we applied the Fisher's r to z transformation (Fisher, 1915; 1921), performed on the following website: http://vassarstats.net/rdiff.html to compare the two groups, as done in Scarpina and colleagues (2019, 2022) and Brusa and colleagues (2020). Outliers (if present) were not removed, as done in previous studies (Sirigu et al., 1996; Zapparoli et al., 2013; Williams et al., 2015; Scarpina et al., 2019, 2022; Brusa et al., 2020). This approach is consistent with the idea that one participant might require more time to perform and imagine performing movements, in other words different participants will have different baselines. Differences at baseline however do not hinder the expected correlation between the two (imagined versus performed movements) components. Taking into account though that this approach might alter the chances to obtain a normal distribution of data, we performed non-parametric analysis, which is described as robust against statistical effects when outliers are not removed (Croux and Dehon, 2010).

Mental Letter Discrimination Task. As done in the Hand Laterality Task, trials in which participants gave the wrong response were discarded from the analyses, and outliers were removed using a cut-off of two standard deviations above and below the individual participant mean.. Reaction Time and Accuracy were computed for each orientation (0°; 90°; 180°; 270°) in mirror and canonical positions. We performed a mixed ANOVA with *Orientation* (0° vs 180°) and *Type* (canonical vs mirror) as within subjects factors and *Group* (participants with AN vs controls) as between subjects factor. Post hoc comparisons were carried out using estimated marginal means Bonferroni corrected for multiple comparisons, in case of significant interactions. Since previous evidence (Fiori et al., 2013; 2014; Scarpina et al., 2019, 2022; Brusa et al., 2020), a higher level of accuracy and faster Reaction Time for stimuli at 0° in comparison to those at 180° can be expected, as well as for stimuli in canonical format than in mirror format. For this task too, we explored speed-accuracy trade-off, computing the IES. We performed a mixed ANOVA with *Orientation* (0°

vs 180°) and *Type* (canonical vs mirror) as within-subjects factors and *Group* (participants with AN vs controls) as between-subjects factor. Post hoc comparisons were carried out using estimated marginal means Bonferroni corrected for multiple comparisons, in case of significant interactions.

Mental Bars Movement Task. For each group, the relationship between the time required to answer with the right hand with the left hand was analyzed using Spearman's correlation. According to previous evidence (Scarpina et al., 2019, 2022; Brusa et al., 2020), we should expect this relationship to be significant. Fisher's transformation (Fisher, 1915; 1921) was used to directly compare groups' performance.

Sample size calculation. We used G*Power3 (Faul et al., 2007) to verify *a priori* the sample size for our study. For the Hand Laterality task, a total sample of 36 participants with two equal sized groups of n = 18 was necessary to achieve a power of 0.95, considering the use of a two-tailed test, a medium effect size (d= 0.65), and an alpha of 0.05. For the Mental Motor Chronometry Task, a sample size of 14 participants was required to achieve a power of 0.95, considering the use of a one-tailed test, a medium effect size (d = 0.77), and an alpha of 0.05. Thus, we recruited 18 participants for each group, overall 36 participants.

Results.

Participants. Eighteen women affected by AN were enrolled (Age in years M=25.77; SD=6.74; range=18-38; Education in years M=13.5; SD=2.95; range=8-18; BMI M=15.06; SD=3.28; range=10.49-25.27). According to the diagnostic criteria (American Psychiatric Association, 2013), one patient suffered from binge-eating/purging type AN, while the overall group of restricting type AN. In the Supplementary Materials, we report the results relative to the psychological assessment of our participants (Table S1).

We included a group of eighteen females as controls (Age in years M=43.11; SD=6.83; range=32.56; Education in years M=13.88; SD=4.49; range=8-22; BMI M=21.77; SD=1.84; range=18.68–25.39).

After pre-processing, in the control group, no participant was excluded because a low level of accuracy (threshold fixed at 50%) in the Hand Laterality Task and in the Mental Letter Discrimination Task. We excluded data relative to seven participants affected by AN. In detail, one participant had a level of accuracy below the threshold of 50% accuracy for stimuli displayed at 0° in the Hand Laterality Task, four participants in the Mental Letter Discrimination Task, and two participants in both tasks. As such, after preprocessing, the experimental group consisted of eleven participants[1] (Age in years M=26.75; SD=6.94; range=18-38; Education in years M=13.75; SD=3.46; range=8-18; BMI M=15.58; SD=3.59; range=11.66-25.27). Overall, the two groups were comparable in terms of Age, Education, and body mass index. Also, included and excluded participants with AN reported the same scores at the questionnaires investigating eating habits. Concerning the SCL-90, the only difference emerged in relation to the hostility score: patients included in the analyses reported a significantly higher score in comparison to excluded patients [U(18)=14.5; p=0.04]. No difference emerged in the components of the psychological well-being measured through the PGWBI. Finally, no difference emerged in the score relative to the Body Uneasiness Test. Our analysis suggests that the seven participants affected by AN performance that warranted exclusion was not due to psychopathological differences or body image characteristics.

As shown in Table 1, the included participants affected by AN and the controls had the same level of education, although participants with AN were significantly younger than controls. Changes in motor imagery abilities are known to occur in the life-span: elderly individuals have decreased or qualitatively different performance in motor imagery tasks when compared with youngers

[1] In the Supplementary Materials (Table S2), we explore if any difference in terms of demographic or bodily characteristics, as well as in terms of psychological functioning and eating habits, could explain their difference performance at the task between the included and excluded participants with AN.

(Zapparoli et al., 2013). However, it should be noticed that none of our controls was aged over 65 years, which is usually the threshold to see changes (World Health Organization, 2016). Nevertheless, in the Supplementary Materials (S4), explore the effect of age as covariate, to ensure significant effects are not due to this difference. As expected, participants with AN showed a significantly lower body mass index, as well as larger hand width and a shorter hand length, affecting the hand shape index, in comparison to controls.

[Table 1 around here]

Body Uneasiness Test. Scores at the questionnaire are reported in Table 1. Participants with AN show higher scores in comparison to the controls in all the scales, suggesting a significant higher level of body uneasiness.

Hand Laterality Task. For Reaction Time, we excluded 5.11% of data of participants with AN and 4.86% of data relative to the controls, as they were outside the two standard deviation range. Means, and standard deviations are reported in the lower part of Table 2.

[Table 2 around here]

Effect of orientation. For accuracy, a significant main effect of *Orientation* emerged [$F(1,27)=161.66$; $p<0.001$; $\eta^2_p=0.85$]: accuracy was higher for stimuli at 0° (M=90.68; SD=4.19) than at 180° (M=72.19; SD=8.54), as expected. However, we also observed a significant main effect of *Group* [$F(1,27)=10.97$; $p=0.003$; $\eta^2_p=0.28$], with participants with AN (M=85.22; SD=11.9) showing a higher level of accuracy than controls (M=79.12; SD=10.69). This result seems to suggest that participants with AN perform better than controls. Finally, the interaction *Orientation*Group* [$F(1,27)=1.05$; $p=0.31$; $\eta^2_p=0.03$] was not significant. As reported in Supplementary Materials (S4) the main results were not related to the age.

[Table 2 around here]

A significant main effect of *Orientation* emerged also for RT [$F(1,26)=79.1$; $p<0.001$; $\eta^2_p=0.75$] with reaction time faster for stimuli at 0° (M=2262; SD=400) than at 180° (M=3882; SD=1139), as expected. No significant main effect of *Group* emerged (participants with AN M=2981; SD=1702; controls M=3102; SD=730) [$F(1,26)=0.01$; $p=0.89$; $\eta^2_p=0.001$]. The interaction *Orientation*Group* was not significant [$F(1,26)=1.5$ $p=0.23$; $\eta^2_p=0.05$].

When we explored speed-accuracy trade-off through the inverse efficiency score (IES), we confirmed the main effect of *Orientation* [$F(1,26)=104.96$; $p<0.001$; $\eta^2_p=0.8$]: the IES relative to the stimuli oriented at 0° (M=24.81; SD=0.76) was lower than the 180° (M=53.32; SD=3.18). No main effect of *Group* (participants with AN M=37.06; SD=2.97; controls M=41.07; SD=2.21; $F(1,26)=1.17$; $p=0.28$; $\eta^2_p=0.04$] or significant interaction *Posture*Group* [$F(1,26)=0.002$; $p=0.95$; $\eta^2_p<0.001$] emerged.

Effect of biomechanical constraints. We found a significant main effect of *Posture* for accuracy [$F(1,27)=4.89$; $p=0.036$; $\eta^2_p=0.15$]: accuracy was significantly higher for stimuli showing hands in a comfortable position (M=86.83; SD=99) than awkward position (M=81.56; SD=7.57), as expected. The main effect of *Group* (participants with AN M=82.53; SD=6.09; controls M=86.93; SD=11.37) was not significant [$F(1,27)=3.52$; $p=0.07$; $\eta^2_p=0.11$]. Crucially, the interaction *Group*Posture* [$F(1,27)=5.82$; $p=0.02$; $\eta^2_p=0.17$] was significant. As it can be observed inspecting the data in Table 2, although controls showed significantly higher accuracy for stimuli of hands in a comfortable position (M=86.89; SD=3.07) than awkward position (M=78.18; SD=5.17) [$p=0.001$], such a difference did not emerge for participants with AN, who showed the same level of accuracy for visual stimuli of hands in comfortable (M=86.74; SD=14.53) and awkward positions (M=87.12

SD=7.78) [p=0.89] (Figure 1). When the other comparisons were analyzed, it clarified that participants affected by AN showed a significantly higher level of accuracy for stimuli showing hands in an awkward position [p=0.001] in comparison to controls, although for visual stimuli of hands presented in comfortable positions, the level of accuracy was comparable between the two groups [p=0.96]. As reported in Supplementary Materials (S4) the main results were not related to the age.

Overall, no biomechanical constraints effect was observed in our participants with AN, when compared to controls. This result might suggest that they did not apply an imagery strategy grounded on sensorimotor bodily representation to solve the task (i.e., Sirigu et al. 1996; Parsons, 1987; Schwoebel et al. 2001; Coslett et al. 2010); in other word, they seemed to process body related stimuli (i.e., hands) as visual objects.

[Figure 1 around here]

For RT, we confirmed the main effect of *Posture* [$F(1,27)=12.75$; $p=0.001$; $\eta^2_p=0.32$], with comfortable postures (M=2547; SD=650) faster to process than the awkward ones (M=2734; SD=675). No main effect of *Group* (participants with AN M=2459; SD=1054; controls M=2751; SD=130) [$F(1,27)=1.41$; $p=0.24$; $\eta^2_p=0.05$] or significant interaction *Posture*Group* [$F(1,27)=0.87$; $p=0.35$; $\eta^2_p=0.03$] (Table 2) emerged.

The analysis of the inverse efficiency score (IES) confirmed the main effect of *Posture* [$F(1,27)=7.29$; $p=0.012$; $\eta^2_p=0.21$]: IES relative to comfortable postures (M=29.76; SD=1.89) is lower than that for awkward ones (M=33.14; SD=1.71). No main effect of *Group* (participants with AN M=29.36; SD=2.64; controls M=33.55; SD=2.06) [$F(1,27)=1.56$; $p=0.22$; $\eta^2_p=0.05$] or significant interaction *Posture*Group* [$F(1,27)=2.51$; $p=0.12$; $\eta^2_p=0.08$] emerged. Overall, this suggests that the absence of biomechanical constraints in participants with AN in our study is a result of trade-off phenomenon.

Mental Motor Chronometry Task. When we focused on controls' performance, a significant positive relationship emerged for the left hand [$\rho(18)=0.81$; $p<0.001$]. Such a relationship emerged as a trend for the right hand [$\rho(18)=0.44$; $p=0.06$]. To better understand this finding, which we expected to be significant, we computed the Bayes factor using the software JASP (Jasp Team, 2019) to classify the strength of evidence (Jeffreys, 1939; Kass & Raftery, 1995; Dienes, 2014). This computation was performed to test whether the non-significant result supports a null hypothesis over a theory, or whether the data are just insensitive (Dienes, 2014), The Bayes factor computed confirmed moderate evidence in favor of the relationship between imagining and performing movements for the right hand ($BF_{10}=4.07$) (Lee & Wagenmakers, 2014), reassuring us that the result is not against our reference theory. Focusing on the performance of participants affected by AN, we observed a significant positive relationship for the right hand [$\rho(11)=0.74$; $p=0.008$]. Such a significant relationship did not emerge for the left hand [$\rho(11)=0.08$; $p=0.81$]; however, we computed a BF_{10} of only 1.33, suggesting weak evidence in favor of a relationship between imagining and performing movements for the left hand.

Crucially, according to Fisher's analyses, there was no significant difference between the two groups for the right hand [$z=-1.09$; $p=0.27$]; differently, a significant difference emerged for the left hand [$z=-2.39$; $p=0.01$]: controls showed greater variance in the performance relative to the left hand (that is the not dominant hand for all participants) in comparison with participants affected by AN (Figure 2).

[Figure 2 around here]

Mental Letter Discrimination Task. We excluded 6.81% of data in the group of participants with AN and 3.81% of data in controls, as these data points were out of the two standard deviation range. Means, and standard deviations are reported in Table 3.

[Table 3 around here]

Considering accuracy, a significant main effect of *Orientation* emerged [$F(1,27)=36.55$; $p<0.001$; $\eta^2p=0.57$]; higher level of accuracy emerged for visual stimuli at 0° (M=95.05; SD=4.52) than stimuli at 180° (M =74.56; SD=19.63), as expected. No main effect of *Type* emerged (canonical M=84.02; SD=19.4; mirror M=85.58; SD=15.55) [$F(1,27)=1.8$; $p=0.19$; $\eta^2p=0.06$] nor a significant interaction *Orientation*Type* [$F(1,27)=1.33$; $p=0.25$; $\eta^2p=0.04$]. The main effect of *Group* (participants with AN M=84.46; SD=24.35; controls: M=85.01; SD=11.75) was not significant [$F(1,46)=2.47$; $p=0.12$; $\eta^2p=0.05$]; however, the interaction *Group*Type* was significant [$F(1,27)=6.5$; $p=0.01$; $\eta^2p=0.19$]. In participants with AN, we found a significant lower level of accuracy for letters showed in canonical (M=80.3; SD=28.11) than in the mirror (M =88.63; SD =19.67) view [$p=0.02$], in the opposite direction than the expected one (i.e., higher level of accuracy for canonical than mirror position). However, such a difference was not significant in controls' performance (canonical M=86.3; SD=11.16; mirror M=83.72; SD=12.33) [$p=0.33$] (Figure 3 upper part). When we focused on the other comparisons, no significant difference emerged between groups in the level of accuracy relative to canonical [$p=0.14$] and mirror [$p=0.17$] letters. Finally, the interactions *Group*Orientation* [$F(1,27)=0.03$; $p=0.85$; $\eta^2_p=0.001$] and *Group*Orientation*Type* [$F(1,27)=3.62$; $p=0.06$; $\eta^2_p=0.11$] were not significant.

[Figure 3 around here]

Considering RT, a significant main effect of *Orientation* emerged [$F(1,24)=327.4$; $p<0.001$; $\eta^2_p=0.93$]; faster response was observed for visual stimuli at 0° (M=1492; SD=338) than stimuli at 180° (M=2816; SD=664), as expected. Also, a significant main effect of *Type* emerged [$F(1,24)=105.49$; $p<0.001$; $\eta^2_p=0.81$], with faster reaction time for canonical letters (M=1972; SD=779) than mirror letters (M=2312; SD =880), in line with the expected effect. The interaction *Orientation*Type* was not significant [$F(1,24)=1.91$; $p=0.17$; $\eta^2_p=0.07$]. We found that participants with AN (M=1763; SD=805) were significantly faster than controls (M=2352; SD=796) [main effect of *Group*, $F(1,24)=32.47$; $p<0.001$; $\eta^2_p=0.57$]. We observed a significant *Group*Type* interaction [$F(1,24)=42.78$; $p<0.001$; $\eta^2_p=0.64$]. As shown in Figure 3 - bottom panel, although controls showed significant faster RT for letters showed in canonical view (M=2078; SD=726) than letters showed in mirror view (M=2627; SD=777) [$p<0.001$], in line with the expected effect, participants with AN showed the opposite pattern: significantly faster RT for letters in mirror view (M=1744; SD=777) than in canonical view (M=1782; SD=853) [$p=0.03$]. Moreover, participants with AN were significantly faster for canonical [$p=0.003$] and mirror view [$p<0.001$] than controls. Moreover, the interaction *Group*Orientation* [$F(1,24)=7.95$; $p=0.009$; $\eta^2_p=0.24$] was significant. We observed that participants with AN had faster RT for visual stimuli at 0° (M =1279; SD =357) than controls (M =1615; SD =259) [$p<0.001$]; moreover, participants with AN had faster RT for visual stimuli at 180° (M=2298; SD=830) than controls (M=3089; SD =320) [$p<0.001$]. Nevertheless, the performance of both groups was in line with the expected effect: faster reaction time for visual stimuli at 0° than 180° [both comparisons significant at $p<0.001$] (Figure 4). Finally, the interaction *Group*Orientation*Type* [$F(1,24)<0.001$; $p=0.97$; $\eta^2_p<0.0001$] was not significant. Thus, according to our results, participants with AN were slower and less accurate in recognizing letters in canonical view than those in mirror view: this behavior was in opposite direction respect to the experimental effect traditionally registered in this task (Scarpina et al., 2019, 2022; Brusa et al., 2020), according to which an advantage emerges for letters showed in the canonical view because of the application of a mental rotation strategy (i.e., Shepard and Metzler, 1971; Tarr and Pinker, 1989).

[Figure 4 around here]

When we considered the IES score, we confirmed the significant main effect of *Orientation* [F(1,24)=211.01; p<0.001; η^2_p=0.89]: the IES was significantly higher in the case of stimuli at 0° (M=15.7; SD =3.48) than 180° (M=39.15; SD=15.53). Interestingly, a significant main effect of *Group* emerged [F(1,24)= 19.58; p<0.001; η^2_p=0.44]: the IES was significantly lower for participants with AN (M=23.28; SD=19.82) for controls (M=29.4; SD=13.43). The interaction *Group*Orientation* was significant [F(1,24)=7.94; p=0.009; η^2_p=0.24]: participants with AN showed a significant lower IES for stimuli at 0° (M=13.57; SD=3.45) than stimuli at 180° (M=34.02; SD=24.62) [p<0.001], as well as controls a significant lower IES for stimuli at 0° (M=16.94; SD=2.86) than stimuli at 180° (M=41.87; SD=5.78) [p<0.001] (Figure 5, upper part). Moreover, we observed that for both stimuli at 0° [p<0.001] and 180° [p=0.01], participants with AN reported significant lower IES than controls. Thus, in participants with AN we observed a different performance in the visual imagery effect. Also, a significant main effect of *Type* emerged [F(1,24)=39.91; p<0.001; η^2_p=0.62]; the IES was lower for stimuli in canonical view (M=23.94; SD=11.64) than in mirror view (M=30.49; SD=19.28). Moreover, a significant interaction *Group*Type* emerged [F(1,24)=27.34; p<0.001; η^2_p=0.53]: crucially, a significant main difference emerged for controls between canonical (M=25.47; SD=11.65) and mirror (M=33.33; SD=14.08) [p<0.001], although such a difference did not emerged for participants with AN (canonical M=21.19; SD=11.39; mirror M=25.38; SD=25.83) [p=0.54] (Figure 5, below part). The scores for the participants with AN were significantly lower than controls for both canonical [p=0.016] and mirror [p<0.001] letters. Finally, the interaction *Orientation*Type* [F(1,24)=3.38; p=0.07;

η^2p=0.12] and the interaction *Group*Orientation*Type* [F(1,24)=2.16; p=0.15; η^2_p=0.08] were not significant. The IES analysis confirms the results from the main analyses on Reaction Time and Accuracy. Thus, overall, the performance of participants affected by AN is different from that of controls, for both the effect of orientation and type.

[Figure 5 around here]

Mental Bars Movement Task. Both participants affected by AN [ρ(18)=0.81; p=0.002] and controls [ρ(18)=0.93; p<0.001] showed a significant positive relationship between the time required to answer with the right hand and with the left hand, as shown in Figure 6. The performance was not significantly different between groups, according to Fisher's analysis [z=1.21; p =0.22].

[Figure 6 around here]

Discussion.

Previous studies in the literature on AN (Guardia et al., 2010, 2012; Keizer et al., 2011; Metral et al., 2014; Beckmann et al., 2021) mostly explored obstacle-avoidance actions, in which body movements are assessed during interactions with objects in the environment. The aim of our work was to document, for the first time, motor imagery in AN when actions with an internal body-centered frame are tested. Furthermore, we explored participants' behavior in two tasks (Scarpina et al., 2019, 2022; Brusa et al., 2020) which required different levels of awareness: the Hand Laterality Task (i.e., the more implicit one), in which participants performed laterality judgments, and the Mental Motor Chronometry Task (i.e., the more explicit one), in which participants imagined performing and performed movements with hands.

In the Hand Laterality Task, we observed an unexpected result for biomechanical constraints. While controls showed a behavior (i.e., a higher level of accuracy in the case of visual stimuli showing hands in a comfortable position than in an awkward position) in agreement with the previous evidence in the literature (Parsons, 1987; Fiori et al., 2013; 2014, Scarpina et al., 2019, 2022; Brusa et al., 2020), our participants with AN counterintuitively performed better than controls: they judged the laterality of hands in comfortable and awkward positions with the same, very high, level of accuracy. Our hypothesis, based on evidence from studies on external frames of reference (Guardia et al., 2010, 2012; Keizer et al., 2011; Metral et al., 2014; Beckmann et al., 2021), was to either find an altered behaviour in AN also when actions are processed accordingly to an internal body-centered frame of reference, or to find no differences when compared to controls, but - as said - we did not expect to find a more accurate performance in individuals affected by AN. Numerous previous evidence from healthy (i.e., Parsons, 1987; Brusa et al., 2020) as well as individuals with a clinical condition affecting motor planning or execution (Schwoebel et al., 2001; Coslett et al., 2010; Fiori et al., 2013, 2014; Scarpina et al., 2019, 2022) are in agreement in suggesting that participants find simpler to judge the laterality of hands showed in those anatomical positions that are easier and more comfortable to be reached, following the natural bodily biomechanical constraints. In our work, we did not observe this advantage for easier anatomical positions in the performance of our participants with AN; instead, they showed a higher level of accuracy also for awkward positions. Intriguingly, this result could imply that our participants did not solve the task via a motor imagery process grounded on sensorimotor egocentric representations; rather, they might have used a more visuospatial based mental rotation strategy to solve the task (Shepard and Metzler, 1971; Tarr and Pinker, 1989; Parsons, 1994; Sekiyama, 1982; Conson et al. 2010; Fiori et al., 2013), meaning that they processed body stimuli as if they were objects. The fact that individuals with AN used a visuospatial mental rotation strategy rather than a motor one suggests that they solved the task not using a first-person perspective. As explained in our Introduction, a body-centered representation according to a first-person perspective (Gallese 2003; Lorey et al., 2009; Olsson & Nyberg, 2010; Hanakawa, 2016) means that space and objects are represented in relation to ourselves and our physical configuration (Vogeley and Fink, 2003).

However, in an allocentric representation as in in the visuospatial mental rotation strategy, the object-representation and the object-to-object relations would be conceived as independent from the agent/viewer's position (Vogeley and Fink, 2003). This unexpected tendency to use an allocentric reference in the case of body stimuli seems to be supported also by the results of the Mental Letter Discrimination Task. Here, we observed that our controls show the expected advantage in recognizing objects shown in their canonical rather than in the mirror representation. This advantage for objects showed in canonical orientations – when present - suggests that the objects rotation is performed adopting a first-person perspective (Ruby & Decety, 2001; Sirigu & Duhamel, 2001). Instead, our participants with AN showed a similar performance in those two conditions, that was overall better than controls. As such, we could argue that they did not adopt a first-person perspective also in the case of the Mental Letter Discrimination Task, mirroring the evidence from the Hand Laterality Task. Our results relative to objects rotation are in agreement with the neuropsychological evidence provided by Lander and colleagues (2019) on impaired visual egocentric representations and intact allocentric visual functions in women with AN when objects (and not body parts, as in our paper) are processed. It should be noted that the authors tested the level of accuracy but velocity of response was not recorded, and that they used two pen-and-pencil tests, the object perspective taking test, for the egocentric representation, and the mental rotation test, relative to the allocentric one. Given we did use different tasks and also considered reaction times, our study nicely complements the available knowledge suggesting a quite robust pattern.

That said, our results from the Hand Laterality Task pose a crucial question: why would individuals affected by AN be more prone to use a visual imagery strategy (rather than a motor imagery one) when processing body parts, which instead are processed as objects? We may offer some possible explanations. Individuals affected by AN generally show a higher attentional bias to body shape-related information (Rieger et al., 1998; Shafran et al., 2007; Smeets et al., 2009). Urgesi and colleagues (2012) suggest that patients with AN are more accurate in detail-based processing of the human body, since their tendency to routinely explore body parts as a consequence of their obsessive worries about body appearance. Checking behavior represents a core feature of various mental disorders, included eating disorders (i.e., Mountford et al., 2007; Bamford et al., 2014; Calugi et al., 2017). The repeated and ritualistic monitoring of several aspects of the body represents a behavioral manifestation of a disturbed body image, fostering the development and maintenance of the eating disorder in AN (Rosen, 1996). Thus, the attentional bias toward body-related cues in AN is enhanced, perhaps improving its processing, as reflected by the higher level of accuracy showed by our participants when compared to controls. This hypothesis, according to which checking behaviors might prompt and enhance a visual strategy in which the body is treated like an object, might have crucial clinical implications not only in AN, but also in other clinical conditions characterized by enhanced and pathological attention towards the body and bodily sensations, such as body dysmorphic disorder, healthy anxiety disorders, or obsessive-compulsive disorders. An alternative explanation is grounded on a specific type of behaviour generally found in AN, changing the processing of body stimuli. Individuals affected by AN usually manifest the checking of one's own body through different behaviors, one of the most common between individuals with this condition being repeatedly looking at one's own body in the mirror (Hartmann et al., 2019). Crucially, when we observe ourselves in a mirror, we observed a specular image; in other words, an external reflection of ourselves. Because of the higher tendency to mirror self-reflection, participants with AN might have internalized their own body considering this mirror perspective, rather than a self-perspective, possibly affecting the way they represent their own body (in a third/allocentric perspective rather than in a first/egocentric one). This peculiar hypothesis about the effect of prolonged experience of mirror-reflection on own body action representation sounds promising as it links a behavior that is highly descriptive of a negative body image in AN (i.e., looking into a mirror) with a cognitive processing (i.e., visual and motor imagery). Finally, another alternative explanation should be mentioned: our participant with AN might be unable to adopt a first-person perspective during the processing of body-parts stimuli because of altered sensory processing. Self-perception, which is a key subjective state not only for self-location (i.e., “Where am I in space?”), but also for the first-person perspective (“From where do I perceive the world?”) (Blanke and Metzinger, 2009), is a complex cognitive process, grounded on interoceptive, proprioceptive, and motor signals, and their multisensory integration (Frith, 2005, Gallagher, 2000, Jeannerod, 2003; Petkova et al., 2011). Some neuropsychological evidence suggests that in the case of altered multisensory integration process, especially in the case of somatosensory (proprioceptive and tactile), visual, and visuo-vestibular input (Blanke et al., 2004, Lopez et al., 2008), difficulties in processing the space according to a first-person perspective are enhanced (Blanke et al., 2002, De Ridder et al., 2007). Crucially, altered processing of low-level proprioceptive and tactile information (i.e., Keizer et al., 2011; 2012; Spitoni et al., 2015; Crucianelli et al., 2016). and integration of multisensory body signals were described previously in AN (i.e. Gaudio et al., 2014; Zopf et al., 2016; Gledill et al., 2019; Provenzano et al., 2020; for a theoretical view refer to Riva et al., 2018), which may impact on the ability to assume a first-person perspective during spatial processing.

Overall, and independently from what the possible explanation is (i.e., a higher attentional bias to body shape-related information, higher tendency to self-reflection in the mirror, or altered multisensory bodily processing), our results are in agreement with the Allocentric Lock Hypothesis (Riva, 2012; 2014; 2018): individuals with AN tend to experience and remember their own body in an allocentric (i.e., an observer) view, because of their negative body image. According to Riva and colleagues (2015), the use of a third-person perspective is the neuropsychological equivalent of self-objectification, in other words, the internalization of an observer's perspective on oneself (Legrand, 2010). Following this hypothesis, one might predict that a similar performance would emerge in those clinical conditions in which body or body parts are experienced as an object (i.e., as something that does not belong to own body) such as in the case of body dysmorphic disorders, bodily delusions or disorder of bodily self-awareness.

The hypotheses we present might work to explain the results from the more implicit task. However, the picture depicted by the more explicit task, the Mental Motor Chronometry Task, is different.

Our participants with AN's performance were similar to controls for the right hand, but not for the left hand. Differently from what reported in the Hand Laterality Task and the Mental Letter Discrimination Task, no differences emerged between groups in the control task (i.e., the Mental Bars Movement Task) testing visual imagery process. Thus, an imagery dysfunction emerged in AN only when such process pertains bodily actions, and not object movements. Peculiarly, as previously stated, this alteration emerged specifically for the left hand, that is the non-dominant hand in our participants since only right handers were enrolled in this study. The effect of handedness in motor imagery has been previously explored (such as Choisdealbha et al., 2011; Jongsma et al., 2013). However, very few and not conclusive evidence is available on the relationship between handedness and body representation in AN. Christman and collegaues (2007) observed that a strong right-handedness was associated with a larger discrepancy between actual and perceived body mass index, in individuals with an increased eating disorder symptomatology. Nico and colleagues (2010) reported that women with AN are less accurate in estimating the width of their left upper body, which seems in agreement with our results. Summarizing the result from this task, in our participants alterations of motor imagery process might emerge in relation to the asymmetric motor skills. Moving with the not-dominant (in this case, left) body side is generally more difficult for right-handers, requiring to allocate more attentional resources. Moreover, in explicit motor imagery tasks, altered top-down cognitions about one's own body and its appearance might emerge abruptly since the increased self-monitoring during the task execution (De Lange et al., 2008), as in the case of AN. Indeed, as stated by Williams and colleagues (2009), "*motor imagery involves generating an action plan consistent with the kinematics of actions as we tend to perform them with our particular bodies*".

Overall, our results favor the hypothesis of altered motor imagery processes in AN, independently from the level of awareness required, since alterations emerged in the more explicit (i.e., Mental Motor Chronometry Task) and the more implicit (i.e., Hand Laterality Task) tasks. Moreover, in AN there might be a tendency to consider the body as an object, adopting more promptly a visual imagery strategy (which focused a third-person perspective) rather than a motor strategy task (in which the first-person perspective is enhanced). This result is relevant clinically because the use of third-person perspective may be considered the neuropsychological equivalent of self-objectification (Riva et al., 2015), which is a bodily experience directly linked with psychological well-being and health (Riva et al., 2015). Two longitudinal studies (Dakanalis et al., 2016, 2017) describe how self-objectification is the most crucial factor in predicting the onset and maintenance of eating disorders. Because of this evidence, self-objectification should be targeting in rehabilitative approaches in AN. For example, body therapies, such as dance/movement therapy, might be very useful in increasing bodily perception and actions considering not only the physical movements, but also the emotional, interpersonal, and cognitive components emerging during actions. Nevertheless, in psychological counseling, patients should be assisted in considering the body they see reflected in the mirror as *their own bod*y and not as an object, restoring the experience of the self-mirror reflections. Moreover, some preliminary - even though not conclusive - evidence derives from the application of technologies such as virtual reality in helping patients in improving their experience in term of body representation (Serino et al., 2017; 2019; Porras-Garcia et al., 2020); however, the time extension of after-effect of such bodily experiences needs to still be verified.

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Table 1. Demographical information, body characteristics as measured in this study, and score at the Body Uneasiness Test. In bold, significant difference (p value < 0.05).

	Participants affected by Anorexia Nervosa N = 11	**Controls** N = 18	**Statistical comparison**
Age in years	M = 26.75 SD = 6.94 range = 18-38	M = 43.11 SD = 6.83 range = 32-56	t(27)=6.42; **p<0.001**; d'=2.82
Education in years	M = 13.75 SD = 3.46 range = 8-18	M = 13.88 SD = 4.49 range = 8-22	t(27)=0.24; p=0.8; d'=0.03
Body Mass Index	M = 15.58 SD = 3.59 range = 11.66 – 25.27	M = 21.77 SD =1.84 range = 18.68 – 25.39	t(27)=5.45; **p<0.001**; d'=2.35
Hands width in cm	M =8.03 SD = 0.98 range = 7.1-9.5	M = 6.71 SD = 0.81 range = 5.85 – 8.18	t(27)=5.06; **p<0.001**; d'=1.5
Hands length in cm	M = 8.73 SD = 1.26 range = 6.9-10.9	M = 9.28 SD = 0.5 range = 8.45-10.33	F=16.16, p<0.001 t(13.02)=3.67; **p= 0.003**; d'=0.63
Hand Shape Index	M = 111.53 SD = 26.16 range = 73.15-142.48	M = 72.53 SD = 9.75 range= 61.56-88.10	F=36.48; p< 0.001: t(11.81)=4.51; **p=0.001**; d'=2.2

Body Uneasiness Test			
Global Severity Index	M = 3.4 SD = 0.67 range = 2.35-4.44	M = 0.8 SD = 0.39 range = 0.2-1.6	U(29)=198; **p<0.001**; d'=5.07
Weight phobia	M= 3.94 SD = 0.74 range = 2-4.88	M = 1.48 SD = 0.71 range = 0.3-3.1	U(29)=194; **p<0.001**; d'=3.41
Body image concerns	M = 3.71 SD = 0.77 range = 2.22-4.67	M = 0.83 SD = 0.53 range =0.2-1.9	U(29)=198; **p<0.001**; d'=4.57
Avoidance	M = 2.79 SD = 0.88 range = 1.33-4.67	M = 0.31 SD = 0.39 range = 0-1.5	U(29)=197; **p<0.001**; d'=4
Compulsive self-monitoring	M =3.06 SD = 1.05 range = 1.5-4.5	M = 0.88 SD = 0.63 range = 0.2-2.5	U(29)=190.5; **p<0.001**; d'=2.68
Depersonalization	M = 3.13 SD = 1.15 range = 1.8-5	M = 0.15 SD = 0.16 range = 0-0.4	U(29)=198; **p<0.001**; d'=4.19
Positive Symptom Total	M = 25.58 SD = 7.47 range = 11-35	M =11.33 SD = 5.6 range = 4-23	U(29)185.5; **p<0.001**; d'=2.2
Positive Symptom Distress Index	M = 3.23 SD = 0.96 range = 1.62-5.43	M = 1.8 SD = 0.44 range = 1.2-2.8	U(29)=183; **p<0.001**; d=2.1

M = mean; SD = standard deviation

Table 2. Mean (M) and standard deviation (SD) for the percentage (%) of accuracy and the reaction time in millisecond (ms) for the two groups (controls N = 18 vs group of participants affected by AN N = 11) are reported for the two main experimental effects (i.e., effect of orientation and effect of biomechanical constraints) relative to the Hand Laterality Task.

		Effect of orientation				**Effect of biomechanical constraints**			
		Accuracy in %		Reaction Time in ms		Accuracy in %		Reaction Time in ms	
		0	180	0	180	Comfortable	Ackward	Comfortable	Ackward
Controls	M	88.93	69.33	2390	3814	86.89	78.18	2678	2826
	SD	*2.30*	*5.20*	*83*	*149*	*3.07*	*5.17*	*63*	*139*
Participants with AN	M	93.56	76.89	2052	4004	86.74	87.12	2334	2585
	SD	*5.06*	*10.92*	*599*	*1956*	*14.53*	*7.78*	*1048*	*1097*

Table 3. Mean (M) and standard deviation (SD) for the percentage (%) of accuracy and the reaction time in millisecond (ms) for the two groups (controls N = 18 vs group of participants affected by AN N = 11) are reported relative to the Mental Letter Discrimination Task.

		Accuracy in percentage				**Reaction Time in millisecond**			
		0°		180°		0°		180°	
		canonical	mirror	canonical	mirror	canonical	mirror	canonical	mirror
Controls	M	96.05	94.96	76.57	72.50	1364	1867	2792	3386
	SD	*1.34*	*2.15*	*7.33*	*6.46*	*36*	*61*	*71*	*138*
Participants with AN	M	93.18	95.45	67.42	81.82	1261	1300	2419	2189
	SD	*8.18*	*5.73*	*35.05*	*26.04*	*457*	*228*	*800*	*885*

Figure 1. Mean (bar) and standard error (vertical line) for accuracy expressed in percentage (y-axis) in the Hand Laterality Task are shown for hands in a comfortable position versus hands in an awkward position (i.e. the effect of biomechanical constraints) for the two groups (left side: controls; right side: participants with AN). * p value < 0.001.

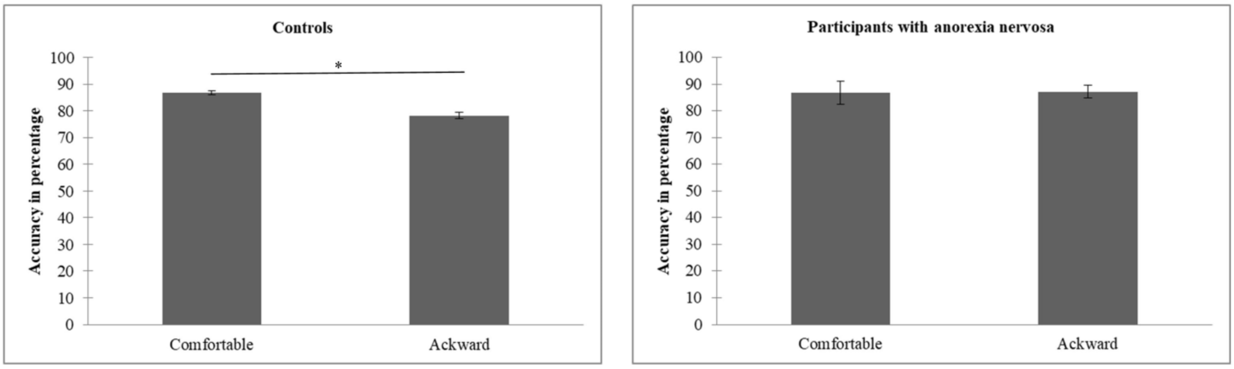


Figure 2. The relation between the time required to imagine movements (x-axis) and the time required to execute movements (y-axis) in seconds is shown for the right and the left hands for the two groups in the Mental Motor Chronometry Task: participants affected by AN in dark (upper panels) vs controls in grey (below panels). p value in bold when < 0.05.

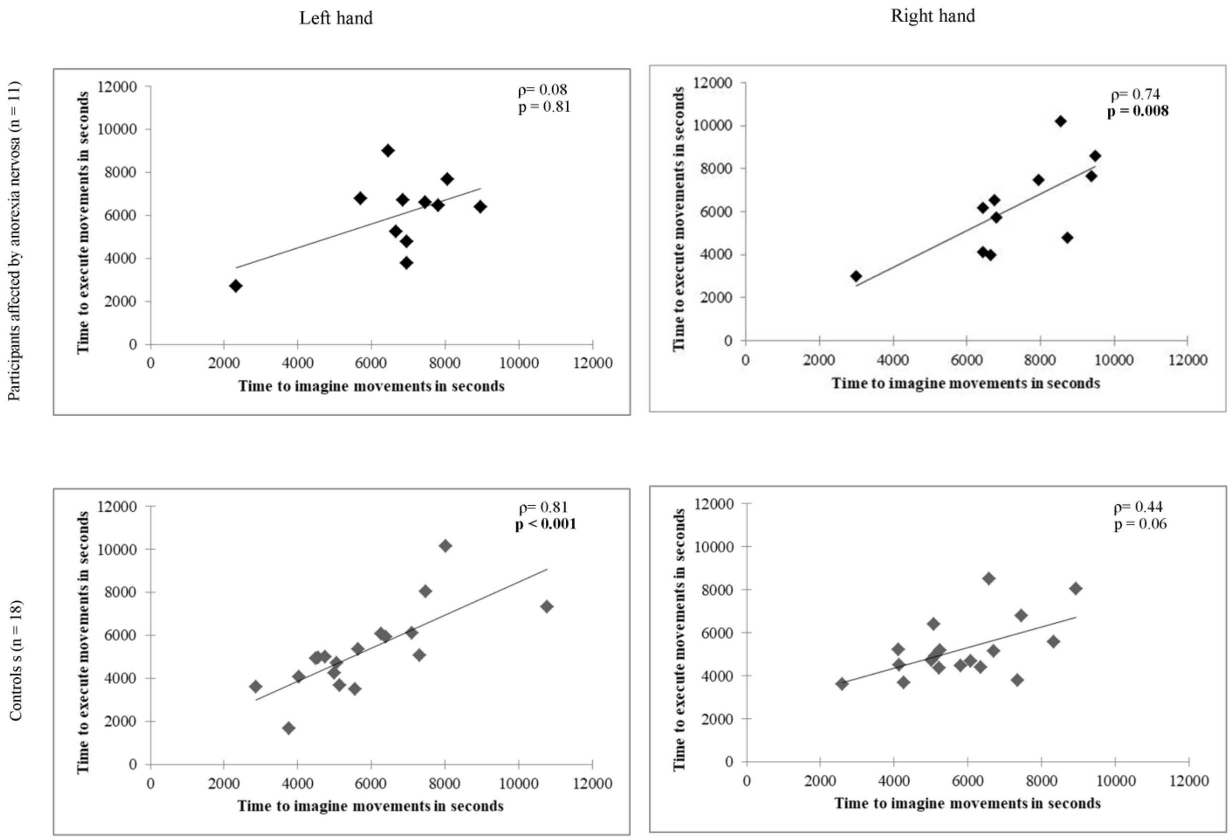
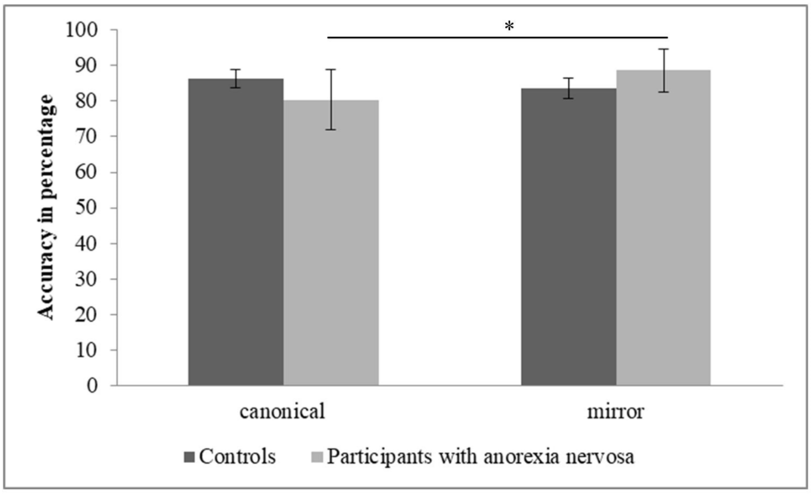


Figure 3. Mean and standard error (vertical line) relative to the level of accuracy in percentage (y axis) in the upper part, and reaction time reaction time expressed in millisecond (y-axis) for the two groups (dark grey: controls; light grey: participants with anorexia nervosa) relative to the effect of *Type* (canonical vs mirror) for the Mental Letter Discrimination Task. * indicates a significant difference with a p value < 0.5.



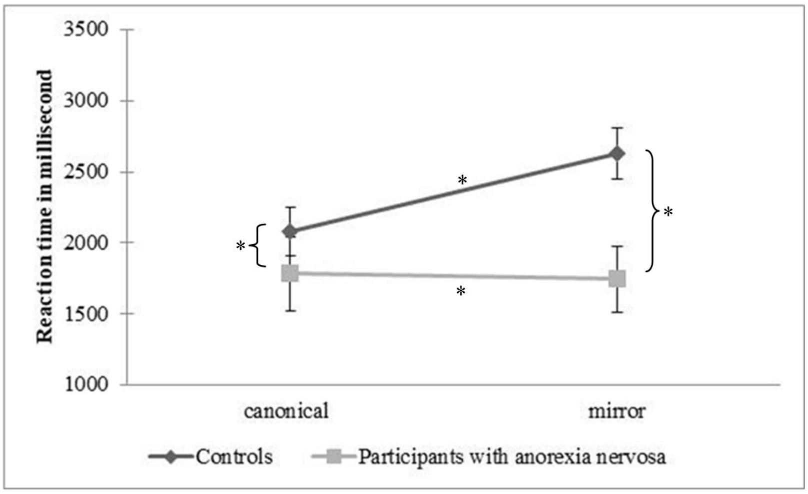


Figure 4. Mean and standard error (vertical line) relative to the reaction time expressed in millisecond (y-axis) for the two groups (dark grey: controls; light grey: participants with anorexia nervosa) relative to the effect of *Orientation* (0° vs 180°) for the Mental Letter Discrimination Task. * p value < 0.5.

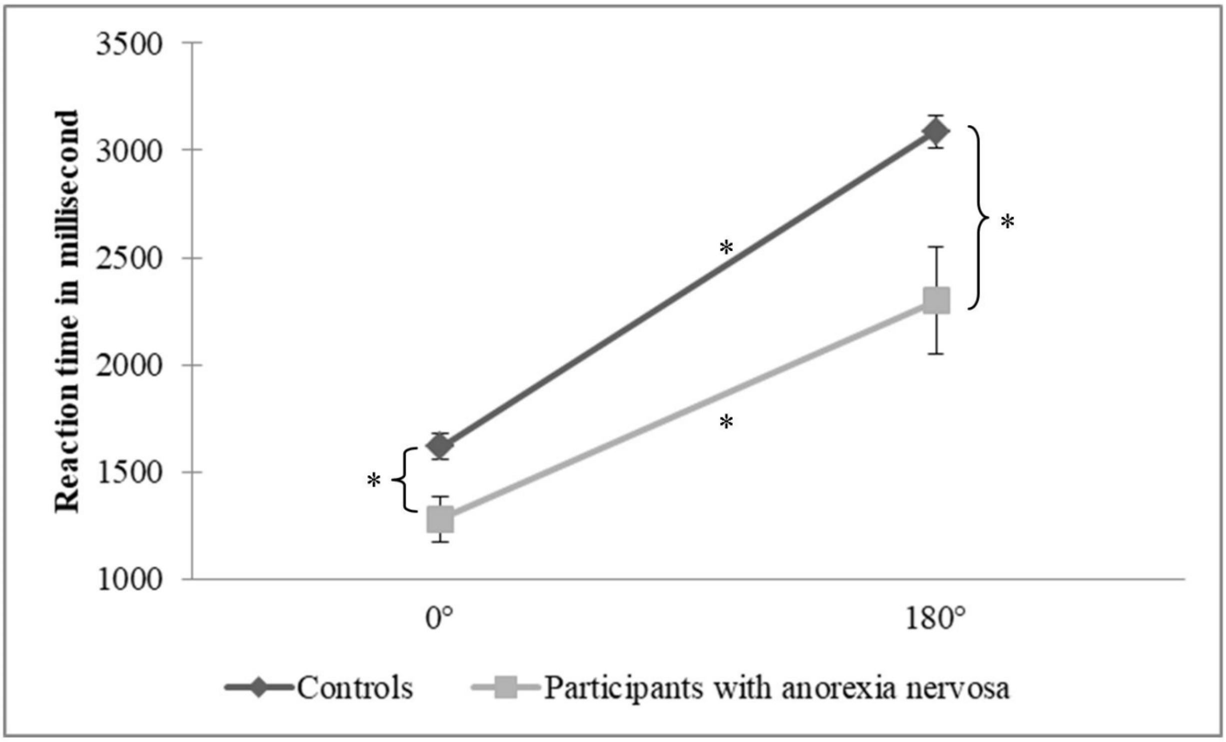


Figure 5. Means (bar) and standard deviation (vertical lines) relative to the Inverse efficiency score (y-axis) computed in relation to the effect of Orientation (0° vs 180°) (upper part) and the effect of Type (canonical view vs mirror view) relative to the Mental Letter Discrimination Task are showed about the controls (left side) and the participants with anorexia nervosa (right side). * indicates a significant difference with a p value < 0.5.

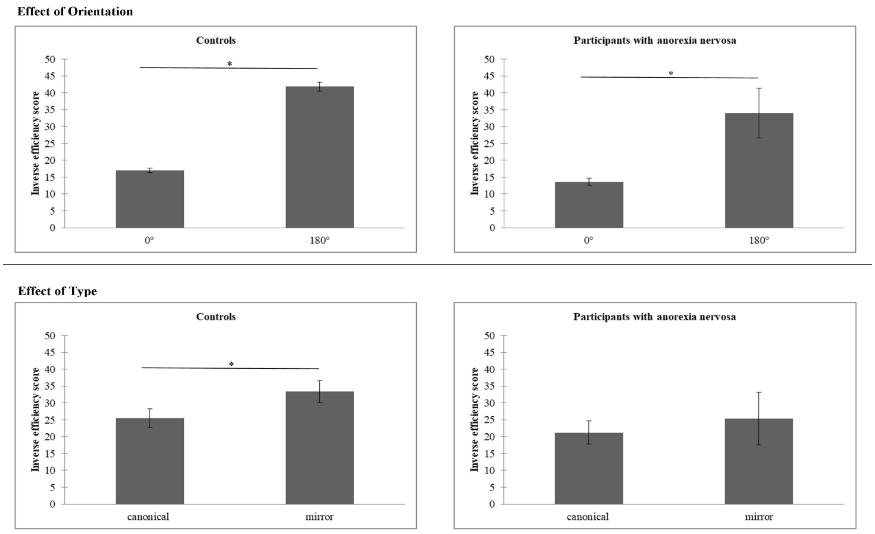
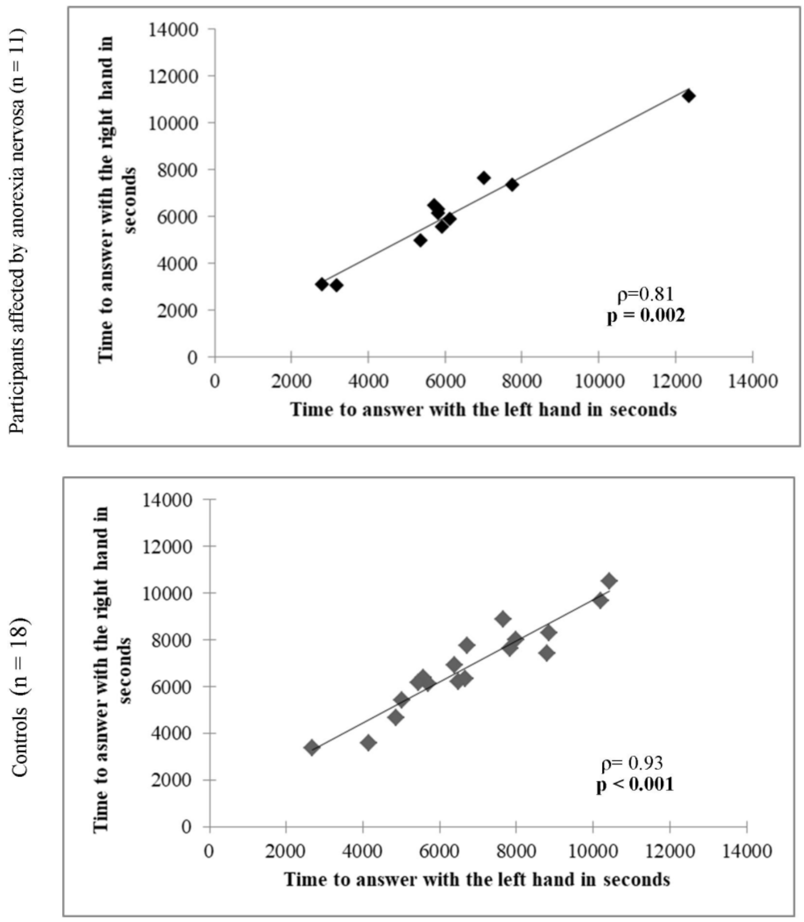


Figure 6. The relation between the time required to answer with the left hand (x-axis) and with the right hand (y-axis) in seconds is shown for the two groups in the Mental Bars Movement Task: participants affected by AN in dark (upper panel) vs controls in grey (below panel). p value in bold when < 0.05



Supplementary Materials.

S1. Experimental Tasks.

Hand Laterality Task. Sixteen pictures (eight for the right hand, eight for the left hand) in back or palm perspective were used. Stimuli are shown in Figure S1. Overall, the task consisted of ninety-six trails, divided into two blocks (48 trials for each block): each stimulus is presented six times (three in the first and three in the second block) in a randomized order. Each trial was preceded by a fixation cross, which lasted 1500 milliseconds. Each stimulus stayed on the screen until participants provided an answer or for a maximum time of 5000 milliseconds (i.e., if participant did not answer the trial would finish after this time). Participants sat in front of the computer screen with their left and right index fingers on the "z" and "m" keys of the keyboard. They were asked to judge if the stimulus represented a right or a left hand by pressing, as quickly and as accurately as possible, the "z" key if the picture on the screen was a left hand or the "m" key if the picture was a right hand in one block, and the reverse in the other block. Block order was randomized between subjects.

Mental Letter Discrimination Task. The visual stimuli were the letters "F" (as shown in figure S1) and "J" shown in canonical or mirror-reversed positions (*Type*), in four different *Orientations*: 0°; 90°; 180°; 270°. Stimuli are shown in Figure S1. Number of trials and blocks, as well as stimulus timing was the same as in the Hand Laterality Task. Participants judged if an alphanumeric character was shown in a canonical or mirror-reversed position. They sat in front of the screen (at a distance of 50 cm) with their left and right index fingers on the "z" and "m" keys respectively. They were asked to press as quickly and as accurately as possible the "z" key if the picture on the screen represented a canonical letter or the "m" key if the picture represented a mirror-reversed letter in one block, with reversed responses in the other block. As in Hand Laterality Task, the block order was randomized between subjects.

Mental Motor Chronometry Task. The four assessed movements were: 1. index and thumb opposition; 2. thumb extension from the fist; 3. middle finger crossed on the index finger; 4. extension of the index and the little fingers. In the *imagery condition,* participants were required to imagine performing each movement as quickly and as accurately as possible, five times consecutively. In the *execution condition*, they performed each movement, again five times consecutively. The order of movements and conditions was the same for all participants; specifically, the imagery condition was performed always first. The starting hand was counterbalanced between subjects. Both the right and left hand were tested. Overall, the task was composed by 16 trials (four gestures for two hands (right and left) and two conditions (imagined vs executed)). During the task, participants sat in front of a computer screen with their left or right index finger (depending on the starting hand) on the spacebar. After the instructions indicating which movement participants had to imagine or to perform, they closed their eyes and imagined or executed the target movement five times consecutively. When finished, participants pressed the spacebar. For each movement, *time* required to imagine and to execute the five repetitions of each movement was collected, in seconds.

Mental Bars Movement Task. In this task, participants imagined four movements: *i)* two bars getting close to each other; *ii)* one bar raising up from the other bars; *iii)* two bars crossing each other; and, *iv)* two bars extending together from bottom to up. The order was the same for all participants. At the beginning of each trial, participants read written instructions relative to the movement; they also saw an example. They then closed their eyes and imagined the target movement five times, as quickly as possible. When finished, they immediately pressed the spacebar. Two blocks of eight trials were tested: in one block participants responded with the right hand and in the other block they responded with the left hand. The starting hand was counterbalanced between subjects, as in the Mental Motor Chronometry Task. For each bar movement, the time required to imagine the five repetitions was collected in seconds.

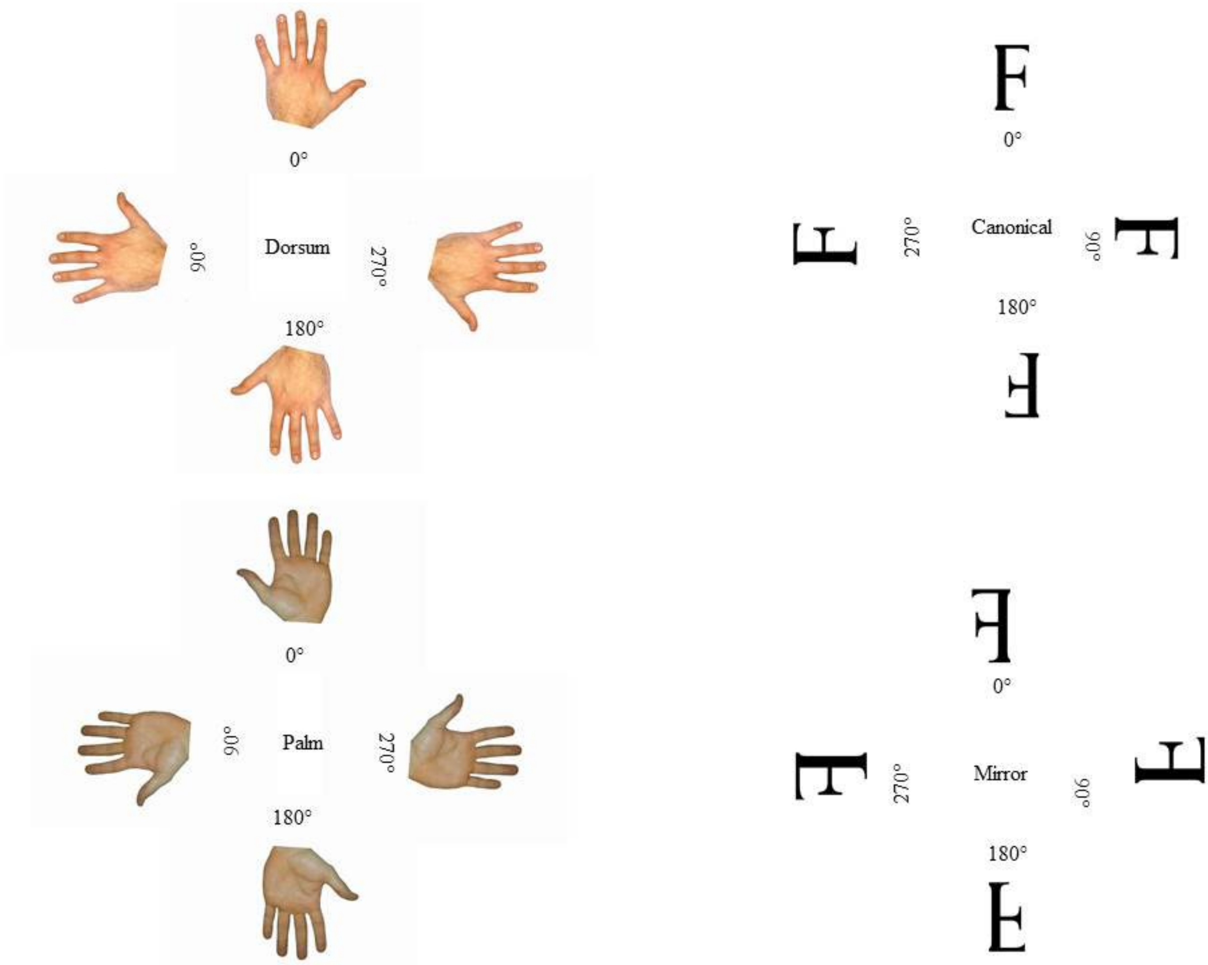


Figure S1. Example of left hand stimuli for the Hand Laterality Task and of the letter F in canonical or mirrored-reversed position for the Mental Letter Discrimination Task are shown.

S2. Participants.

An assessment of eating behavior and psychological functioning of our participants affected by AN, through traditional questionnaires which are routinely used in our hospital, was also performed. We show these data in Table S1 below.

Table S1. Mean, standard deviation and range relative to the eating behavior and the psychological functioning scores of our participants affected by AN.

	M	SD	range
Eating Disorder Inventory™–3			
Drive for Thinness	23.38	5.5	12-28
Bulimia	8.33	10.14	0-28
Body Dissatisfaction	30.16	7.91	13-40
Eating Disorder Risk	61.88	18.99	25-96
Low Self-Esteem	17.27	4.89	10-24
Personal Alienation	16.61	5.58	8-28
Interpersonal Insecurity	13.66	7.94	1-27
Interpersonal Alienation	13	6.56	3-27
Interoceptive Deficits	25.61	8.08	5-36
Emotional Dysregulation	11.38	6.19	3-21
Perfectionism	12.94	6.04	2-22
Asceticism	14.5	5.78	5-24
Maturity Fears	19.22	6.17	4-30
Ineffectiveness	33.88	9.92	18-52
Interpersonal Problems	26.66	13.49	7-54
Affective Problems	37	12.82	12-57
Overcontrol	27.44	10.99	7-46
General Psychological Maladjustment	144.22	38.98	72-223
Binge Eating Scale			
Score	33.76	10.29	20-53
SCL – 90			
Somatization	2.44	1.46	0.67-6.17
Obsession-compulsion	2.58	0.78	1.3-3.7
Interpersonal sensitivity	2.17	0.93	0.44-3.56
Depression	2.85	0.8	1.69-4.85
Anxiety	2.53	0.87	0.9-3.9
Hostility	1.37	0.89	0.33-3.17
Phobic anxiety	1.54	1.04	0-3.29

Paranoid ideation	2.04	0.92	0.33-3.53
Psychoticism	1.6	0.75	0.5-3.4
Total score	2.23	0.75	1.1-3.54
Psychological General Well Being Index			
anxiety	4.27	4.56	0-13
depression	4.9	3.72	0-10
positive well-being	2.6	2.11	0-6
self-control	4.36	3.13	0-11
general healthy	7.18	2.96	2-12
vitality	5.09	5.14	0-17
total score	28.45	15.78	5-59

M = mean; SD = standard deviation

S3. Preprocessing data.

As described in the main text, seven participants with AN were excluded from the main analyses during the preprocessing phase. We performed a comparison between the group of excluded and the group of included participants to check if any difference in terms of demographic or bodily characteristics, psychological functioning, and eating habits, could reveal a pattern explaining why these participants did not met the inclusion criterion of at least 50% of accuracy in the most easy conditions. Results of this comparison are shown in Table S2. Our analysis does not reveal a meaningful pattern apt at explaining why these seven participants were not able to solve the tasks. Given also the individual variability observed in these seven individuals, with one participant excluded because of the performance at the Hand Laterality Task; two participants because of the performance in both tasks, and four participants because of the performance at the Mental Letter Discrimination Task, we cannot provide a meaningful explanation at this stage, but recommend that future studies explore whether other factors (such as executive functioning, impulsiveness, or other neuropsychological processes) influence performance at motor and visual imagery tasks.

Table S2. Mean and standard deviation (in brackets) of demographical characteristics and scores at the questionnaire on eating behaviors and psychological functioning, showed separately for the participants excluded and included in the study.

	Included N = 12	Excluded N = 7	Statistical results (Mann-Whitney)
Age	26.75 (6.94)	23.83 (6.46)	U = 26; p = 0.34
Education	13.75 (3.46)	13 (1.67)	U = 28; p = 0.43
Body Mass Index	15.58 (3.59)	14.01 (2.51)	U = 28: p = 0.45
Eating Disorder Inventory™–3			
Drive for Thinness	23.16 (5.44)	23.83 (6.11)	U = 39.5; p = 0.33
Bulimia	8.08 (10.12)	8.83 (11.14)	U = 33.5; p = 0.81
Body Dissatisfaction	30.5 (8.08)	29.5 (8.26)	U = 29.5; p = 0.54
Eating Disorder Risk	61.75 (18.42)	62.16 (21.88)	U = 37.5; p = 0.88
Low Self-Esteem	18.08 (5.21)	15.66 (4.13)	U = 25.5; p = 0.32
Personal Alienation	18.08 (6)	13.66 (3.32)	U = 18.5; p = 0.1
Interpersonal Insecurity	15.5 (8.89)	10 (4)	U = 21; p = 0.15
Interpersonal Alienation	15.08 (6.58)	8.83 (4.44)	U = 15.5; p = 0.054
Interoceptive Deficits	26.58 (8.65)	23.66 (7.08)	U = 24; p = 0.25
Emotional Dysregulation	11.58 (6.15)	11 (6.84)	U = 32; p = 0.7
Perfectionism	13.33 (6.41)	12.16 (5.7)	U = 32; p = 0.7
Asceticism	15.58 (5.85)	12.33 (5.46)	U = 26; p = 0.34
Maturity Fears	18.25 (7.36)	21.16 (1.94)	U = 50; p = 0.18
Ineffectiveness	36.16 (10.65)	29.33 (6.88)	U = 21; p = 0.15
Interpersonal Problems	30.58 (15.02)	18.83 (3.54)	U = 17.5; p = 0.08
Affective Problems	38.16 (13.41)	34.66 (12.38)	U = 29.5; p = 0.54
Overcontrol	28.91 (11.66)	24.5 (9.81)	U = 29; p = 0.51
General Psychological Maladjustment	152.08 (42.57)	128.5 (27.08)	U = 21; p = 0.17
Binge Eating Scale			
Score	34.63 (10.36)	32.16 (10.92)	U = 21.5; p = 0.17
SCL – 90			
Somatization	2.68 (1.6)	1.94 (1.07)	U = 28.5; p = 0.48
Obsession-compulsion	2.7 (0.73)	2.36 (0.9)	U = 28; p = 0.45
Interpersonal sensitivity	2.37 (0.8)	2.36 (0.9)	U = 21; p = 0.15
Depression	3 (0.86)	1.77 (1.13)	U = 27.5; p = 0.42
Anxiety	2.75 (0.82)	2.08 (0.84)	U = 18; p = 0.09
Hostility	1.58 (0.82)	0.97 (0.95)	**U = 14.5; p = 0.043 ***
Phobic anxiety	1.69 (1.16)	1.26 (0.74)	U = 27; p = 0.39
Paranoid ideation	2.33 (0.76)	1.47 (1.01)	U = 17.5; p = 0.08
Psychoticism	1.75 (0.85)	1.28 (0.36)	U = 23.5; p = 0.24
Total score	2.42 (0.73)	1.86 (0.71)	U = 18.5; p = 0.1
Psychological General Well Being Index			
anxiety	4.75 (4.65)	7 (6.16)	U = 46.5; p = 0.32
depression	4.91 (3.55)	6.16 (4.44)	U = 39; p = 0.77
positive well-being	2.83 (2.12)	5.66 (3.14)	U = 53.5; p = 0.09
self-control	4.75 (3.27)	7.66 (2.8)	U = 54.5; p = 0.08
general healthy	6.91 (2.98)	5.33 (3.26)	U = 26; p = 0.34

vitality	5.33 (4.97)	6 (4.14)	U = 42; p = 0.57
total score	29.5 (15.48)	37.83 (16.37)	U = 43.5; p = 0.48

N = 18; M = mean; SD = standard deviation

S4. The role of age.

As described in the main text, participants with AN were youngers than controls. As one might wonder whether the effects observed are due to age differences between samples, we report here additional statistical analyses in which we check for the role of age on the behavioral performance.

Specifically, in the case of the Hand Laterality Task, we observed a significant main effect of group, when we tested the level of accuracy about the effect of orientation. Thus, we run again the statistical model, introducing *Age* as covariate. *Age* resulted significant [$F(1,26)=6.9$; $p = 0.014$; $\eta^2_p= 0.21$] and it interacted significantly with *Orientation* [$F(1,26) = 6.9$; $p = 0.01$; $\eta^2_p = 0.21$]. Nonetheless, the significant main effect of *Group* was still observed [$F(1,26) = 18.19$; $p < 0.002$; $\eta^2_p= 0.41$]: when we considering the corrected values (*Age* correction value = 36.68), participants with AN still show a higher level of accuracy [M = 86.05; SD = 1.35] than controls [M = 78.62; SD = 1.45]. The same approach was used to test if age interacted with the level of accuracy when we tested the effect of biomechanical constraints, for which we observed a significant interaction *Group*Posture* in the main analysis. Crucially, *Age* was not a significant covariate in this case [$F(1,26) = 2.81$; $p = 0.1$; $\eta^2_p= 0.09$]. Thus, overall, these supplementary analyses suggest that the main results for the Hand Laterality Task are not related to the different ages between the two samples of participants.

The same rationale was followed about the Mental Letter Discrimination Task. We checked if the significant interaction *Group*Type* observed for the level of accuracy is linked to age. Thus, we included this demographical factor as a covariate in the statistical model. However, it did not result to be significant [$F(1,26) = 0.17$; $p = 0.67$; $\eta 2p = 0.007$]. Similarly, *Age* was not a significant factor when used as covariate in the statistical model for the RT [$F(1,23) = 1.23$; $p = 0.27$; $\eta 2p = 0.05$].

Overall, we can conclude that the differences between the two groups in the Mental Letter Discrimination Task are not linked to age.

Of note, these statistical results agree with previous evidence on the role of age for biomechanical constraints effects. As described in the main text, motor imagery abilities decrease in elderly individuals, and specifically after 65 years (Zapparoli et al., 2013). On the other hand, there is some evidence in the literature suggesting that the development of motor imagery seems to emerge very early in young children (around 7–8 years) (Conson et al., 2013a; Sekiyama et al., 2014), and becomes progressively stable across adolescence, finally becoming comparable to adults in late adolescence (17-18 years) (Conson et al., 2013a). Further evidence about the presence of biomechanical constraints effects in late adolescents and younger adults can be found in other experimental studies adopting the Hand Laterality Task. For example, Conson and colleagues (2013b) report that twenty-four controls have a behavioral performance in line with the expected biomechanical constraints effects one would see in adults. This behavior emerged also in a successive study, in which eighteen healthy adolescents (mean age = 14.8, SD = 3.5; age range 10–20) were tested (Conson et al., 2016). Overall, the previous evidence (Conson et al., 2013ab, 2016; Sekiyama et al., 2014) together with the supplementary analyses we conducted on our own data supports the hypothesis according which the absence on the biomechanical constraints effects in our participants affected by AN is not linked to the different ages between the two samples of participants.

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