This is the author version of an article published as:


Access to the published version:
http://dx.doi.org/10.1016/j.psychres.2016.09.003

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Investigating body distortions in Anorexia Nervosa: Evidence for changed processing of multisensory bodily signals

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Abstract

Body size and shape distortion is a core feature of Anorexia Nervosa (AN)—patients experience their body as fat while objectively being very thin. The cause of this distortion is unclear and disturbances in body perception could be involved. Body perception comprises estimating shape and location of one’s body and requires integrating multisensory signals. We investigated if and how body location perception is changed and tested 23 AN patients and 23 healthy controls (HC) in a Rubber Hand Illusion (RHI) reaching paradigm. We presented two types of multisensory conflicts (visual-proprioceptive hand location; visual-tactile touch synchrony) and tested if the impact of visual-proprioceptive and visual-tactile signals on hand location perception differs between AN and HC groups. We found significant group differences in shifts of reaching trajectories, indicating that the influence of proprioceptive signals on hand location estimates is reduced in AN. Hand location estimates were relatively more biased towards external visual information, and shorter illness durations predicted a larger visual bias. Although touch synchrony also significantly influenced hand location estimates, this effect did not differ between groups. Our findings provide compelling evidence that multisensory body location perception - specifically the processing of visual-proprioceptive signals – is changed in AN.

Keywords: Anorexia Nervosa; body perception; reaching; hand location; multisensory; proprioception; rubber hand illusion paradigm
1. Introduction

Perceptual body size and shape distortion is a core clinical feature in Anorexia Nervosa (AN). Patients experience their own body or parts of their body as fat while objectively being very thin and also engage in extreme measures to lose weight, such as restricting food intake, vomiting and overexercising (American Psychiatric Association, 2013). The mechanisms that play a role in the development, maintenance and treatment of this extremely distressing and persistent disorder likely involve different factors and complex interactions that are not well-understood (Fairburn and Harrison, 2003).

One factor that might be important in AN is a change in body perception. Body perception involves the formation of mental models describing one’s body shape and location (Graziano and Botvinick, 2002; Longo et al., 2010). Such models are crucial for self-representations and interactions with objects and other persons in the environment (Graziano and Botvinick, 2002). Estimating body shape and location comprises the integration of multiple sources of sensory information — for example proprioceptive input from joints, muscles, tendons and skin-stretch-sensitive receptors, tactile input from skin receptors and visual input from retinal receptors (Botvinick and Cohen, 1998; Proske and Gandevia, 2012). These incoming multisensory signals are combined with internally stored body information (Apps and Tsakiris, 2014; Blanke et al., 2015; Carruthers, 2008; Kilteni et al., 2015). Multisensory body perception may be disturbed in AN, causing distortions or mismatches between how the body is perceived and what the body is physically like.

The Rubber Hand Illusion (RHI) can be used as an experimental paradigm to investigate multisensory body perception (Ehrsson, 2012). In the RHI setup, an artificial hand is placed next to the participant’s hand, which is hidden from view. Participants may then experience the viewed artificial hand as their own hand especially when both hands are stroked.
synchronously for some time (Botvinick and Cohen, 1998). Importantly, the RHI setup enables the researchers to present multisensory conflicts (for example visual-proprioceptive hand location; visual-tactile touch synchrony) to tease apart the relative influence of different sensory signals on the perception of body location (Shimada et al., 2009; Tsakiris and Haggard, 2005; Zopf et al., 2010; Zopf et al., 2011).

The extent of the RHI is often measured using explicit bodily judgements, where participants are asked to rate their agreement with statements such as “It seemed as if the rubber hand was my hand” on 7-or 10-point Likert scales (Botvinick and Cohen, 1998; Christ and Reiner, 2014; Longo et al., 2008; Zopf et al., 2010). Furthermore, the RHI changes the perception of hand location, determined by having participants report a number on a ruler or point to the position of the hidden hand (Botvinick and Cohen, 1998; Christ and Reiner, 2014; Longo et al., 2008; Zopf et al., 2010). The difference between hand estimates before and after inducing the RHI is often reported as ‘proprioceptive drift’ (Tsakiris and Haggard, 2005).

Previous studies found that eating disorder patients exhibit higher RHI scores (Eshkevari et al., 2012, 2014; Keizer et al., 2014). This suggests that eating disorder patients experience the RHI more strongly and that their body perception is more sensitive to visual body information. However, differences in explicit bodily judgements could reflect differences in body perception and/or cognitive-emotional factors. For example, eating disorders have been linked to increased perfectionism (Bardone-Cone et al., 2007), which could lead to more positive judgement responses because participants are motivated to comply with the experimental task. Furthermore, AN patients are dissatisfied with their bodies (Bruch, 1962), and thus may readily report changes in body ownership and perceived hand location.

Previous research assumed that hands are ‘emotionally neutral’ in eating disorders (Eshkevari et al., 2012, 2014; Keizer et al., 2014; Mussap and Salton, 2006). We directly test this
assumption with a body parts satisfaction scale (Petrie et al., 2002) that included an item for hands. Overall, we think that previous RHI findings do not provide compelling evidence that eating disorders involve changes in multisensory body perception because cognitive-emotional factors commonly associated with eating disorders can also influence explicit bodily judgements.

To avoid the direct influence of emotional-cognitive factors on perceptual measures, it is possible to employ implicit action-oriented tasks instead of explicit body-oriented judgements. Several researchers have employed implicit action-oriented measures to demonstrate the existence of perceptual body distortions in eating disorders (Guardia et al., 2010; Keizer et al., 2013; Nico et al., 2010). These studies have provided good evidence that eating disorders do involve a consistent mismatch between represented and physical body size.

Implicit action-oriented tasks tap into the (mostly unconscious) perception and representation of one’s current body location and posture (de Vignemont, 2010), known as the “body schema” (Gallagher, 2005). In contrast, explicit body-oriented judgements require conscious representations and also involve perceptual, conceptual and emotional information that is not directly used in actions. These types of representations are also known as “body image” (Gallagher, 2005).

Previously, we have shown that not just explicit body-oriented judgements, but also implicit action-oriented measures of body location are modulated by multisensory RHI manipulations (Zopf et al., 2010; Zopf et al., 2011). This work demonstrated that action-oriented tasks can be used to obtain implicit and objective measures for multisensory body location perception (Zopf et al., 2010; Zopf et al., 2013; Zopf et al., 2011). These tasks involve decisions and actions on stimuli near the body without explicit bodily judgements. In one study we
combined the RHI paradigm with a reaching task and participants reached towards visual targets on a touch screen after RHI manipulations (Zopf et al., 2011). Multisensory conflicts in the RHI change the estimation of hand location (Botvinick and Cohen, 1998), thus influencing the way that participants reach towards visual targets (Zopf et al., 2011). Because there is a mismatch between the new hand location estimate and the hand’s physical location, a constant reaching endpoint error towards the opposite side of the visible artificial hand can be observed (see Figure 1).

Hand location estimates and reaching endpoint errors are determined by both visual-proprionicceptive hand location conflicts and visual-tactile touch synchrony manipulations in the RHI paradigm. First, hand location estimation is influenced by hidden proprioceptive hand information as well as by visual hand information (Holmes et al., 2006; Rossetti et al., 1995; van Beers et al., 1999). Because of the spatial mismatch in the RHI setup, proprioception and vision indicate different hand locations. Proprioceptive and visual information is integrated and the hand is represented to be somewhere between the hidden and the real hand. Secondly, synchronously stroking both the rubber and the participant’s hidden hand leads to a relative increase in the influence of visual hand information when compared to asynchronous touch (Zopf et al., 2011). This is thought to occur because touch synchrony signals that the viewed hand is one’s own hand (Makin et al., 2008; Zopf et al., 2011) or because asynchrony disrupts visual-proprioceptive integration (Rohde et al., 2011). Thus reaching endpoint error in the RHI paradigm indexes the relative influence of proprioceptive hand information, visual hand information and touch synchrony for body location perception.

In this study we investigated if and how multisensory body location perception is changed in AN using an implicit task. To this end, we combined an action-oriented reaching task with the RHI paradigm and presented two types of multisensory conflicts (visual-proprioceptive
hand location; visual-tactile touch synchrony). We tested 23 AN patients and 23 healthy controls (HC). Comparing AN patients with healthy controls, we could test if AN patients’ body location perception is influenced differently by diverse types of multisensory conflict.

Previous researchers have reported significantly positive correlations between explicit body perception measures in the RHI and eating disorder psychopathology measures of drive for thinness, bulimia, body dissatisfaction, interoceptive deficits, emotional dysregulation, self-objectification, depression and anxiety (Eshkevari et al., 2012; but also see Keizer et al., 2014). To further explore if individual differences in multisensory body perception in the AN group are related to differences in AN psychopathology, we also employed several eating disorder psychopathology measures.
2. Methods

2.1. Participants

Individuals in the AN group were required to meet DSM-IV and DSM-5 diagnostic criteria for AN. Participants for the HC group did not have a history of any eating disorder or any other psychiatric illness (self-reported). We tested 23 AN patients and 23 female HC who we matched as closely as possible for age (AN group M=21.87, SD=2.79, HC group M=21.48, SD=2.35) and handedness (2 left handed in each group). The average BMI for the AN group was 15.82 kg/m² (SD= 1.27) and for the HC group 21.16 kg/m² (SD= 2.10). The average illness duration was 5.26 years for the AN group (SD=3.60, range 0.58 to 14 years).

The study was approved by the Macquarie University Human Research Ethics committee. Patients were hospital inpatients at the Wesley Eating Disorder Centre, Sydney, Australia and were medically stable (re-fed for at least three weeks). Healthy controls were recruited through the Macquarie University participant pools. All participants received $50 for their participation.

2.2. Pathology rating scales

We employed several self-report measures to quantify traits, cognitions, attitudes and moods that are typically associated with Anorexia Nervosa:
2.2.2. Eating Disorder Inventory – 3 (EDI-3)

The EDI-3 measures psychological traits that play a role in eating disorders (Garner, 2004). Participants respond to 91 items on a six-point Likert scale ranging from ‘Always’ to ‘Never’. We report the eating disorder (ED) specific composite (ED Risk, includes subscales Drive for Thinness, Bulimia and Body Dissatisfaction) and a general psychological trait composite (General Psychological Maladjustment, includes subscales Low Self-esteem, Personal Alienation, Interpersonal Insecurity, Interpersonal Alienation, Interpersonal Insecurity, Interoceptive Deficit, Emotional Dysregulation, Perfectionism, Asceticism and Maturity Fears) (Clausen et al., 2011; Garner, 2004).
2.2.3. **Body Shape Questionnaire (BSQ)**

The BSQ is a measure of body shape preoccupations and concerns over the past four weeks (Cooper et al., 1987). It contains 34 items and responses are given on a six-point Likert scale ranging from ‘Never’ to ‘Always’.

2.2.4. **Self-disgust Scale (SDS)**

The SDS measures the extent of experiencing disgust toward the self (Overton et al., 2008). We used a modified version consisting of 16 items rated on a Likert scale ranging from ‘Strongly disagree’ to ‘Strongly agree’ (Moncrieff-Boyd et al., 2014).

2.2.5. **Body Parts Satisfaction Scale (BPSS-revised and modified)**

The BPSS is a body image attitude scale and measures satisfaction with individual body parts (Petrie et al., 2002). We modified the scale and added one further item probing satisfaction with hands. Participants rated their satisfaction on a six-point Likert scale ranging from ‘Extremely dissatisfied’ to ‘Extremely satisfied’.

2.2.6. **Depression, Anxiety and Stress Scale (DASS-21)**

The DASS is a common self-report measure of depression, anxiety and stress (Lovibond and Lovibond, 1995).
2.3. Body perception measures

The task design was based on our previous study (Zopf et al., 2011). We measured the influence of RHI manipulations on subsequent reaching responses towards visual targets. We recorded movement endpoints and trajectories (details below).

We also measured explicit bodily judgements that are typically modulated in the RHI, using a set of rating statements adapted from existing RHI questionnaires (Botvinick and Cohen, 1998; Longo et al., 2008). We used six illusion statements: “It seemed as if the rubber hand was my hand”; “It seemed like I was looking directly at my own hand, rather than at a rubber hand”; “It seemed as if I were feeling the touch in the location where I saw the brush”; “It seemed like my hand was in the location where the rubber hand was”; “It seemed as if I was in control of the rubber hand”; “It seemed as if I could have moved the hand if I had wanted”). In addition, we chose six control statements that share a similar wording with the illusion items (e.g. “my own hand”; “location”; “control”) but are not typical embodiment experiences in the RHI (Botvinick and Cohen, 1998; Kalckert and Ehrsson, 2012; Keizer et al., 2014): “It seemed as if I had more than one right hand”; “It seemed like my own hand disappeared”; “It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand”; “It seemed as if my hand was drifting towards the rubber hand”; “It seemed as if the rubber hand was controlling my will”; “It seemed as if the rubber hand could have controlled my movements”. Participants responded on a seven-point Likert scale, ranging from -3 (‘strongly disagree’) to +3 (‘strongly agree’).
2.4. Setup

Participants placed their right index finger inside an open framed platform that was positioned in front of a computer touch screen. The exact finger position was marked by a slightly elevated point. On the right side of the frame a realistic looking right prosthetic hand (Otto Bock Australia Pty Ltd.) was positioned. The distance between participant and rubber hand was 20 cm. The experimenter used two soft 4 cm wide paint brushes to deliver RHI stroking. Participants could not view their own hand at any time during the experiment. A black cloth was attached to the frame and occluded the participant’s hand, but it did not restrict forward movements. Furthermore, a vertical blind attached to the frame occluded the view of the forward moving hand, but allowed viewing the upper half of the touch screen. Hand movements were tracked at 100 Hz via two infrared markers taped to the top of the right index finger just behind the nail cuticle. We placed dummy markers on the rubber hand. The experiment was performed in a dark room and the rubber hand was illuminated with light from the touch screen. Presentation software (Neurobehavioral Systems) was used to control stimulus delivery and movement recording.

[Figure 1 around here]

2.5. Procedure

There were two RHI stroking conditions: synchronous and asynchronous stroking. The exact stroke timing was signalled to the experimenter via headphones and consisted of a 250 ms beep with inter-sound-intervals of 1250 ms. In the asynchronous stroking condition there was a noticeable delay between strokes on the participants’ hand compared to the viewed rubber
hand. The stroking signal consisted of a 250 ms beep with inter-sound-intervals of 500 ms. Each stroke started at the base of the knuckles and moved towards the fingertips. Participants performed two blocks of each stroking condition, for a total of four blocks with the order counterbalanced across participants. Each block started with a 2 minute stroking period followed by a reaching response. A 22.5 s stroking period preceded each subsequent reaching response. During stroking periods a white image on the LCD touch screen provided illumination to view the stroking of the rubber hand. The end of the stroking period was signalled by the disappearance of the white image and the appearance of a white fixation cross in the centre of the touch screen. After 2 s, the fixation cross disappeared and a white target line (height 40 cm, width 0.5 cm) appeared. Participants had to respond immediately by making a ballistic movement towards the target location and touch the screen collinear with the target line beneath the viewing field. Targets could appear in one of 15 locations, equally spaced between the two hands. Each location was sampled once per block, resulting in 15 randomly presented trials and 30 trials in total for each condition.

To ensure that the motion was ballistic, participants had to respond fast and cross the halfway distance to the target within 600 ms after target onset. Trials in which participants responded too slowly were excluded from data analysis and participants were reminded to respond faster. To further reduce any movement adjustments, the target disappeared when participants’ hands crossed the halfway distance to the target. At the completion of a reaching response participants put their hands back to the starting position and the next stroking period began. Prior to the experiment, participants practised the reaching task in 10 trials. After each block of the main experiment participants were asked to complete the RHI rating scales.

AN patients filled out the clinical questionnaires at the hospital, and control participants completed these after the experimental part.
2.6. Statistical Analyses

We tested pathology, body part satisfaction and body perception rating scales for normality within each group separately (Shapiro-Wilk tests). For all rating scales we found evidence for non-normal distributions for either one or both groups. For these measures, we thus report medians and interquartile ranges and conducted non-parametric within- and between-group comparisons (Friedman, Wilcoxon signed-rank, Mann-Whitney U tests).

For the reaching task, the data of correct movement trials for each participant and condition were averaged and entered into mixed ANOVA (within-subject factor touch synchrony and between-subject factor group).

For the AN group only, we also run Pearson correlation analyses to test the association between body perception and AN psychopathology measures (BMI, EDI risk and trait-scales, body shape concern, self-disgust, DASS total, and hand satisfaction). The normality assumption is not needed for Pearson correlation analyses (Nefzger and Drasgow, 1957). For the body perception measures we averaged the values across synchronous and asynchronous conditions and run correlations separately for the implicit reaching endpoint measure and the explicit RHI rating scales scores. Furthermore, for the reaching endpoint error, we also tested the association with illness duration and age using a multiple linear regression analysis.
3. Results

3.1. Pathology rating scales

As expected, we found significantly increased scores for the AN group for trait, cognition, attitude and mood rating scales (Table 1).

[Table 1 around here]
3.1.1. Body Part Satisfaction

For AN patients we found that the degree of satisfaction differs significantly between body parts (Friedman test, $\chi^2(15)=157.45, p<0.001$, dark grey bars in Figure 2). For example, AN patients reported satisfaction ratings above the neutral score (3.5) for hands (Median = 4) and very low satisfaction ratings (Median =1) for body parts such as stomach and legs. We compared satisfaction between hands and the other 10 individual body parts (Wilcoxon signed-rank tests, Bonferroni-corrected significance threshold ($\alpha_{\text{adjusted}} =0.05/10) =0.005$) and found that AN patients were significantly more satisfied with hands compared to stomach ($Z=-3.45, p<0.001, r=-0.52$), legs ($Z=-3.62, p<0.001, r=-0.53$), lower legs ($Z=-2.97, p=0.003, r=-0.44$), buttocks ($Z=-3.85, p<0.001, r=-0.57$), face ($Z=-3.83, p<0.001, r=-0.56$), arms ($Z=-3.22, p=0.001, r=-0.48$) and back ($Z=-2.85, p=0.004, r=-0.42$), but not compared to shoulders ($Z=-1.73, p=0.084, r=-0.25$), chest ($Z=-2.35, p=0.019, r=-0.35$) and hair ($Z=-1.35, p=0.176, r=-0.20$). Healthy controls report satisfaction ratings above the neutral score (3.5) for all scale items (light grey bars in Figure 2). However, some items were also scored lower than others (for example the lowest median score of 4 was found for weight, general muscle tone and stomach) and this variation was statistically significant (Friedman test, $\chi^2(15)=36.39, p=0.002$). For healthy controls, we also compared satisfaction between hands and other body parts (Wilcoxon signed-rank tests, Bonferroni-corrected significance threshold ($\alpha_{\text{adjusted}} =0.05/10) =0.005$) and found no significant differences.

When directly comparing the groups, we found that AN patients reported significantly lower body satisfaction for the items ‘overall satisfaction with size and shape of your body’, ‘weight’, ‘general muscle tone’, ‘complexion’, ‘height’, ‘stomach’, ‘legs’, ‘lower legs (calves)’, ‘buttocks’, ‘overall face’, ‘arms’, ‘shoulders’, ‘chest’, ‘back’ and also for ‘hands’ (Table 2 and Figure 2). Overall, this shows that in AN, the degree of satisfaction differs between body parts, and hands are less emotionally salient compared to other body parts.
However, AN also involves a general change in body satisfaction compared to healthy controls that includes hands.

[Figure 2 and Table 2 around here]
3.2. Body perception measures

3.2.1. Rating scales

As expected, we found a significant effect of synchrony and for both groups, illusion rating scores in the synchronous condition were higher compared to the asynchronous condition (Bonferroni-corrected significance threshold \( \alpha_{\text{adjusted}} = 0.05/2 = 0.025 \), AN group: \( Z = -3.90, p < 0.001, r = -0.58 \); HC group: \( Z = -3.55, p < 0.001, r = -0.52 \), Figure 3). Furthermore, we tested the effect of rating type for both groups and conditions (Bonferroni-corrected significance threshold \( \alpha_{\text{adjusted}} = 0.05/4 = 0.0125 \)). We found significantly higher scores for illusion ratings as compared to control ratings for the synchronous condition (AN group: \( Z = -4.01, p < 0.001, r = -0.59 \); HC group: \( Z = -4.10, p < 0.001, r = -0.60 \)), but not for the asynchronous condition (AN group: \( Z = -1.88, p = 0.060, r = -0.28 \); HC group: \( Z = -2.40, p = 0.017, r = -0.35 \)).

Regardless of touch synchrony and rating type, we found generally higher agreements with the rating scale items in the AN compared to the HC group (Figure 3). Testing for group effects, we found significant group differences for both illusion conditions as well as for illusion and control rating scales (Bonferroni-corrected significance threshold \( \alpha_{\text{adjusted}} = 0.05/4 = 0.0125 \), synchronous illusion ratings \( Z = -2.66, p = 0.008, r = -0.39 \); asynchronous illusion ratings \( Z = -2.61, p = 0.009, r = -0.38 \); synchronous control ratings \( Z = -3.01, p = 0.003, r = -0.44 \); asynchronous control ratings \( Z = -3.43, p = 0.001, r = -0.51 \)). Generally increased RHI rating scores could reflect differences in body perceptions and/or cognitive-emotional factors.

[Figure 3 around here]
3.2.2. Reaching task

We used an action-oriented reaching task to obtain an implicit and objective measure of body location perception. We analysed reach endpoint errors (in mm) calculated as the difference between movement endpoints and target positions. In AN, endpoint errors were increased, indicating that hand location estimates were more influenced by the visual artificial hand information and relatively less by the proprioceptive hidden hand information (main effect group: $F[1, 44]=5.29, p=0.026, \eta^2=0.107$, Figure 4). Furthermore, replicating our previous research (Zopf et al., 2011), we found that touch synchrony modulates hand location estimates which leads to significant shifts of reach trajectories and increased endpoint errors after synchronous compared to asynchronous stroking ($F[1, 44]=21.71, p<0.001, \eta^2=0.329$). This effect of touch synchrony was significant for both groups (AN group: $t(22)=-2.92, p=0.008, d=-0.61$, HC group: $t(22)=-3.68, p=0.001, d=-0.77$) and group did not modulate this effect of touch synchrony (group * touch synchrony interaction was not significant: $F[1, 44]=0.209, p=0.65, \eta^2=0.003$).

We also analysed initial movement direction as a second measure for reaching trajectory and estimated hand location. The results for initial movement direction are in line with the endpoint error findings (Table 3). Furthermore, we found that touch synchrony and group did not significantly affect any other aspects of the performed movement (endpoint error variance, curvature, mean velocity and reaction time, Table 3).
3.2.3. Relationship reaching endpoint error and AN psychopathology measures

Furthermore, we explored the link between body perception changes due to visual proprioceptive conflict (averaged across synchronous and asynchronous conditions) and eating disorder psychopathology measures in AN. We tested the association between the implicit body perception measure (reaching endpoint error) and BMI, EDI risk and trait scales, body shape concerns, self-disgust, DASS total, and hand satisfaction (Bonferroni-corrected significance threshold ($\alpha_{\text{adjusted}} = 0.05/7 = 0.007$)). In line with previous research, we also ran correlations between explicit RHI measures (RHI rating scales) and eating disorder psychopathology measures (Bonferroni-corrected significance threshold ($\alpha_{\text{adjusted}} = 0.05/7 = 0.007$)). No correlations were significant with and without corrections for multiple comparisons (all $p>0.05$).

3.2.4. Relationship reaching endpoint error and illness duration

We explored the association between illness duration and AN endpoint error. Because age correlates with illness duration ($r(23) = 0.721, p<0.001$) and age has been shown to change visual-proprioceptive hand position estimates (Cowie et al., 2013), we performed a multiple linear regression analysis. This allowed us to control for age when investigating the association between illness duration and AN endpoint error. Duration of illness and age were entered simultaneously and the regression model was significant ($F(2,22) = 4.51, p=0.024$), predicting 31.1% of the AN endpoint error effect variance (adjusted $R^2=0.242$). Illness duration had significant positive regression weights ($B=3.27, 95\%\text{CI} [0.998, 5.551], \beta=0.807, t=3.00, p=0.007$), indicating that with longer illness duration the AN endpoint error effect is expected to decrease, when controlling for age. Furthermore, we found a statistical trend for age as a negative predictor for AN endpoint error, when controlling for illness duration ($B=-2.91, 95\%\text{CI} [-5.953, 0.028], \beta=-0.554, t=-2.07, p=0.052$). We also tested the relationship
between age and endpoint error in the healthy control group and found a negative but not significant correlation coefficient ($r(23)=-0.274$, $p=0.205$).
4. Discussion

We investigated the influence of different types of multisensory conflicts on reaching performance and used reaching endpoint error as an implicit action-oriented measure for the perception of hand location. This allowed us to investigate if and how body location perception is changed in AN. We probed the relative influence of different sensory factors (proprioception, touch and vision) that are known to be important for the perception of body location. In AN, hand movement trajectories were more shifted resulting in larger endpoint errors and initial movement angles. This suggests that in AN, hand location estimates are more influenced by external visual hand information and relatively less by proprioceptive hand information. Other aspects of the movement including curvature and temporal parameters did not differ between groups. Furthermore, we found that shorter illness durations predict a larger visual bias in AN when controlling for age. In contrast, we did not find evidence that the processing and influence of touch synchrony for body location perception is changed in AN.

We also found significant group differences for the explicit body-oriented illusion rating scale judgements. This finding is in line with previous work (Eshkevari et al., 2012; Keizer et al., 2014) as well as with our implicit reaching measure results. However we also found significant group differences for RHI control statements that are typically not endorsed in the RHI. Thus it is unclear to what extent the group differences in explicit body-judgements are due to differences in multisensory perception or body-specific and body-non-specific cognitions and emotions. Importantly, the effect for the implicit measure we found here, provides compelling evidence that visual-proprioceptive body location perception is different in AN.
The AN bias toward external visual body information could be due to changes in the processing of proprioceptive signals. Other AN findings support this notion of a proprioceptive deficit (Grunwald et al., 2001; Grunwald et al., 2002). For example, in haptic tasks without vision, active exploration of objects depends on proprioceptive body position and tactile information. In one haptic study, AN patients were asked to explore and then reproduce sunken-relief patterns (Grunwald et al., 2001). The patterns AN patients reproduced showed significantly less resemblance to the originals compared to the reproductions by healthy controls, suggesting differences in the processing and storage of proprioceptive and tactile information.

Typically, where visual information is available, proprioceptive and visual hand location information is integrated to form hand location estimates (Holmes et al., 2006; Rossetti et al., 1995; van Beers et al., 1999). In AN there could be a deficit in proprioceptive-visual integration and vision could become a more dominant source of information. It may also be possible that proprioceptive-visual integration is not changed in AN, but the sensory precision of proprioception is reduced. Sensory precision or reliability determines the relative influence of sensory cues when these are integrated with other cues (Ernst and Banks, 2002). For example, proprioceptive information is less reliable estimation than visual information in the horizontal plane and more reliable in the depth plane (van Beers et al., 2002). Thus for hand location estimates in the horizontal plane the influence of proprioceptive information is relatively decreased while in the depth plane it is increased. A potential decrease in proprioceptive precision in AN could explain the apparent increased bias towards visual hand location information we found in this study.

What could cause the changes in the perception of body location we observed in AN? One factor could be recurrent physical body change, which directly affects proprioceptive receptor
input and could reduce proprioceptive reliability. We found that short illness durations predict a larger visual bias in AN. Physical body change could be most pronounced in early phases of the illness due to extensive weight control measures such as dieting. Physical body change is also involved in weight gain and in AN recovery. Indeed, recovery and weight gain do not seem to alter the observed haptic deficits and perceptual body representation changes in eating disorders (Eshkevari et al., 2014; Grunwald et al., 2001).

Furthermore, malnutrition in combination with genetic and developmental factors could lead to disturbances of brain networks involved in body perception (Gaudio and Quattrocchi, 2012; Kingston et al., 1996; Mondraty and Sachdev, 2011). For example, parietal cortex activity changes have been observed in patients suffering from eating disorders (see Gaudio and Quattrocchi, 2012 for a review; Mohr et al., 2010). Parietal cortex activity is linked to the processing of proprioceptive sensory information and the integration with multisensory body information to update body size and location information (Culham et al., 2006; Ehrsson et al., 2005; Ehrsson et al., 2004). In addition, frontal, occipitotemporal and insular areas are linked to the processing of body information (Berlucchi and Aglioti, 2010; Ehrsson et al., 2004; Tsakiris et al., 2007) and functional changes in AN have also been observed for these areas (see Gaudio and Quattrocchi, 2012 for a review). As with bodily change, the effects of malnutrition on neural networks could also be most dramatic at the onset of the disorder. Longer-term neural changes could account for the persistence of changes in the perception of body location even after AN recovery and weight-stabilization (Carter et al., 2004; Eshkevari et al., 2014; Grunwald et al., 2001).

Neuroimaging studies in eating disorder patients also found structural and functional changes in the extrastriate body area (EBA) (Suchan et al., 2010; Uher et al., 2005), which is a higher visual area that is specialized in the processing of visual body information (Downing et al.,
2001). For example, one study found that left EBA grey matter density is reduced in AN (Suchan et al., 2010). It may thus be possible that in AN, the ability to recognize the visual features of one’s own body is reduced and an external hand is more likely accepted to visually signal body location information. Although typically, the processing of visual hand details, such as the perceived similarity between one’s own hand and the external hand, does not influence the RHI (Longo et al., 2009). More research is needed to clarify to what extent AN differences in visual-proprioceptive perception may be due to changes in the processing of visual signals, the processing of proprioceptive signals and how these signals are integrated.

Interestingly, a visual bias toward artificial hand information has also been found when comparing young children aged between 4 and 9 with adults (Cowie et al., 2013; Cowie et al., 2016). This age is characterized by ongoing physical body change as well as neural development, especially of multisensory association areas (Casey et al., 2005). This raises the possibility that in AN, body perception networks are either less developed and/or revert to less mature systems with AN onset.

We did not find significant correlations between changes in body perception (implicit and explicit) and measures of psychopathology in the AN group. Previously, Eshkevari et al. (2012) did report significant positive correlations between explicit RHI and several eating disorder psychopathology measures. However, they run the correlation analysis across the entire sample including healthy controls. Thus it is possible that their significant correlation findings were mostly due to group differences. Keizer et al. (2014) conducted correlation analyses for both groups separately and did not find significant correlations between explicit RHI and psychopathology measures. Thus so far there seems to be no evidence for a significant relationship between AN psychopathology and body perception measures. This
could indicate that changes in body perception cannot predict individual differences in AN psychopathology. However, the hand is emotionally not the most salient body part for AN patients. It may thus be possible that body perception measures for other body parts such as stomach, hips and legs are more likely related to AN psychopathology (Spitoni et al., 2015). Furthermore, one limitation of our study was a relatively small sample size for correlation analyses and future studies with a larger sample size could more conclusively investigate this link.

In this study we investigated the effect of visual-proprioceptive conflicts and visual-tactile synchrony on hand location perception in AN. We found that the effect of visual-tactile synchrony did not differ between groups. We did however find an effect of visual-proprioceptive conflict. This type of conflict leads to reaching errors also in conditions without stroking (Holmes et al., 2006; Rossetti et al., 1995). Based on our finding, we expect group differences also in no touch conditions. In this study we were unable to add a third condition with no touch due to time constraints, but future studies could test this prediction.

Using a body part satisfaction scale, we found that AN patients are more satisfied with their hands compared to other body parts such as stomach and legs. At the same time, AN patients are generally less satisfied with their body compared to healthy controls and this includes hands. Thus hand perception research that involves explicit bodily judgements may be confounded by emotional and cognitive factors when investigating eating disorder and unhealthy body change (Eshkevari et al., 2012; Keizer et al., 2014; Mussap and Salton, 2006). Action-oriented tasks allow implicit measures of body perception and are useful to study body perception while minimizing the influence of the body-related emotions and cognitions common in eating disorders (Guardia et al., 2010; Keizer et al., 2013; Nico et al., 2010; Smeets et al., 2009).
We found significant group differences in visual and proprioceptive signal integration for body location perception when we systematically introduced multisensory conflicts. In daily life, conflicts between visual and proprioceptive hand location information are not common and thus reaching performance would not be significantly affected, especially when both types of information are present and congruent.

Body size and shape perception also relies on the integration of visual and proprioceptive information (Proske and Gandevia, 2012) and it has been suggested that distorted body shape perceptions in AN could also be due to changes in how visual and non-visual shape representations are integrated (Longo, 2015). Contrary to our finding on body location perception, a decreased influence of visual body information was hypothesised (Longo, 2015). Furthermore, not just the perception of our body, but also the perception of objects that we interact with is shaped by the integration of visual and proprioceptive information. A classic demonstration is the size-weight-illusion in which participants tend to underestimate the weight of a larger object (e.g., a box) when compared to a smaller object with the same mass. This illusion is thought to be due to the integration of object information derived from vision and proprioception and an implicit assumption that weight scales with viewed size (Flanagan and Beltzner, 2000). AN patients are prone to the size-weight illusion, but to a lesser extent compared with healthy controls (Case et al., 2012). In contrast to our finding of a relative increased influence of visual information on body location perception, this suggests less influence of visual object information for the perception of heaviness in AN patients. Further research is needed to investigate what underlies changes in the processing of visual and proprioceptive signals in AN and how this may affect the perception of all aspects that rely on visual and proprioceptive signals, such as the location, shape, size and weight of the body as well as external objects (Case et al., 2012; Keizer et al., 2011; Longo, 2015; Spitoni et al., 2015).
The development of new therapeutic interventions may also benefit from this research. For example future interventions could target body location perception and specifically visual-proprioceptive integration, such as in physical therapy. Because body shape perception is also based on the integration of visual and proprioceptive signals, this may also reduce body shape distortions. More research will be needed to understand how body perception can be trained and if this could be effective in the treatment of eating disorders.

To conclude, employing a reaching paradigm we found evidence that, in Anorexia Nervosa, the relative influence of proprioceptive signals is decreased and the relative influence of external visual information increased for the perception of body location. This provides compelling evidence that multisensory body perception is changed in AN. We suggest that the AN bias toward external visual body information is due to changes in the processing of proprioceptive signals. Recurrent physical body change as well as disturbances of body perception brain networks due to malnutrition, genetic and developmental factors could potentially cause the change in multisensory body perception in AN. Future research is needed to investigate how other factors such as developmental, genetic and social factors interact with changes in AN multisensory body perception to further understand the role of multisensory body perception in this complex disorder.
Acknowledgements

R. Zopf is supported by a Discovery Early Career Researcher Award from the Australian Research Council (ARC) (DE140100499). The ARC did not play a direct role in any part of the study.

Conflict of Interest

We declare that there is no conflict of interest.
References


Figure Captions

**Figure 1. Schema of experimental setup and movement endpoint error.** Participants sat in front of a vertically positioned touch screen. The participant’s right hand was hidden from view. On the right of the table an artificial hand was placed which was illuminated by light from the touch screen during stroking periods. The infrared markers placed on the hands allowed movement capture with an optical motion capture system mounted above the participant (not depicted). The experimenter sat on the right side of the table to apply synchronous or asynchronous brush strokes using two identical brushes (not depicted). In this setup, visual hand and hidden hand information is integrated and as a result, the hand position estimate is shifted towards the viewed rubber hand. This creates a mismatch between estimated and actual hand position, and when the participant reaches towards a visual target a systematic endpoint error can be observed. Endpoint errors index the relative influence of different sensory information (proprioception, vision, touch).

**Figure 2. Body Part Satisfaction rating results.** Median satisfaction (1= extremely dissatisfied to 6= extremely satisfied) with the body and several individual body parts for the Anorexia Nervosa (AN) group (dark grey bars) and the healthy control (HC) group (light grey bars). Compared to the HC group, AN patients were significantly less satisfied with all body parts, except hair (* p<0.05 after Bonferroni correction for multiple comparisons). Error bars represent interquartile ranges (IQR).

**Figure 3. RHI rating results.** Median illusion embodiment and control ratings for synchronous and asynchronous conditions for both the Anorexia Nervosa (AN) and the healthy control (HC) group. Comparing groups, we found significant differences for both touch synchrony conditions and both rating types.
**Figure 4. Reaching endpoint error.** Mean constant endpoint errors (in mm) calculated as the difference between movement endpoints and target positions for both the Anorexia Nervosa and the healthy control (HC) groups. Error bars indicate the 95% CIs. The mean endpoint error indexes the relative influence of different sensory factors on hand location estimates. The touch synchrony influences hand estimates (main effect touch synchrony ($F[1, 44]=21.71, p<0.001, \eta^2=0.329$), while the effect of touch synchrony does not differ between the groups ($F[1, 44]=0.20, p=0.650, \eta^2=0.003$). In AN, hand location estimates are relatively more shifted and thus more influenced by the visual artificial hand information (main effect group: $F[1, 44]=5.29, p=0.026, \eta^2=0.107$).
Figure 1. Schema of experimental setup and movement endpoint error.
Figure 2. Body Part Satisfaction rating results.
Figure 3. RHI rating results.
Figure 4. Reaching endpoint error.
<table>
<thead>
<tr>
<th>Pathology</th>
<th>AN group (N=23)</th>
<th>HC group (N=23)</th>
<th>Mann-Whitney U test</th>
<th>Effect size - r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median IQR</td>
<td>Median IQR</td>
<td>Z</td>
<td>p</td>
</tr>
<tr>
<td>EDI – ED Risk</td>
<td>65 15</td>
<td>15 18</td>
<td>-5.75</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EDI – General Psychological Maladjustment</td>
<td>138 42</td>
<td>32 27</td>
<td>-5.77</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Body Shape Questionnaire</td>
<td>141 39</td>
<td>62 88</td>
<td>-5.16</td>
<td>&lt;0.001</td>
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<tr>
<td>Self-disgust Scale</td>
<td>55 8</td>
<td>15 8</td>
<td>-5.73</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DASS total</td>
<td>39 17</td>
<td>7 5</td>
<td>-5.62</td>
<td>&lt;0.001</td>
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<tr>
<td>DASS depression</td>
<td>16 6</td>
<td>2 2.25</td>
<td>-5.46</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DASS anxiety</td>
<td>9 6</td>
<td>1.5 3</td>
<td>-5.16</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DASS stress</td>
<td>14 6</td>
<td>3 5</td>
<td>-4.91</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

AN, Anorexia Nervosa; HC, healthy control; IQR, Interquartile Range; EDI, Eating Disorder Inventory; DASS, Depression, Anxiety & Stress Scale.
Table 2. Body Part Satisfaction rating results. Medians and interquartile ranges (IQR) for all items are given for both the Anorexia Nervosa (AN) group and the healthy control (HC) group as well as statistics for group comparisons (Mann-Whitney U test Z, p-values and effect sizes r).

<table>
<thead>
<tr>
<th>Part</th>
<th>AN group (N=23)</th>
<th>HC group (N=23)</th>
<th>Mann-Whitney U</th>
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<tbody>
<tr>
<td></td>
<td>Median</td>
<td>IQR</td>
<td>Median</td>
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<tr>
<td>Overall satisfaction body</td>
<td>1</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Weight</td>
<td>1</td>
<td>1</td>
<td>4</td>
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<tr>
<td>General muscle tone</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Complexion</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Height</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Stomach</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Legs</td>
<td>1</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Lower legs (calves)</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Buttocks</td>
<td>2</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Overall face</td>
<td>2</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Arms</td>
<td>2</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Shoulders</td>
<td>3</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Chest</td>
<td>3</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Back</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Hair</td>
<td>4</td>
<td>1</td>
<td>4.5</td>
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<tr>
<td>Hands</td>
<td>4</td>
<td>2</td>
<td>5</td>
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</table>

AN, Anorexia Nervosa; HC, healthy control; IQR, Interquartile Range
Table 3. Reaching task results. Anorexia Nervosa (AN) and healthy control (HC) group condition mean values and 95% CI for reaching parameters as well as ANOVA results (within-subject factor Synchrony and between-subject factor Group).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AN Synchronous</th>
<th>AN Asynchronous</th>
<th>HC Synchronous</th>
<th>HC Asynchronous</th>
<th>ANOVA</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% CI</td>
<td>Mean</td>
<td>95% CI</td>
<td>Mean</td>
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<td></td>
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<tr>
<td>Endpoint error (mm)</td>
<td>-33.0</td>
<td>-39.4, -26.5</td>
<td>-27.1</td>
<td>-33.2, -21.0</td>
<td>-21.9</td>
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<tr>
<td>Initial movement angle (degree)</td>
<td>78.6</td>
<td>75.4, 81.8</td>
<td>74.5</td>
<td>71.8, 77.2</td>
<td>73.6</td>
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<tr>
<td>Endpoint error variance (STD) (mm)</td>
<td>17.0</td>
<td>14.5, 19.6</td>
<td>16.1</td>
<td>14.4, 17.8</td>
<td>16.8</td>
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<tr>
<td>Curvature (Ratio max pathoffset/distance)</td>
<td>0.097</td>
<td>0.084, 0.111</td>
<td>0.097</td>
<td>0.083, 0.110</td>
<td>0.107</td>
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<tr>
<td>Mean velocity (m/s)</td>
<td>0.332</td>
<td>0.316, 0.348</td>
<td>0.335</td>
<td>0.319, 0.351</td>
<td>0.350</td>
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<tr>
<td>Reaction time (ms)</td>
<td>670</td>
<td>635, 706</td>
<td>668</td>
<td>635, 702</td>
<td>653</td>
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</table>

Endpoint error - difference between movement endpoints and target positions
Initial movement angle - angle of the instantaneous velocity when 10% of the movement distance towards the screen was reached
Endpoint error variance - endpoint error standard deviation for each participant
Curvature - the maximal path offset (distance perpendicular to the straight line between starting position and end position of the movement) divided by the length of a straight line between movement starting and end positions
Mean velocity - velocity across all data points
Reaction time - time from target onset to touch