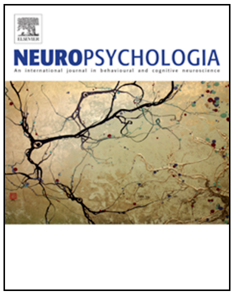

Visuo-tactile shape perception in women with Anorexia Nervosa and healthy women with and without body concerns

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Title

Visuo-tactile shape perception in women with Anorexia Nervosa and healthy women with and without body concerns

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Abstract

A key feature of Anorexia Nervosa is body image disturbances, the study of which has focused mainly on visual and attitudinal aspects and did not always contain homogeneous groups of patients, and/or did not evaluate body shape concerns of the control group. In this study, we used psychophysical methods to investigate the visual, tactile and bimodal perception of elliptical shapes in a group of patients with Anorexia Nervosa (AN) restricting type and two groups of healthy participants, which differed from each other by the presence of concerns about their own bodies. We used an experimental paradigm designed to test the hypothesis that the perceptual deficits in AN reflect an impairment in multisensory integration. The results showed that the discrimination thresholds of AN patients are larger than those of the two control groups. While all participants overestimated the width of the ellipses, this distortion was more pronounced in AN patients and, to a lesser extent, healthy women concerned about their bodies. All groups integrated visual and tactile information similarly in the bimodal conditions, which does not support the multi-modal integration impairment hypothesis. We interpret these results within an integrated model of perceptual deficits of Anorexia Nervosa based on a model of somatosensation that posits a link between object tactile perception and Mental Body Representations. Finally, we found that the participants' perceptual abilities were correlated with their clinical scores. This result should encourage further studies that aim at evaluating the potential of perceptual indexes as a tool to support clinical practices.

Keywords

Shape perception; multisensory integration; Anorexia Nervosa; body dissatisfaction; body representation; somatosensory system; touch.

Introduction

Anorexia Nervosa is a multi-faceted psychiatric disorder characterized by disturbed eating behaviors where the patients' attitudes towards their bodies, as well as perceptions of weight and shape are distorted (AN; American Psychiatric Association, 2013). Body parts such as the head, the abdomen or the thighs appear larger to AN patients than what they are in reality (Cash & Deagle, 1997; Smeets et al., 2009). In contrast, patients with AN do not perceive the body shapes of other individuals as distorted. Given the presumed absence of a generalized perceptual deficit, the origin of AN perceptual distortion remains mysterious and the question why patients with AN perceive their body shape as distorted despite receiving, presumably, accurate visual and tactile feedback is still open.

Mental Body Representations in AN

Various hypotheses have been advanced to explain perceptual distortions in AN. One explanation is that AN affects Mental Body Representations (MBRs), to use a term proposed by Serino and Haggard (2010) to refer to various high-level representations of one's own body that play a role in perception or action. MBRs include, body image, body schema and the superficial form, distinctions going back to Head & Holmes (1911) seminal work. While derived from sensory input, MBRs are typically persistent, abstract, and multimodal (Serino & Haggard, 2010). Importantly, there is not yet a general agreement about the neuro-anatomical correlates of MBRs, which are usually defined in functional terms.

Body image is a conscious representation used in the perception of one's own body size, shape or weight (Cash & Brown, 1987; de Vignemont, 2010; Longo, Azañón, & Haggard, 2010; Longo & Haggard, 2012). It includes a perceptual dimension, which can be assessed with many different techniques like the analogue scale, image marking methods, optical distortion methods such as distorting photography, distorting a mirror, video distortion technique, and figural drawing scales (for a review see Gardner & Brown, 2011). Body image also includes a subjective dimension that consists of the feelings that individuals develop towards their bodies' appearance. Numerous studies have shown that the two dimensions of the body image are dysfunctional in AN (Cash & Brown, 1987; Thomas F. Cash & Deagle, 1997). In particular, these studies have shown that the perceptual distortions correspond specifically to a fattening of the body shape. Importantly, the vertical dimension, the shape of other individuals and the shape of objects are not distorted (Bowden et al., 1989; Slade & Russell, 1973). Moreover, studies that have used the Signal Detection Theory framework suggest that these perceptual distortions do not have a sensory origin because AN patients can detect changes in body shape as well as controls (Gardner & Moncrieff, 1988; Smeets et al., 1999).

Recent studies have shown that AN might also affect the body schema, which is an unconscious sensorimotor representation of the body that is invoked in action (de Vignemont, 2010). For example, it has been shown that patients move as if their bodies were larger than they really are when passing through doors, which suggests that body schema is also distorted in patients with Eating Disorders (Guardia et al., 2010; Keizer et al., 2013; Nico et al., 2010; Urgesi et al., 2011).

Finally, AN can also affect the superficial schema, which is also known as the tactile form (Gadsby, 2017) and/or body form representation (Medina & Coslett, 2010). The superficial form provides the information needed to localize the position of the tactile stimulus on the skin and to estimate the physical distance between two tactile stimuli or the size of an object touching the skin. For example, Keizer and colleagues (2011, 2012) have shown that AN patients tend to overestimate the distance between two tactile stimuli relative to controls in the abdomen and the head. In a later study Spitoni et al. (2015) showed that this distortion occurred only along the altered dimension of the body.

While these studies show that AN affects patients' own body representations in multiple ways, there is no general agreement on the cause of this disturbed experience. One hypothesis is that *affects* might cause MBR distortions (Gadsby, 2017). Indeed, some studies have shown that negative mood induction in participants with normal weight (Baker et al., 1995) and who have no indication of Eating Disorders (Plies & Florin, 1992) increases body overestimation. In addition, other studies have shown a relation between body dissatisfaction and tactile perception of distance (Keizer et al., 2011; Spitoni et al., 2015), but not in a somatosensory time duration task (Spitoni et al., 2015). These results pointed to a significant correlation between body satisfaction and the tendency to overestimate distance on the body.

Another hypothesis is that body shape distortions in AN reflect a broader impairment in *multisensory integration* (see Gaudio et al., 2014 for a review). For example, Case et al. (2012) investigated haptic-visual-proprioceptive integration using the size-weight illusion (SWI). They found that patients with AN were significantly less susceptible to the illusion than healthy controls (HC). Some authors (Eshkevari et al., Rieger et al., 2012) have investigated visuo-tactile-proprioceptive integration using the Rubber Hand Illusion (RHI). ED patients reported higher embodiment scores and higher proprioceptive drift than HC showing that they experience a stronger RHI than the control sample. Although these two studies suggest an altered capacity of AN patients to process and integrate multisensory bodily perceptions, their conclusions differ with respect to the weight given to each sensory modality. On the one hand, SWI results suggest that patients gave more weight to visual signals than to somatosensory ones. On the other hand, RHI results support the view that patients with AN showed a reduction in somatosensory processing, or an excessive reliance on visual information, or both the previous hypotheses. While interesting, SWI and RHI do not and cannot measure the weight of each sensory modality independently. As suggested by Gaudio et al. (2014), this issue needs to be addressed with paradigms and tasks that can more precisely assess the role of each sensory modality and more directly test the hypothesis of aberrant multisensory integration in AN patients.

Eating disorder heterogeneity

A challenge in Eating Disorder studies is the wide heterogeneity of symptoms and eating habits, which can complicate comparisons between studies. At the neurophysiological level, there is evidence that severe malnutrition can affect sensory nerves anatomically and functionally both in the visual (Caire-Estévez et al., 2012; Moschos et al., 2011) and somatosensory system (Alloway et al., 1985; Renthal et al., 2014; Teixeira et al., 2016). However, not all studies have found a corresponding visual or somatosensory acuity deficit. For example, Caire-Estévez et al. (2012) found that visual acuity was impaired while Moschos and colleagues (2011) did not. A possible reason for this discrepancy is that the Caire-Estévez et al. (2012) study included only AN Restricting type patients while the Moschos et al. (2011) study included AN Binge/Purging patients as well. In the tactile modality, two studies found low-level sensory deficits in AN restricting type patients who are severely underweight (Epstein et al., 2001; Spitoni et al., 2015). In particular, Epstein et al. (2001) found that AN patients had difficulties in recognizing which fingers were being touched when closing their eyes and Spitoni et al. (2015) found that the threshold of AN patients was larger in a two point discrimination (2PD) task. However, they did not find alteration in the elementary tactile detection of patients as assessed with the Von Frey task (VF). When the sample of ED is open to more than AN restricting type and the BMI is not severely underweight, neither elementary tactile detection assessed with the VF nor thresholds in the 2PD task appear to be compromised (Keizer et al., 2012). Altogether, these studies show that low-level sensory deficits might depend on the AN type and degree of malnutrition.

The second issue in ED studies is that the control groups are not always well defined with respect to body satisfaction. As a result, it is difficult to pinpoint the origin of perceptual deficits, which might be linked to body dissatisfaction in general and/or to more specific ailments present only in AN.

To address these issues, this study includes three groups of participants. The AN group included only female patients with an AN restricting type diagnosis in a state of malnutrition shown by their low BMIs (see Table 1). In contrast, all participants in the healthy control groups were gender- and age-matched, with a healthy weight and no psychiatric disorder diagnosis. After completing body satisfaction tests, the participants in the control group were divided into two groups according to their score: a group that was as concerned about their bodies as patients with AN and a group with lesser concerns.

Objectives

The main objective of this study is to test the multisensory integration impairment hypothesis. To that end, we used an experimental paradigm that has been extensively used to show that people integrate redundant sensory information optimally (Ernst, 2012; Helbig & Ernst, 2007; Hillis et al., 2004; Körding et al., 2007; Risso et al., 2019). The idea behind this paradigm is to assess the reliability of each sensory modality independently and then compare the performance measured in the bimodal conditions with the prediction derived from the performance in unimodal conditions to test the optimal integration hypothesis (Ernst & Banks, 2002; see Methods). While different stimuli have been used to demonstrate optimal multisensory integration, we adapted a task used by Helbig & Ernst (2007) where participants must judge the shape of a small ellipse in the tactile and/or visual modalities. It is noteworthy that this task makes it possible to assess both the perceptual biases, the weights and reliabilities of each sensory modality independently in addition to the multisensory integration hypothesis. Therefore, this paradigm also allows us to address several questions, which might shed light on the nature the perceptual deficits in AN. The first question is whether AN patients will perceive the shape of the ellipse in a more distorted way than controls and whether the distortions, if any, will be larger in the tactile or visual modality. The fact that the same stimuli are used in all conditions allows for a direct comparison of the results across sensory modalities. A second question of interest is whether AN affects the reliability of sensory cues in the tactile and visual modalities. Since the weight of a sensory modality is proportional to its reliability in the optimal integration framework (see Methods), this paradigm might allow us to test the hypothesis that somato-sensation has more weight than visual information (Eshkevari et al., 2012; Longo, 2015) or viceversa (Case et al., 2012). The third question is whether tactile and visual information are integrated optimally (Gaudio et al., 2014), which can be addressed by comparing prediction derived from unimodal conditions and the results in the bimodal conditions (see Optimal Integration Model in the Methods Section).

A secondary objective is to find out whether body concerns can be linked to perceptual deficits or whether these deficits are specific to AN. To do so we compared the performance of the patients to that of the controls with and without body concerns. Evidence in this direction would support the hypothesis that affects might be linked with the corresponding deficits. A final objective is to find out whether perceptual biases and clinical scales characterizing eating disorders and body shape concerns are correlated.

Materials and Methods

Ethics statement

This study adhered to the principles of the Declaration of Helsinki (2013) and was approved by the ethics committee of the San Raffaele Hospital of Milan (Prot. CUBE-2015). Each participant received oral and written information on the purpose and procedure and signed an informed consent form before taking part in the study.

Participants

Table 1. Demographics and clinical assessment of the Healthy Controls (HC), Healthy Controls with Body Concerns (BCHC) and Anorexia Nervosa patients (AN).

	HC (N=19)	**BCHC (N=9)**	**AN (N=17)**
Age, M (SD)	24.47 (1.26)	25.67(2.18)	26.12 (9.34)
BMI, M (SD)	19.86 (1.94)	20.49 (1.43)	15.15 (2.64)
Right-handedness, N (%)	17 (94.74%)	8 (88.89%)	15 (88.24%)
BSQ global score, M (SD)	54.26 (8.53)	117.44 (35.36)	116.12 (42.86)
EDI-2 global score, M (SD)	14.95 (9.58)	68.56 (45.93)	90.59 (39.72)

The study included three groups of adult women: 17 Anorexia Nervosa (AN) patients, 19 Healthy Controls (HC) and 9 healthy controls with body shape concerns (BCHC). Patients with AN were recruited from the Center for Eating Disorders at San Raffaele Hospital in Milan. Patients were tested during their rehabilitation program. All the patients were diagnosed with Anorexia Nervosa disease by a senior psychiatrist and were characterized by a Restricting subtype and no psychiatric comorbidities (excluding personality disorders). We included both hospitalized patients and patients involved in non-residential treatment. One AN patient was removed from all the analyses because she could not perform the task (see Data Analysis below) and subsequent investigation revealed an

IQ slightly below average. The mean duration of illness was 6.75 ± 6.92. All the patients followed Cognitive Behavioral Therapy and Nutritional Therapy and fourteen of them were under pharmacological treatment. The women in the HC and BCHC groups differ from the AN group in that they have never exhibited Eating Disorder (ED) symptoms. In addition, women in the HC group did not report body shape concerns as assessed by the Body Shape Questionnaire (BSQ; Cooper et al., 1987) nor did they report psychological or behavioral traits common in ED as assessed by Eating Disorder Inventory 2 (EDI-2; Garner, 1991). In contrast, women in the BCHC group had a BSQ global score ≥ 80. Importantly, no member of the HC and BCHC groups was diagnosed with ED. All had a BMI of above 17 kg/m^2, which corresponds to the upper limit for the first level of AN severity according to the DSM-5 (American Psychiatric Association, 2013). Demographics and clinical assessment of the three groups are given in Table 1. The BMI was significantly different between groups (one-way ANOVA: F (2, 42) = 27.65, p < 0.001). As expected, post-hoc analysis using the Tukey HSD test showed that BMI in AN patients was significantly lower than in HC (p<0.001) and BCHC individuals ($p < 0.001$) and that the BMI of the HC and BCHC groups did not differ ($p = 0.758$). The global EDI-2 (F (2, 42) = 25.75, $p < 0.001$) and BSQ (F (2, 42) = 22, $p < 0.001$) scores were different across groups. The Tukey HSD showed higher EDI-2 and BSQ scores for the AN patients and BCHC groups in both the clinical tests related to the HC ($p < 0.001$ for all tests) and no statistically significant differences between the AN and BCHC groups for the EDI-2 ($p = 0.234$) and BSQ ($p =0.994$) scores. The age of the participants was matched in the three groups (F (2, 42) = 0.37, $p = 0.696$).

Clinical Questionnaires

The participants filled out clinical self-report questionnaires regarding body shape concerns, common traits in ED, depression and anxiety symptoms. The questionnaires are described below:

Body Shape Questionnaire (BSQ). The Body Shape Questionnaire is a self-report measure of general concerns about body shape, specifically the subjective experience of “feeling fat” (Cooper et al., 1987). It includes 34 items scored on a 6 point Likert scale (where 1= never and 6=always) with a possible total score ranging from 34 to 204. A score below 80 represents the absence of concerns related to body shape, while higher scores represent a more negative attitude towards body shape (Taylor, 1987). The BSQ is easy to fill out and can be rapidly completed by participants. Significant correlations between the BSQ and the total score on the Eating Attitude Test and the Body Dissatisfaction subscale of the EDI-2 establish its concurrent validity. A Cronbach’s alpha between 0.82 and 0.88, with a test-retest correlation of 0.97 was shown (Franko et al., 2012). Its discriminant validity has also been shown to be satisfactory. The BSQ has demonstrated high concurrent and discriminant validity (Cooper et al., 1987).

Eating Disorder Inventory 2 (EDI-2). We used the Italian version of the Eating Disorder Inventory (EDI-2) (Garner et al., 1995). The EDI-2 is a self-report questionnaire developed by Garner and widely used both in research and clinical settings to assess the symptoms and psychological features commonly associated with EA (Garner et al., 1983). It includes 91 items on a 6 point Likert scale (from “always” to “never”), divided into 11 subscales: Drive for Thinness, Bulimia, Body Dissatisfaction, Ineffectiveness, Perfectionism, Interpersonal Distrust, Interoceptive Awareness, Maturity Fears, Asceticism, Impulse Regulation, Social Insecurity. Internal consistency (Cronbach’s alpha values between. 82 and .93; Thiel & Paul, 2006), convergent and discriminant validity for the EDI-2 were established. Higher scores on the EDI-2 represent greater presence of attitudinal and behavioral features associated with the ED.

Sensory and Multisensory Processing Assessment Task

In this study, we assessed the sensory biases and integration of patients and control participants with the Multisensory Processing Assessment (MPA) task, which can be used in a clinical setting easily, as it does not require complicated material. In this task, participants had to distinguish the shape of small ellipses using only visual, only tactile or both visual and tactile information. In a previous study, Helbig and Ernst (Helbig & Ernst, 2007) demonstrated that healthy participants integrate the tactile and visual information in this task.

Figure 1. Experimental setup. The left panel shows a participant reaching for the stimuli in the bimodal condition. The right panel shows a detail from the back side. Note that LED lights surrounded the aperture behind the black panel to control lightening conditions.

Participants sat in front of the experimental setup that comprised a chin rest and a metallic structure to present the stimuli. The stimuli consisted in a high relief ellipse (1.25 mm relief) that protruded on one or both sides of a flat 3D printed black plate (60 mm × 80 mm). The stimuli were inserted vertically between two rails of the metal structure behind a front panel with a 50 mm circular hole at the center (Fig. 1). The lighting was controlled by dimming the lights in the room and by illuminating the shape with LED lights placed on the back side of the front panel around the hole. In front of the hole, a semi-transparent screen blurred vision in order to equalize the reliability of visual and tactile information (see below). The height of the chin rest was adjusted so that the stimulus would be at eye level. The distance between the eye and the stimulus was about 35 cm.

At each trial, the experimenter inserted a stimulus plate in the structure and brought it behind the hole. In the visual condition, the stimulus had a high relief ellipse on the front side, which the participants could see through the hole of the panel. In the tactile condition, the participants extended their arm and reached behind the panel to touch the high relief ellipse printed only on the back side of the stimulus plate. Participants touched the stimulus without moving their finger for about 3 s (unlike Helber & Ernst (Helbig & Ernst, 2007) who allowed the participant to move the finger). In the bimodal conditions, the participants looked at a double-sided printed ellipse. Participants could see the ellipse on the front side of the stimulus while touching the ellipse on the back side. The presentation of the stimulus lasted about 3 sec. in all conditions and the task of the subjects was to report verbally whether the stimulus was elongated vertically or horizontally.

In order to avoid visual dominance, we degraded the visual information by placing plastic film on a transparent screen in front of the hole (Fig. 1). We adjusted the distance of the screen in preliminary experiments with other (healthy) participants so that the discrimination threshold of the visual information would approximatively match the threshold in the tactile modality.

Table 2. Visual, tactile and bimodal stimuli used in the unimodal and bimodal conditions.

	1	2	3	4	5	6	7	8
Ellipse Series A								
Vertical (y, mm)	7	8	8.8	9.4	10	10	10	10
Horizontal (x, mm)	10	10	10	10	9.4	8.8	8	7
EA_{diff}	-3.0	-2.0	-1.2	-0.6	0.6	1.2	2.0	3.0
Ellipse Series B								
Vertical (y, mm)	8	9	9.8	10	10	10	10	10
Horizontal (x, mm)	10	10	10	9.6	.4	7.8	7	6
EA_{diff}	-2.0	-1.0	-0.2	0.4	1.6	2.2	3.0	4.0

The eccentricity of the stimuli EA_{diff} corresponds to the differences between the length of the x and y axes. See text for information on how stimuli in series A and B were used in the unimodal and bimodal conditions.

In each condition, we used the method of constant stimuli to find out the eccentricity of the ellipse that participants perceived as circular, and the minimal eccentricity difference that participants could be perceived as elliptical. Following Helbig and Ernst (2007), the *ellipse eccentricity*, $EA_{diff} = y - x$, corresponds to the difference between the lengths of the vertical (y) and horizontal (x) axes.

The experiment included two unimodal conditions and three bimodal conditions. In the unimodal conditions (V or T), the eccentricity EA_{diff} of the ellipses ranged from –3.0 to 3.0 mm (ellipses in Series A, see. Table 2). In the bimodal conditions (B), the visually and tactilely presented ellipses could be consistent or inconsistent. In the bimodal consistent condition (B0), we used ellipses from Series A printed on both sides of the stimulus plate. In the bimodal inconsistent conditions, there was a conflict between the eccentricities of the visual and tactile ellipses. The *conflict*, $\Delta = EA_{diff,V} - EA_{diff,T}$. is defined by the difference between the eccentricities of the visual and tactile ellipses. A positive conflict corresponds to a visual ellipse that is more elongated along the vertical direction than the tactile ellipse while a negative conflict corresponds to the opposite case. In the first bimodal inconsistent condition (BM1) with conflict $\Delta = -1$, we used ellipses from Series A on the front (visual) side and the corresponding ellipses from Series B on the back (tactile) side. In the other bimodal inconsistent condition (BP1) with conflict $\Delta = +1$, we used ellipses from Series B in the front (visual) side and ellipses from Series A on the back (tactile) side.

The experiment was divided into four blocks of 80 trials. Each block included two series of eight trials in the five experimental conditions. The eight possible ellipse eccentricities for each condition were randomized within each single series and the experimental condition changed every two series. The order of the conditions within each block was the same for all blocks (V, T, BM1, B0 and BP1). In total, the eight ellipses were presented 8 times in each condition, yielding a total of 5 x 64 = 320 trials. The whole experiment lasted about one and half hours and was administered in a single day. Breaks were included as often as needed to avoid fatigue and insure maximum attention during the experiments.

Optimal integration model

The optimal integration model (see Introduction) prescribes that the best estimate concerning the attribute of interest corresponds to a weighted average between the cues (Ernst & Banks, 2002):

$$s_B = w_V s_V + w_T s_T \quad (1)$$

where s_V and s_T are the visual and tactile size cues. For this study, the two sensory cues correspond to the eccentricity of the ellipse that is seen and/or touched. The weights given to each sensory signal: w_V and w_T, should be proportional to the reliability of the stimulus:

$$w_V = \frac{R_V}{R_V + R_T} = \frac{\sigma_T^2}{\sigma_V^2 + \sigma_T^2} \quad w_T = \frac{R_T}{R_V + R_T} = \frac{\sigma_V^2}{\sigma_V^2 + \sigma_T^2} \quad (2)$$

where the reliability $R_i = 1/\sigma_i^2$ is simply the inverse of the noise (variance) of the corresponding cue. Assuming that the visual and tactile cues are independent and normally distributed, it can be shown that the optimal (or Maximum Likelihood) estimate s_{VT} that combines the two cues has a variance:

$$\sigma_B^2 = \frac{\sigma_V^2 \sigma_T^2}{\sigma_V^2 + \sigma_T^2} \tag{3}$$

that is not only lower than that of the single cues but the lowest possible given the noise associated with each cue.

Predicted bias in the bimodal conditions

In the following, we assume that the tactile and visual cues s_i (I = T or V) can be biased:

$$s'_i = s_i + b_i$$

where s'_i is the perceived eccentricity of the ellipse, s_i the actual eccentricity of ellipse (EA$_{\text{diff},i}$) and b_i the bias reflecting the distortion of the ellipse shape. From the definition of EA$_{\text{diff}}$, a negative bias indicates a widening of the ellipse or elongation of the horizontal axis relative to the vertical axis. By definition, the PSE denotes the eccentricity of the ellipse s that is perceived as circular

$$s'_i = s_i + b_i = PSE_i + b_i = 0$$

which implies that $PSE_i = -b_i$. Therefore, a positive PSE corresponds to a widening of the ellipse.

If the sensory cues are biased and averaged as in equation 1, one can derive a prediction for the bias in the bimodal conditions:

$$\begin{aligned} s'_{B,\delta} &= w_V\, s'_V + w_T\, s'_T \\ &= w_V\,(s_V + b_V) + w_T\,(s_T + b_T) \\ &= w_V\,(s_V + b_V) + w_T\,(s_V - \Delta + b_T) \\ &= s_V + w_V\, b_V + w_T b_T - w_T\ \Delta \\ &= s_V - (w_V\, PSE_V + w_T PSE_T + w_T\ \Delta) \end{aligned}$$

where $\Delta = s_V - s_T$ is the conflict between the visual and tactile cues. The PSE in the bimodal conditions predicted the MLE is therefore

$$PSE_{B,\Delta} = w_V PSE_V + w_T PSE_T + w_T \Delta \tag{4}$$

If the two cues are inconsistent ($\Delta \neq 0$), the above equation shows that the PSE is shifted by an amount that is proportional to the tactile weight $w_T\Delta$. This equation also predicts the PSE for the visual dominance hypothesis ($w_V = 1$ and $w_T = 0$) and tactile dominance hypothesis ($w_V = 0$ and $w_T = 1$). In particular, the bimodal PSE$_{VT}$ under the visual dominance hypothesis should correspond to the unimodal PSE$_V$ and not be affected by the conflict Δ since $w_T = 0$. In contrast, the bimodal PSE$_{VT}$ under the tactile dominance hypothesis should correspond to the unimodal tactile PSE$_T$ ± Δ. Finally, the best modality hypothesis corresponds to the visual or tactile dominance hypothesis depending on which modality has the lowest discrimination threshold.

In summary, the optimal integration hypothesis yields two predictions that can be tested experimentally in the bimodal conditions. First, the bimodal discrimination thresholds should be lower than the unimodal thresholds. Second, the PSEs should be shifted toward the most reliable cue in proportion to the relative reliability (or weight) of that cue, which can be demonstrated experimentally when there is a conflict between the two cues.

Data analysis

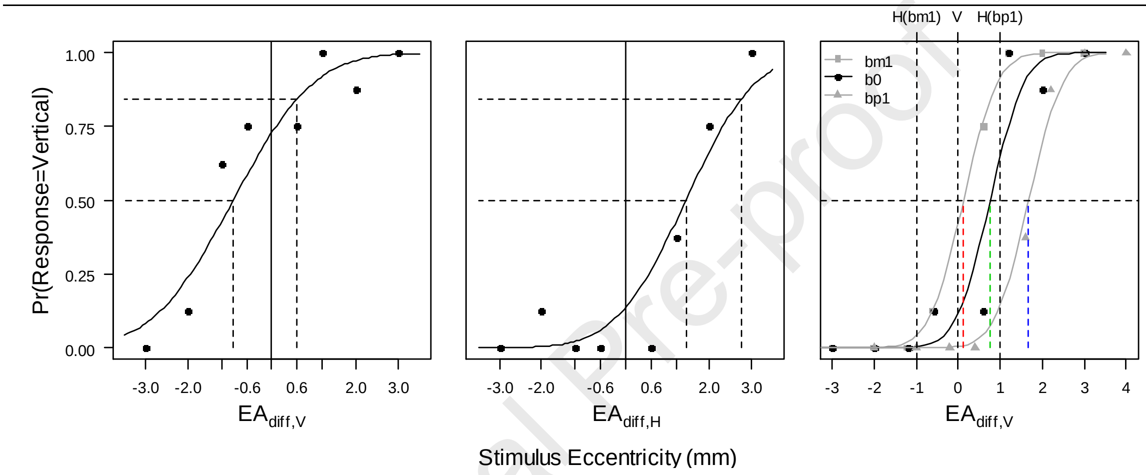

Figure 2. Psychometric functions from a control participant. The cumulative normal psychometric curves represent the probability of perceiving the ellipse as vertically oriented as a function of the actual ellipse eccentricity (EA_{diff}). In the unimodal condition, the vertical solid line indicates the circular shape. The dotted line corresponding to 50% indicates the Point of Subjective Equality (PSE) and the horizontal distance between the two vertical dotted lines corresponds to the 84% discrimination threshold (DL). In the bimodal conditions, data from the three conditions were fitted together using a common slope but a different intercept model. The vertical lines represent the prediction of the Maximum Likelihood Estimation (MLE) model (in absence of biases) if the participant relied only on the tactile modality to judge the shape of the ellipses. In contrast, the psychometric curves should overlap if the participant relied only on the visual modality.

The responses of each participant in each condition were fitted with a cumulative normal probability distribution using maximum likelihood estimation to obtain a psychometric function representing the probability of judging the stimulus as vertically oriented (see Fig. 2). The three bimodal conditions were fitted together, with a common slope but a different intercept for each condition. The psychometric functions in the bimodal conditions were computed as a function of the eccentricity of the visual cue and the shift between them reflects the influence of the tactile cue. For each psychometric curve, we computed the PSE, i.e. the ellipse that was perceived as vertically oriented in 50% of the trials and was thus perceived as a circle. The discrimination threshold (DL)–-

or Just Noticeable Difference (JND) – was defined as the difference between the PSE and the ellipse that was perceived as vertically oriented in 84% of the trials. The DL corresponds to the standard deviation of the normal distribution underlying the psychometric function and is an estimate of noise σ associated with the unimodal or bimodal cues (see equations 2 and 3).

For each participant, we computed the weight of each cue (eq. 2) and the optimal DL predicted by MLE from the unimodal DLs (eq. 3). The data of one AN patient was not included in the analyses because she could not perceive the eccentricity of the ellipses in the tactile modality at all (DL_H = 64.19) and also had a large threshold in the visual and bimodal conditions (DL_V = 3.11; DL_B =3.00)

We used a two-way mixed ANOVA with the group as a between-subject factor and the experimental condition (visual, tactile and bimodal) as a within-subject factor to analyze the PSEs and DLs in the unimodal and bimodal conditions. The ANOVA was followed by Tukey post-hoc tests to test the difference between groups pairwise. Then, we used paired t-tests to compare the observed PSEs or DL with the corresponding predicted values. Finally, we performed a Canonical Correlation Analysis (CCA) between the psychophysical and clinical variables in order to find the two linear combinations (or canonical variables) that are maximally correlated with each other.

To give some indication of the power of the study, we report the power of various t tests and two-way mixed ANOVAs to detect meaningful differences between groups or experimental conditions. With respect to the PSE, we computed the power of one-sample t tests to detect a 5% distortion of the ellipse ($EA_{diff} \approx 0.5$ mm, Cohen's effect size $d = EA_{diff}/s_{PSE} = 0.5/0.42 = 1.19$), the power of independent-sample t tests to detect a 5% distortion between groups (d = 1.19), and the power of paired t tests to detect the effect of the conflict predicted by the optimal integration hypothesis in the bimodal conditions ($d = w_T \Delta / s_{PSEdiff} = 0.5 \cdot 1/0.52 = 0.96$, see eq. 4). The power of these tests ranged 72% to 99% depending on the size of the group (in general t test involving the BCHC group were less powerful). With respect to the DLs, we computed the power of paired t test to detect the increase of sensitivity in the bimodal prediction predicted by the optimal integration hypothesis, which corresponds approximatively to a 30% decrease of the bimodal threshold assuming equal unimodal thresholds (see eq. 3). The corresponding effect size is $d_z = 0.3\ DL_u/s_{DLdiff} = 0.3 \cdot 1.55/\ 0.49 = 0.94$, where DL_u is the average DL in the unimodal conditions of the pilot experiment. The power ranged from 68% for the BCHC group to 96% for the HC group. We also computed the power of a two-sample test to detect a 30% change in the DLs between two groups. The effect size was smaller ($d = 0.3 \cdot DL_u / s_{DL} = 0.3 \cdot 1.55/0.60 = 0.775$) because the standard deviations in the pilot experiment were larger. The power ranged from 43% for a difference between AN and BCHC group to 60% for a difference between the AN and HC group. Finally, we used simulations to compute the power of two-way mixed ANOVA contrasting the three groups and three conditions with the same assumptions as for the t tests (Kerns, 2020). For the DLs, the power for the group, condition and interaction effects was 81%, 98% and 76% respectively. For the PSEs, the power of the two-way mixed ANOVA was above 99% for all effects. Power analyses are sensitive to changes in the parameter values and should be taken only indicatively. Estimates of the variability of the discrimination thresholds and PSEs s_{DL} and s_{PSE} were obtained by pooling together the results of the pilot studies. We used the results of the main study to compute the standard deviations $s_{PSEdiff}$ and s_{DLdiff} of the difference for each subject between the PSEs or DLs in each sensory modality because different subjects participated to the tactile and visual conditions in the pilot experiments. All analyses were conducted with R version 3.6.1 (R Core Team, 2010).

Results

Table 3. DLs and PSEs in unimodal and bimodal conditions for each experimental group.

Mean± Median Absolute Deviation (MAD) adjusted to give a robust estimate of the standard deviation

	PSE		DL		
	Visual	**Tactile**	**Visual**	**Tactile**	**Bimodal**
HC	-0.11 ± 0.53	0.54 ± 0.45	1.18 ± 0.28	0.90 ± 0.34	0.68 ± 0.18
BCHC	0.03 ± 0.35	0.71 ± 0.24	1.24 ± 0.52	0.96 ± 0.33	0.87 ± 0.18
AN	0.10 ± 0.31	1.07 ± 0.55	2.05 ± 0.65	1.40 ± 0.28	1.18 ± 0.37

Table 3 reports the Point of Subjective Equalities (PSEs) and Discrimination Thresholds (DLs) in the unimodal conditions for each group and the standard deviation of the individual differences between the PSEs or DLs in the two unimodal conditions. The table includes also the common slope of the psychometric functions fitted to the three bimodal conditions together (see Fig. 2).

Unimodal conditions

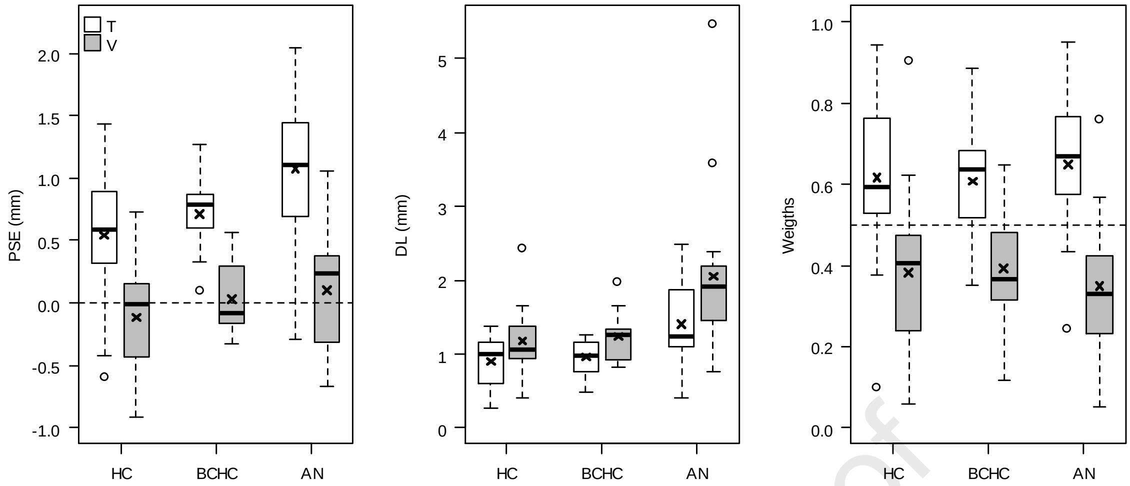

Figure 3. Points of Subjective Equality (left), discrimination thresholds (middle) and weights (right) in the unimodal conditions (T: tactile, V: visual). The boxplots show the means (crosses), the median (horizontal bars) and inter-quartile range (boxes). The whiskers extend to the most extreme data point, which is no more than 1.5 times the IQR.

Figure 3 (left panel) shows the PSEs for the three groups in the unimodal visual and tactile conditions. In the unimodal conditions, the tactile PSE increased on average from 0.5 mm (5%) for the HC to 1.07 mm (11%) for the AN group while the visual threshold increased from -0.1 mm to 0.1 mm for the same two groups (see Table 3). This positive bias of the PSE in the tactile modality, which increased for the AN group, indicates that vertically elongated ellipses were perceived as circular, and corresponds to a widening or fattening of the ellipse. One-sample t tests confirmed the PSEs were significantly different from 0 in the tactile modality (HC: *t* (18) = 4.45, *p* < .001, d= 1.02; BCHC: *t* (8) = 6.13, *p* < .001, d =2.04; AN: *t* (15) = 7.25, *p* < .001, d=1.81), but not in the visual modality (HC: *t* (18) = -1.03, *p* = .32, d=0.24; BCHC: *t* (8) = -0.34, *p* = .74, d=0.11; AN: t (15) = 0.84, p =.41, d=0.21). A two-way mixed ANOVA on unimodal PSEs showed an effect of sensory modality (F(1, 41) =37.89, p<.001, η_P^2=0.48) and group (*F* (2, 41) = 7.06, *p* <.01, η_P^2=0.11). The interaction between the group and condition was not statistically significant (F (2, 41) = 0.79, p= .46, η_P^2=0.02). Pairwise t-tests confirmed a statistically significant difference between the tactile and visual modality for all groups (HC: t(18)=-3.44, p<.01, d_{rm}=1.29; BCHC: t(8)=-3.66,p<.01, d_{rm}=2.05; AN: t(15):=-4.65, p<0.001, d_{rm}=1.80). The Tukey pairwise comparison within sensory modalities showed a statistically significant difference only between the HC and AN groups in the tactile modality (t(75.9)=-3.20, p<0.01).

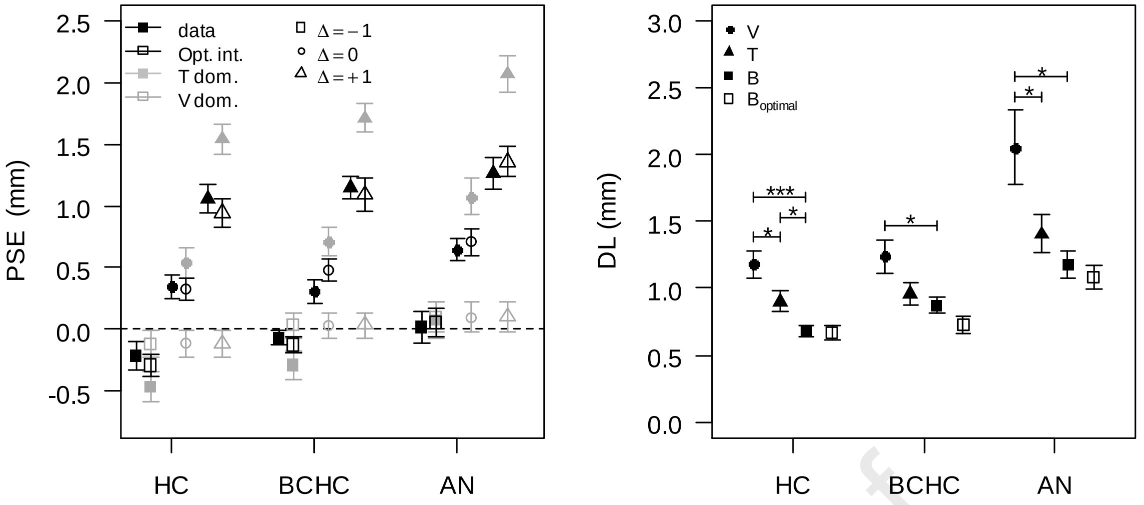

Figure 4. Points of Subjective Equality and Discrimination thresholds in bimodal conditions. *Left*: Average point of Subjective Equality (±SE) in bimodal conditions. Observed (*black solid* symbols) and predicted (*grey* or *empty* symbols) in the bimodal conditions (*black empty*: optimal integration hypothesis, *grey solid*: tactile dominance hypothesis, *grey empty*: visual dominance hypothesis). In the consistent bimodal condition (*circles*), the PSEs for the visual and tactile dominance hypotheses correspond to the PSEs in the unimodal conditions. In the inconsistent bimodal conditions (*squares* or *triangles*), the PSE for the visual dominance hypothesis corresponds to the unimodal condition and is not affected by the conflict since $w_h = 0$ in equation 4. In contrast, the PSE for the tactile dominance hypothesis corresponds to the unimodal $PSE_H \pm \Delta$ (see eq. 4). *Right*: Discrimination thresholds. Average discrimination thresholds (±SE) in the unimodal (*circles* and *triangles*) and bimodal (*squares*) conditions. The *empty squares* ($B_{optimal}$) corresponds to the average discrimination threshold predicted by the optimal cue combination model, which was computed for each subject (see eq. 3). The stars indicate the p value of the corresponding paired t tests (*: p<.05; **; p<.01; ***: p<.001; see also text).

The discrimination thresholds in the visual condition were larger than in the tactile condition for all groups (HC: $t(18) = 2.39$, $p = .03$, $d_{rm}=0.69$; BCHC: $t(8) = 2.12$, $p = .07$, $d_{rm}=0.83$; AN: $t(15) = 2.34$, $p =.03$, $d_{rm}=0.71$). The unimodal discrimination thresholds increased for the AN group with respect to the two other groups. These two effects were confirmed by a mixed ANOVA that showed a main effect of group ($F(2, 41) = 9.94$, $p < .001$, $\eta_P^2=0.33$) and condition ($F(1, 41) = 10.85$, $p <.01$, $\eta_P^2=0.21$). The interaction between groups and conditions was not significant ($F(2, 41) = 1.18$, $p = .32$, $\eta_P^2=0.05$).

Finally, we computed the weight for each sensory condition (see eq. 2). The average weight of the somatosensory cue increased slightly from the HC control group (0.62±0.20) to the AN group (0.65±0.17; see right panel of Fig. 3). A one-way ANOVA revealed that the difference across groups was not statistically significant ($F(2,41) = 0.10$, $p = .90$). Only the tactile weight was included in this analysis because the sum of two weights is equal to one by definition.

Bimodal conditions and optimal Integration

Optimal integration makes two predictions in the bimodal conditions: i) the PSEs should be shifted toward the most reliable cue in proportion to its relative reliability (or weight) when there is a conflict (see eq. 1 and 2) the bimodal discrimination thresholds should be lower than the unimodal thresholds.

Figure 4 (left panel) shows the PSEs in three bimodal conditions for each group (black solid symbols) and the predictions according to the visual dominance hypothesis (grey empty symbols), tactile dominance hypothesis (grey solid symbols) and optimal integration hypothesis (black empty symbols). A two-way mixed ANOVA of the bimodal PSEs revealed a statistically significant effect of the conflict Δ (F(2, 82)=163.14, ε=0.86, p<.001, η_P^2=0.80), which indicates that the PSEs, which are expressed relatively to the eccentricity of the visual ellipse (see Methods), are influenced by the tactile cue. The small increase in the PSEs of the BCHC and AN groups relative to the HC groups was not statistically significant (*F* (2, 41) = 2.08; *p* = .14, η_P^2=0.09). The interaction was also not statistically significant (*F* (4, 82)=0.58, ε=0.86, *p* = .66, η_P^2=0.03).

Figure 4 also shows that the average PSEs in the bimodal conditions (black solid symbols) were close to the value predicted by the optimal integration hypothesis (black empty symbols) for all groups and conditions. Paired t tests confirmed that the differences were not statistically significant (p>0.05). Moreover, the actual PSEs differed markedly from the PSE predicted by the visual and tactile dominance hypotheses in bm0 (Δ=0) and bp1 (Δ=+1) bimodal conditions where these predictions differed from the optimal integration prediction.

Figure 4 (right panel) shows the discrimination thresholds in the unimodal and bimodal conditions. A one-way ANOVA on the bimodal thresholds showed a significant effect of group (F(2,41) = 13.3, p<.001, η^2=0.39), which reflects the worse performance by the AN group relative to the BCHC group and HC group as in the unimodal conditions. In order to test whether the visual and tactile cues are integrated optimally, we compared the observed (B) and predicted (B optimal) bimodal thresholds. For the three groups, the difference was not statistically significant (HC: t(18)=0.26, p=.79, d_{rm}=0.09; BCHC: t(8)=1.38, p=.20, d_{rm}=0.77; AN: t(15) = 0.81, p = .43, d_{rm}=0.25). As predicted by the optimal integration hypothesis, the bimodal thresholds were lower than the visual threshold for the three groups (HC: t (18) = -4.27, p <.001, d_{rm}=1.44; BCHC: t(8) = -2.56, d_{rm}=1.21, p = 0.03; AN: t(15) = -2.83,p = 0.01, d_{rm}=1.06) and lower than the tactile threshold but only for the HC group (t(18) = -2.26, p=.04, d_{rm}=0.80). In fact, the bimodal thresholds are also compatible with the tactile dominance hypothesis for the BCHC and AN groups because the difference between the tactile and bimodal thresholds was not statistically significant (BCHC: t(8) =-0.65, p = 0.53, d_{rm}=0.40; AN: t(15) = -1.61, p = 0.13, d_{rm}=0.45).

Canonical Correlation and Classification Analysis

In this section, we examine the relation between the psychophysical and clinical variables, and whether it is possible to use psychophysical scores to classify controls and patients.

The objective of the Canonical Correlation Analysis is to find the linear combination of clinical variables (BMI, BSQ and EDI) that is best correlated with a linear combination of psychophysical variables, which included the two PSEs and DLs in the unimodal conditions and the DL in the bimodal condition.

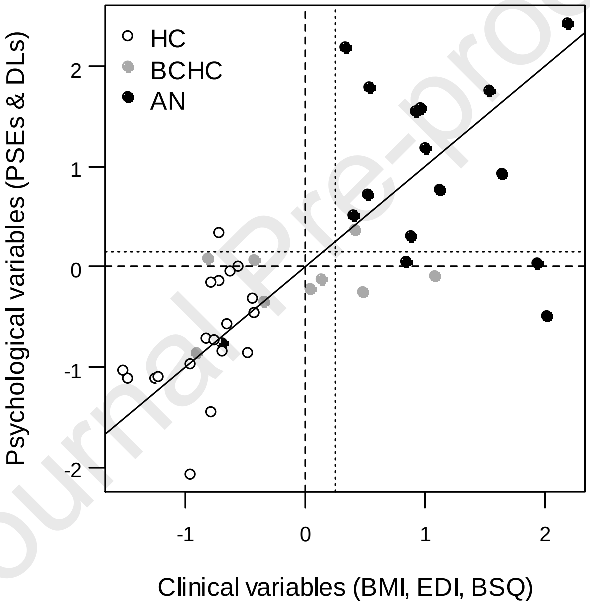

Figure 5. Canonical Correlation Analysis. The solid line corresponds to the regression line. The dashed lines separate the HC group from the AN group while the dotted lines separate the HC and BCHC groups from the AN group.

The two first canonical variates were highly correlated (r = 0.704: Wilk's lambda test: F(15, 99.782) = 2.076, p = .017), indicating that psychophysical and clinical variables share a lot of information. The first canonical variable for the clinical scores gave higher weights to EDI-2 and BMI scores (standardized canonical coefficients: EDI-2 = 0.073, BMI = -0.074, BSQ = 0.037). For the psychophysical scores, the weight was largest for the unimodal PSEs and the tactile and bimodal DLs (PSE_V = 0.067; PSE_T = 0.089; DL_V = 0.001; DL_T = 0.051; DL_B = 0.055). The correlation within each group ranged from 0.19 for the AN group to 0.51 for the HC group, indicating that the global correlation was primarily driven by the difference between groups.

Canonical variates can also be used to classify patients by identifying thresholds that break the continuous values into two or three regions. The first canonical variate based on clinical variables separated the HC (white dots) and AN (black dots) groups almost completely (34/35 or 97% these women were classified correctly), which might be expected since BSQ was used as a criterion to define the BCHC group and the BMI of AN patients differed markedly from both control groups. Interestingly, 91% (32/35) of women belonging to the HC and AN groups were classified correctly by the psychophysical variables in this analysis. The BCHC women formed an intermediate group between the HC and AN groups (grey dots). If one puts together both control groups, the clinical and psychophysical variates correctly classified 91% (40/44) and 89% (39/44) of the women in these two groups respectively.

To assess the significance of these results, we compared the percentage of correct classifications between healthy controls (combining HC and BCHC groups) and AN patients obtained with different methods using leave-one-out cross-validation. The percentage of correct classifications based on psychophysical variables was 80% for the canonical correlation, 89% for logistic regression and 93% for linear discriminant analysis. In comparison, the percentage of correct classifications based on clinical variables was 87% for canonical correlation, 91% for logistic regression and 89% for linear discriminant analysis. These results show that methods like the logistic regression and the linear discriminant analysis are better at classifying participants. The classifiers based on clinical variables included only three variables and usually performed better. On the other hand, we did not attempt to optimize the set of psychophysical variables.

Discussion

The perceptual deficits in Anorexia Nervosa form a disparate set. Psychophysical tasks such as the one used in this study allows one to measure precisely two different but complementary aspects of perception. The points of subjective equality (PSEs) measure the accuracy, veridicality or bias of the perception (e.g. the strength of an illusion), while the discrimination thresholds measure the precision of the perception (e.g. the sensory acuity or noise in a sensory channel). The task used in this study allowed us to measure and compare the visual and tactile biases and performance in the perception of the shape of small ellipses. Finally, in the bimodal condition, this task also allows one to investigate multi-sensory integration processes, asses the weights given to each sensory modality and test the optimal integration hypothesis.

The first section of this discussion is focused on the large tactile biases observed in controls and patients with AN. Then, we compare the discrimination performance and multisensory processes of these two populations. The next sections are focused on the results of the control group with body concerns and how psychophysical variables correlate with clinical ones. Then, we identify the pathways that might be at the origin of the perceptual distortions observed in this study in a model that integrates tactile and visual input with body and object representations. Finally, we discuss the limitations of the study before summarizing the main findings in the conclusions.

Distortions of ellipses' shape

A first motivation for the study was to investigate the perceptual biases in the different sensory modalities and populations. While the ellipses' eccentricity was perceived vertically in the visual modality, all groups notably overestimated the width of the ellipse relative to its height. The shape distortion was about 5% for the healthy control group, 7.1% for the healthy control group with body concerns and 11 % for the AN group. In contrast, the ellipse shape was perceived almost vertically in the visual modality, with a difference of less than 2% between the three groups.

The observation that healthy individuals perceived the ellipses as wider in the tactile modality differs from the results of the original study by Helbig and Ernst (2007). A possible explanation for this discrepancy is that hand orientation can affect the perceived shape of our stimulus. Participants in our study touched the ellipse with the fingertip aligned or close to the vertical direction without moving. In contrast, the participants in Helbig & Ernst's (2007) study appeared to touch the ellipses with an angle close to 45 degrees (see figure 2 in Helbig & Ernst 2007). Our results are in agreement with studies showing that the perceived size of objects is larger when the objects are oriented medio-laterally across the hand rather than proximo-distally (Longo & Haggard, 2011; Longo, 2017a;).

Importantly, we also found that AN patients overestimated the ellipses' width more than the control group. This observation is in agreement with various reports that AN patients overestimate the distance between two points on the skin in an distorted way (Keizer et al., 2011; Keizer et al., 2012; Spitoni et al., 2015; see also Introduction). The classical explanation for size or shape distortions in the tactile modality is that the density of tactile receptors affects the cortical representation of tactile stimuli in the primary somatosensory cortical area. The presence of biases in the haptic perception of the size of objects *across different body parts* is a classic observation known as Weber's illusion. Typically, the perceived size of an object touching the skin (or the perceived distance between two points) decreases in body parts with lower tactile acuity and mechanoreceptor innervation. However, the spatial density of mechanoreceptors does not explain Weber's illusion fully. First, the distortion is attenuated with respect to the actual variations in receptor density and tactile acuity. The magnitude of Weber's Illusion is only 10% of what would be predicted considering the variation in tactile acuity or mechanoreceptor density across skin regions (Taylor-Clarke et al., 2004). Second, the magnitude of the distortion can be further reduced by manipulating the size of the body visually (Taylor-Clarke et al., 2002). These findings show that perceptual distortions also involve higher level, possibly multimodal mechanisms that partly compensate for low-level distortions (Longo & Haggard, 2011).

The results of our study, however, cannot be explained in this manner. As a matter of fact, there is little evidence that receptor density changes *within* a body part and, in particular, that the density of mechanoreceptors is higher in the medio-lateral direction with respect to the proximo-distal direction. To explain this type of distortion, Longo & Haggard (2011) have suggested that it might be caused by the shape of tactile receptive fields (RFs), which are typically more elongated along the proximo-distal axis with the long axis being about twice the length of the short axis (RFs; Brooks et al., 1961; Brown et al., 1975; Powell & Mountcastle, 1959). While this is a possibility, Longo & Haggard (2011) also note that the magnitude of the distortions is typically smaller. In fact, the magnitude of the tactile distortions observed in our study amounted to only 10% of the ellipse size, much less than the 50% that might be predicted from the RF eccentricity. If the shape of the RF field played a role in the distortion, this observation suggests that higher level compensatory processes would attenuate the distortion (Taylor-Clarke et al. 2004). Alternatively, if the shape of the RF did not play a role, then this distortion would necessarily originate at a higher level of somatosensory information processing.

That the AN patients perceived the shape of the ellipses as more distorted than did the controls reinforces the idea that higher-level processes play an important role in any explanation of the observed spatial distortions. As a matter of fact, there is no evidence that mechanoreceptor density and/or the shape of their RFs change in AN with respect to healthy controls. In fact, the results of our study, like those of Spitoni et al. (2015), suggest that higher-level processes involved in the tactile perception of distances or shapes function abnormally in AN. While it is not possible to exclude a priori that different mechanisms underlie the observed perceptual distortions in healthy controls and AN patients, the simplest explanation is that the same processes are involved in both cases.

Discrimination Thresholds

The second motivation for the study was to find out whether AN would affect the reliability of the visual and tactile cues. We found that the tactile and visual discrimination thresholds increased for the AN group relative to the control group, which indicates that patients with AN were worse at discriminating the ellipses shapes than the control group in both sensory modalities. Interestingly, we did not find a statistically significant difference between the two control groups, which suggests that the decrease in reliability of the sensory cues has an origin that is specific to AN.

As reviewed in the Introduction, there is some discrepancy in the literature about the presence of low-level sensory deficits. However, most studies including patients with AN restricting type and a severe degree of malnutrition like our group found that visual or somatosensory acuity decreased in these patients (Caire-Estévez et al., 2012; Epstein et al., 2001; Spitoni et al., 2015). Accordingly, the increase of tactile and sensory threshold in our study might reflect a reduced capacity to reliably estimate the dimension of the ellipses, due to a decrease in the tactile and visual acuity of our patients (sensory thresholds are classically interpreted as a measure of noise of the corresponding sensory cues in Psychophysics, see Gescheider, 1997).

A possible problem with our interpretation is that our task is not a direct measure of sensory acuity since judging the shape of an ellipse requires comparing the extension of the ellipse along two orthogonal axes. Thus, it is not possible to exclude that the higher thresholds observed in our study might reflect a limit in the precision of the comparison process rather than the precision with which each dimension is estimated. It would be useful to add such a measures in future studies.

Another possible problem with our interpretation of the observed increase DL in AN is that some studies that used a Signal Detection Theory framework found that AN patients were not worse at discriminating body shapes than controls in the visual modality (Gardner & Moncrieff, 1988; Smeets et al., 1999). However, the mean BMI (15.15 ± 2.64) and weights (39.8 ± 6.9 kg) of AN patients in our study was markedly lower than in those studies (BMI in Smeets et al. 2009: 17.74 ± 2.95; mean weight in Gardner & Moncrief, 1988: 44.6 kg). This difference between the patients might explain why these studies did not find an effect on the sensitivity.

Another question related to the discrimination thresholds is whether patients with AN give more *weight* to somatosensory inputs than to the visual ones (Eshkevari et al., 2012; Longo, 2015) or viceversa (Case et al., 2012). To address this question we computed the weight of each of the sensory cues for each group. In the optimal integration theoretical framework, the weight of a cue is proportional to its reliability and normalized with respect to the other sensory cues (see eq. 2). The weight of the tactile cue slightly increased by about 4% in the AN group with respect to the HC or BHCH group. However, there was considerable overlap between the groups and the difference was not statistically significant. Our study does not bring strong evidence supporting the idea that the reliability of the tactile cues changed relative to the reliability of the visual cues. Further research with a larger sample and/or different stimuli is needed to find out whether AN affects the weight of the tactile and visual cues.

Multisensory Integration

The third motivation and main objective of this study was to test the hypothesis presented in the Introduction that body shape distortion in AN might be linked with an aberrant multisensory integration process (Case et al., 2012; Eshkevari et al., 2012). More specifically, the aim was to directly test whether AN patients integration multi-modal sensory information optimally (see Methods). Our results show that the PSEs in the bimodal conditions corresponded to the values predicted by the optimal integration hypothesis. They also differed clearly from the values predicted by the tactile or visual dominance hypotheses for all three groups. In summary, the analyses of the PSEs in the bimodal conditions with and without conflict indicate that AN patients integrated tactile and visual processes optimally like the two other control groups. In contrast, the analysis of the bimodal discrimination thresholds provided less clear-cut results. For the HC group, we found that the bimodal thresholds were on average lower than the two unimodal thresholds and did not differ from the predicted optimal threshold in agreement with previous findings (Helbig & Ernst, 2007). For the BHCH and AN groups however, the evidence was less conclusive because the magnitude of the bimodal DLs was close to the tactile threshold or in between the tactile thresholds and the optimal threshold. For both groups, the difference between the bimodal threshold and either the tactile or the optimal threshold was not statistically significant. As noted in the Results, the bimodal thresholds for these two groups are compatible with both the tactile dominance hypothesis and the optimal integration hypothesis. Indeed, the tactile threshold did not differ either from the bimodal threshold or from the optimal threshold.

Body Concerned Healthy Control Group

A secondary objective of the study was to investigate whether body concerns can be linked to perceptual deficits or whether these deficits are specific to AN. Initial evaluation revealed that some healthy controls had body satisfaction scores in the range of the AN patients even though these participants had no history or diagnosis of Eating Disorders and a healthy BMI. To assess whether some perceptual deficits might be linked to body concerns and not specific to AN, we decided to split these participants in two control groups and analyze the BCHC group separately from the HC group who did not have the same body concerns.

With respect to the perceptual biases, we found the PSE of the BCHC participants were somewhere in the middle between the HC and AN groups in all conditions (see Fig. 3 for unimodal conditions and Fig 4 for bimodal conditions). These results suggest that body concerns might be associated with a perceptual bias, independently of the AN diagnosis. Interestingly, previous studies investigating the relationship between perception and body satisfaction found a positive correlation between body satisfaction and tactile perception performances in patients with AN (Keizer et al., 2011; Spitoni et al., 2015). Moreover, Taylor & Cooper (1992) showed that the induction of low mood in a sample of female students led to greater disturbances in body size perception in the form of a more severe tendency to overestimate their body size, and significantly greater dissatisfaction with their body size. Furthermore, among the women who received the negative mood condition, the induction of low mood led to greater disturbances in body size perception (i.e. overestimating their body size significantly more and feeling greater dissatisfaction with their body size) in those who had body shape concerns compared to those with little or no concern with their body shape. Together, these results reinforce the hypothesis of a link between a distorted Body Representation and body dissatisfaction.

In contrast to the PSE, the discrimination thresholds of the BCHC participants did not differ from the HC. In particular, the DLs of the BCHC group did not increase in the unimodal conditions. This result suggests that body dissatisfaction affects the more abstract cognitive model of the body, but not the elementary sensory processing of the participants.

With respect to multisensory integration processing, the results on the discrimination thresholds are not fully conclusive. Overall, we believe that the PSEs provide strong evidence that this group integrated tactile and visual information in the bimodal condition like the two other groups and that this study does not support the idea that *multi-sensory integration processes* involved in the visuo-tactile perception of 2D shapes are specifically affected by AN and/or body dissatisfaction.

Canonical Correlation Analysis

The last objective of this study was to find out whether perceptual biases are correlated with clinical scales characterizing eating disorders and body shape concerns. The main result of the canonical correlation analysis was that the first pair of canonical variates was highly correlated, indicating that psychophysical and clinical variables could categorize patients and controls in their respective group. While the correlation was driven more by group differences than by individual differences, the results of this analysis still suggest that evaluating the perceptual abilities of the patients could provide information that might be relevant clinically. Psychophysical variables classified AN patients and the control group without body concerns almost as well as clinical variables. In both cases, the women with body concerns were distributed in the middle with scores that partially overlapped the two other groups. We believe that this preliminary result should encourage further studies to investigate perceptual processes that might potentially help the clinician in the diagnosis.

An integrated model of perceptual deficits in Anorexia Nervosa

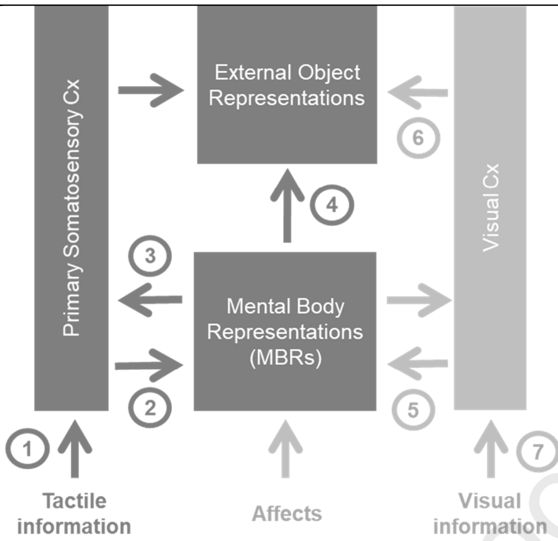

Figure 6. Relation between Mental Body Representations (MBrs) and External Object Representations (adapted and extended from Serino & Haggard 2010). Dark grey circles 1 to 4 identify the pathways discussed in Serino & Haggard (2010). Light grey elements extend the original figure and are discussed in the text. Pathway 1 connects the body to "the somatosensory homunculus", which is topographically organized and reflects the density of mechanoreceptors in the skin. Pathway 2 connects this area to higher-level representations of the body, such as body image, body schema or the superficial schema, which are involved in perception and/or action (Head & Holmes, 1911) (Lloyd et al.,2003; Taylor-Clarke et al., 2002). Pathway 3 represents a top-down influence that might enhance or inhibit low-level tactile processing (Tipper et al., 1998; Taylor-Clarke et al., 2002). Finally, Pathway 4 mediates the formation of object representation from primary tactile sensations (see text).

In a review of somatosensation, Serino & Haggard (2010) developed a model of the interactions between tactile information and body representations in the brain (see Fig. 6). According to this model, the influence of MBRs might partially compensate for spatial distortions that originate from primary somatosensory contexts that are related to variations in mechanoreceptor density across body parts (Taylor-Clarke et al., 2004; Longo & Haggard, 2011). Importantly for the interpretation of our results, this model posits the existence of a pathway (Pathway 4) that mediates the formation of object representation from primary tactile sensations. This pathway would not provide direct information about the tactile object (Pathway 6) but a reference that modulates the perception in a top-down manner. For example, this pathway would explain how manipulating the size of a body part visual (via Pathway 5) can affect the tactile size of the object being touched (Taylor-Clarke et al., 2004).

Although AN is not discussed in Serino and Haggard (2010), their model is useful to interpret the results of our study. First, as noted in the introduction, there is considerable evidence that all MBRs are distorted in this disease. For our study, the most relevant MBR is probably the superficial schema, which mediates the formation of object representations from primary tactile sensations by providing a reference frame and metrical information about the position and size of the tactile stimulus on the skin (Pathway 4). In this framework, the widening of the ellipses' shape observed in AN suggests that the superficial form, like body image and body schema, is distorted in AN. Moreover, the fact that healthy controls with body concerns perceived the shape of the ellipse as wider than healthy controls without body concerns suggests this distortion of the superficial form is not specific to AN but more generally related to body satisfaction and even, possibly, mood (Taylor & Cooper, 1992). In our opinion, it would also make sense to hypothesize that similar but relatively smaller distortions of the superficial form might be at the origin of the perceptual errors of the healthy group without body concerns. This explanation would be in line with the observation that healthy controls perceive body parts as larger than they really are (Longo & Haggard, 2011).

In contrast, the increase of the discrimination thresholds, which is specific to the AN group in the visual, tactile and bimodal conditions might be attributed to a less precise processing of tactile (Pathway 1) and visual (Pathway 7) information. As discussed previously, this interpretation would be in line with previous results on elementary visual and somatosensory perception in patients with AN.

Limitations of the study

The first limitation of the study is the small sample size, in particular for the BCHC group, which primarily affects the power of the comparison among groups. A larger sample size would be needed to perform a reliable within-group correlation analysis since it is known that sample correlations are inaccurate in small sample sizes (Schönbrodt & Perugini, 2013) and sensitive to outliers (Wilcox & Rousselet, 2018). The small size of the BCHC group is due to the difficulty to target this population since it is not known in advance whether the healthy controls will have body concerns comparable to AN patients.

The second limitation of the study is the precision with which discrimination thresholds were measured. In our study, each condition included 64 trials, which is less than the 192 trials per condition used in the Helbig & Ernst (2007) study. The number of trials was limited by the duration of the experiment and availability of AN patients to participate in more sessions. Since a larger number of trials is necessary to estimate the discrimination thresholds with the same precision as the PSEs (King-Smith & Rose, 1997), it is possible that the weak correlations between observed and predicted thresholds in the bimodal conditions within groups might simply reflect the lack of precision in the estimation of the individual discrimination thresholds. A limited number of trials, however, does not invalidate comparison between conditions and/or groups since increasing the number of participants increases the precision of average value. In this respect, it might be noted that the sample size of the HC and AN groups in our study was larger than the number of participants in the original study by Helbig & Ernst (2007) (10 participants).

The third limitation of the study is the difference between the visual and tactile discrimination thresholds in the control group. To test the optimal integration hypothesis, it would be desirable to equalize the two thresholds because this hypothesis predicts that the gain in the bimodal condition is largest when the two sensory cues are equally reliable. When this is not the case, it becomes more difficult to distinguish between the best modality hypothesis and the optimal integration hypothesis because the predictions of the two hypotheses in the bimodal conditions become more similar. In our study, the two unimodal thresholds differed in all groups despite having been adjusted following a pilot study with a different group of healthy participants. The difference was larger for the BHCH and AN groups, which rendered the results more difficult to interpret. In fact, the thresholds in the bimodal conditions did not differ in a statistically significant manner from the threshold observed in the tactile modality and/or from the threshold predicted by the optimal integration hypothesis.

Conclusion

The experimental paradigm in this study allowed us to measure the bias and the reliability of tactile and visual stimuli, separately and together. In this study, we related these two measures of sensory processing to different parts of Serino and Haggard's (2010) model of somatosensation and we proposed that the observed perceptual deficits might be caused by different dimensions of Anorexia Nervosa. First, we suggest that the perceptual biases observed in our study could be caused by distorted mental representations of the body and that body dissatisfaction might contribute to this perceptual distortion in AN patients and healthy women who are particularly concerned about their bodies. Second, we hypothesized that the increase in the discrimination thresholds in the tactile and visual modality that was specific to the AN group might be related to a loss of tactile and/or visual acuity linked with the malnutrition status of the patients. Third, the paradigm used in this study allows us to make quantitative predictions about the performance in bimodal conditions to test different hypotheses about sensory integration. In this respect, our results suggest that AN patients, like the two control groups, integrated tactile and visual information optimally. This result, based on the analysis of the PSEs, should be confirmed with more precise measurements of the discrimination thresholds in the future. Finally, we believe that the study of perceptual deficits in AN might also bring benefits in the future to the clinical evaluation and understanding of Anorexia Nervosa and related eating disorders.

Credit Author Statement

GBB and GR designed the study and analyzed the data. GR supervised the data collection and wrote the first draft. RM helped with the selection of the patients. GBB, GR, RM, LB and SE edited and revised the manuscript.

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Title:

Visuo-tactile shape perception in women with Anorexia Nervosa and healthy women with and without body concerns.

Highlights

- A **psychophysical** study of **visual, tactile** and **bimodal perception** of the shapes of small ellipses with Anorexia Nervosa patients and healthy women with body concerns.

- Patients with Anorexia Nervosa **distort** the shape of ellipses more than healthy controls in the **tactile modality**.

- Patients with Anorexia Nervosa **discriminate** the shape of ellipses **less well** than healthy controls in the **tactile, visual and bimodal conditions.**

- **Absence of multimodal sensory integration deficits** in this task does not support the multimodal integration impairment hypothesis.

- Healthy **women with body concerns** also tend to **distort the shape** of the ellipses but have **no discrimination deficit**.

We encourage you to submit an author statement file outlining all authors' individual contributions, using the relevant CRediT roles

Title:

Visuo-tactile shape perception in women with Anorexia Nervosa and healthy women with and without body concerns.

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