From the body's viscera to the body's image: is there a link between interoception and body image concerns?

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Abstract

Interoception, the sense of the physiological condition of the body originating from within its internal organs, *and* body image, namely the perception, feelings and attitudes one has about one's body, are two fundamental components of our sense of personal identity and overall well-being. However, the relation between interoception and body image remains poorly understood. We here review recent behavioural and neuroimaging evidence from non-clinical and clinical populations (e.g. eating disorders) to propose that basic interoceptive processes *and* interoceptive awareness may crucially contribute to the complex formation of body image, as well as to its disturbances. In particular, lower interoceptive accuracy and awareness are associated with body-image concerns. We provide a potential mechanistic explanation of the link between interoception and body image, which aims to integrate interoceptive and exteroceptive representations of the body. The suggested link between interoception and body image can inform new empirically testable hypotheses on the underlying neurocognitive processes that are central to body image concerns and disturbances, and motivate relevant clinical implications.

Keywords : Interoception; interoceptive accuracy; interoceptive awareness; body image; anorexia nervosa; eating disorders; insula; predictive coding

1. Introduction

The experience of one's own body encompasses a basic somatic form of awareness as well as the complex formation of a body self-image, which both contribute to the basis of a sense of personal identity and its adaptive functioning (Cash, 2004; Damasio, 2010). On the one hand, interoception, the sense of the physiological condition of the body originating from within its visceral organs (e.g. heart, lungs, stomach, bladder etc.) that signal their state (e.g. heartbeat, hunger, dyspnea, distension of the bladder, stomach, rectum or oesophagus etc.) is central for basic homeostatic regulation (Cameron, 2002), for the formation of subjective emotional feelings (Damasio, 2010) and ultimately for the representation of the self as agentive, continuous and invariant over time (Craig, 2010). The current literature reveals that interoception is shaping a wide range of subjective experiences, and fundamental aspects of body experience, such as body ownership (Tsakiris et al. 2011) and self-awareness (Babo-Rebelo et al. 2016). Still, by contrast, relatively little attention has been directed to the relationship between interoception and other aspqects of the bodily self, notably body image. As a concept, body image is aimed at encompassing the multidimensional psychological experience of embodiment that comprises evaluative thoughts, beliefs, feelings and behaviours the individuals may have about their own body (Cash, 2004; Gallagher, 2000). Body image is critically linked to well-being (Cash, 2004), and its distortions lie at the heart of debilitating psychopathologies, such as eating disorders (e.g. Cash & Deagle, 1997). This review paper attempts to illuminate this relationship on the basis of the available empirical evidence. To that end, we will first briefly outline the main features related to the concepts of interoception and the body image, and then present a review of the available empirical data that highlight the important role of interoception for body image. A better understanding of the relationship between interoception and body image may have significant clinical implications insofar interoceptive abilities may form part of the key therapeutic targets when treating individuals with clinical or sub-clinical body image concerns.

1.1 Interoception

Interoception refers to the "afferent information arising from within the body that affects the cognition or behaviour of an organism, with or without awareness" (Cameron, 2002, p. 271). It represents the processing of the body's physiological condition (Craig, 2002), encompassing diverse multimodal signals sensed by internal baroreceptors and chemosensors. The sense of the mainly visceral body is often expanded to signals detected by surface temperature receptors and nociceptors (e.g. Cameron, 2002). At the physiological level, interoception serves the critical biological function of homeostasis, ensuring the stability of the biological organism. At the psychological level, it plays an important role in many theories of emotions suggesting that the extent of an individual's sensitivity to bodily signals is strongly linked to the experience and regulation of emotions (e.g. Damasio, 1994, Füstös et al. 2012). In psychology, interoception is mainly studied in relation to our ability to become aware of interoceptive states. Thus, beyond the homeostatic regulation that they serve, interoceptive states such as heartbeats and hunger for example can be consciously perceived. Therefore the concept of interoception includes interoceptive accuracy (IAcc) , that reflects the extent to which one can detect internal bodily sensations, as well as a more general conscious representation of interoceptive states, termed interoceptive awareness (IAw; Garfinkel et al., 2015). Individual differences in IAcc and IAw can respectively be quantified through experimental tasks that require the participant to attend to visceral signals (e.g. Schandry, 1981) or through self-reported questionnaires (e.g. Garner et al. 1983). Although IAcc can differ across the physiological systems (e.g. gastrointestinal versus cardiac signals), paradigms based on cardiac perception are the most widely used (Kleckner & Quigley, 2014). *Both research* trends (i.e. objective and self-reported measures) have linked interoception with typical and atypical psychological processes (Garfinkel et al, 2016; Murphy et al., 2017), and have contributed to delineate its structural and functional cerebral underpinnings (e.g. Schulz, 2016 for a meta-analysis).

Objective measures of IAcc mostly depend on paradigms of cardiac accuracy that ask participants to estimate the number of heartbeats they feel over short periods of time without taking his pulse (Schandry, 1981). These data have first highlighted a decreased subjective emotional experience in people with lower IAcc, in response to a similar degree of objective bodily arousal (e.g., Critchley et al. 2004; Dunn et al. 2010; Pollatos et al. 2008; Wiens et al. 2000). IAcc has been further associated with basic as well as complex cognitive mechanisms, such as intuitive decision making (Dunn et al., 2010; Werner et al. 2009). Finally, recent data have stressed the role of IAcc for different aspects of body experience. People with lower IAcc revealed a greater tendency to consider one's own body as an object (Ainley & Tsakiris, 2013), and a stronger malleability of body representations under conditions of multisensory exteroceptive stimulation (Tsakiris et al. 2011). Beyond the scope of typical functioning, fluctuations in IAcc and IAw have also been associated to various psychopathologies.

Higher IAcc and IAw have been for instance highlighted in anxiety and panic disorders (Domschke et al. 2010, for a review), while lower IAcc and IAw might co-occur with depression (Dunn et al. 2007), schizophrenia (see Critchley & Harrison, 2013 for examples of misattribution of interoceptive cues) and in eating disorders (Fassino et al. 2004; Matsumoto et al. 2006; Merwin et al. 2010; Pollatos et al. 2008). Importantly, a significant amount of the data obtained by clinical populations are based on self-reports, such as the interoceptive deficit subscale of the eating disorder inventory (EDI; Garner et al., 1983), rather than on objective measure of interoceptive abilities (such as cardiac accuracy paradigms).

Studies that have attempted to locate the cerebral substrates of interoceptive processes have consistently pointed out the critical role of two independent pathways: one involving a cortical network that encompasses the insula (mainly right anterior, e.g. Craig, 2009; Critchley et al. 2004) and the anterior cingulate cortex and another implicating the somatosensory cortices (e.g. Khalsa et al. 2009). Craig (2002) has further outlined an anatomical posterior-to-mid-to-anterior progressive integration of the interoceptive signals in the insula. Briefly, information from within the body (e.g. nocioceptive or cardiovascular signals) are thought to be first represented in the right posterior insula for a primary interoceptive mapping and then transferred to the anterior insula for a higher-order conscious representation of interoceptive states. Consistent with this, Kuehn et al. (2016) reported functional changes in the posterior insula functional connectivity profile of individuals with higher interoceptive awareness during heartbeat monitoring. Recent preliminary meta-analyses support that the anterior cingulate and insular cortices are involved in the conscious processing of interoceptive stimuli (Schulz, 2016), but they also underlie the perception of stimuli that implicitly activate bodily sensations, which form a basis for conscious perception (Meneguzzo et al., 2014).

Thus, so far the literature has successfully circumscribed the neural as well as several psychological correlates of interoception. While interoception has notably been implicated in relation to complex body-related psychological mechanisms, the link that may bridge interoception and body image has yet to be fully uncovered.

1.2 Body image

There is no currently a commonly accepted definition of the term "body image" , and the current review does not intend to dwell on this debate. We here adopt a broad definition of body image, defined as the conscious, predominantly visual, mental representation of one's own body and of our perceptual, cognitive and affective attitudes towards it (Gallagher, 2000; Longo & Haggard, 2012). Rather than being a single construct, several sub-components of body image exist. For instance, Longo, Cardoso and Haggard (2008) distinguished the "self-specific" from the "generic" body images. While the former arises from the recognition that a specific visual object is part of one's own body, the latter describes a general mental representation of the structure of the body. Alternatively, Carruthers (2008) distinguishes between online and offline body representations. The concept of online body representations describe the moment-by-moment constructed and re-constructed mental representation of the body (Carruthers, 2008). Conversely, the concept of offline body representations refers to more stable diachronic mental representation of the body, in a way similar to the aforementioned 'generic' body image (Carruthers, 2008).

Despite the lack of a clear consensus in the literature on the exact number and names of dimensions ascribed to body image, it seems that body image exceeds the mere perceptual representation of one's own appearance and is best described as a multifaceted construct (Cash, 2004). Body image therefore includes at least some perceptive, affective and cognitive components (Cash, 2004; Cash & Deagle, 1997; Cash & Green, 1986). In particular, the perceptive component relates to the detection, estimation and identification of one's own body size, the accuracy of the individuals' judgement of their size, shape and weight relative to their actual proportions. The affective dimension depicts the positive or negative feelings that individuals develop towards their bodily appearance, while the cognitive dimension concerns beliefs about body shape and appearance and the mental representation of the body (Cash & Green, 1986). These three dimensions seem to be underpinned by relatively distinct neural networks (e.g. Friederich et al., 2010; Uher et al., 2005) as summarized in recent reviews papers (Gaudio et al., 2016; Gaudio & Quattrocchi, 2012). For instance, right sensororimotor brain regions (insula and premotor cortex) and the rostral anterior cingulate cortex have been involved in the affective component of body image (Friederich et al., 2010) while the perceptual dimension may engage the lateral fusiform gyrus, inferior parietal cortex and the lateral prefrontal cortex (Uher et al., 2005). Gaudio et al. (2012) sum up the functional neuroimaging data collected in healthy and anorexic samples to classify them in accordance with the three body image components. They stressed that the perceptive dimension mainly engages the posterior parietal lobe network while the affective component activates the prefrontal cortex and the insular and amygdala networks. In contrast, the authors did not associate a specific neural system with the cognitive dimension, although it seems to be related to posterior parietal areas. Gaudio et al. (2016) have recently described functional connectivity alterations in these same brain networks, including the insula.

Distinct experimental and self-reported methods have been used to measure individual differences across different body image components. For instance, paradigms that tackle the perceptual component typically ask participants to choose the image that most closely fits with one's body image (real own or other's body images, e.g. Hodzic et al., 2009; or body line drawings, e.g. Peelen & Downing, 2007), while beliefs and mental representations of body shape and appearance (e.g. the negative body-image word task, see Myake et al., 2010) are representative of the cognitive dimension (see Gaudio & Quattrocchi, 2012 for a review). While a positive body image is predictive of health-related outcomes (e.g., more physical activity; Andrew et al. 2016), disturbances in one or several of the body image components have been emphasized in various clinical conditions (eating disorders, Cash & Deagle, 1997; depression, Jackson et al., 2014) and manifestations (e.g. non suicidal self-injury, Muehlenkamp & Brausch, 2012). In particular, clinical and empirical research deem distortions of body image as core features of the eating disorders psychopathology (e.g. Cash & Deagle, 1997; Fairburn & Harrison, 2003), most notably of anorexia nervosa.

Experimental bodily illusions that induce changes in body-ownership can also inform us on how individuals represent their own body. For example, a series of studies based on the "Rubber Hand Illusion" (RHI; see Tsakiris, 2010, 2016 for reviews) highlight the conditions that give rise to our sense of body-ownership, the feeling that this body belongs to me. In the RHI, watching a rubber hand being stroked synchronously with one's own unseen hand causes the rubber hand to be experienced as part of her or his body. The RHI reflects a three-way interaction between vision, touch, and proprioception: vision of tactile stimulation on the rubber hand captures the tactile sensation on the participant's own hand, and this visual capture results in a mislocalization of the felt location of one's own unseen hand towards the spatial location of the visual percept (Botvinick & Cohen, 1998). Furthermore, the change in body-ownership as a result of the RHI can in turn change body image as participants who experienced the RHI perceived their hand and the rubber hand as significantly more similar in terms of their appearance (Longo et al. 2009), than participants who did not experience the illusion, suggesting that ownership leads to changes in perceived physical similarity. Such findings highlights that touch and vision are fundamental components of body image (e.g. Longo et al. 2008). Preston and Ehrsson (2014) have used full bodily illusions that rely on the same mechanisms as the RHI to show that illusory ownership of a slimmer body resulted in participants perceiving their actual body as slimmer and giving higher ratings of body satisfaction demonstrating a direct link between perceptual and affective body representations. Illusory changes in body size have also been shown to modulate body image satisfsction in a way that is related to non-clinical eating disorders psychopathology (Preston & Ehrsson, 2016).

In summary, the current literature agrees on a multifaceted description of body image sustained by a set of distinct neural regions. However, most empirical data are still predominantly concentrated on the visual component of body image, dealing with it as a top-down and unisensory, predominantly visual, concept. By contrast, other sensory inputs have been insufficiently considered (Gaudio et al. 2014). In particular, we emphasize that the role played by bottom-up processes, notably interoception, in body image components is still scarcely understood. Interoception represents indeed an essential source of information in comprising the sense and experience of one's body. Despite early clinical claims of interoceptive disturbance as central to eating disorders (Bruch, 1973; but see also Krueger, 2002 for the role sensations from within the body in body image formation), interoception has only recently been included in empirical studies of positive and disturbed body image (Eshkevari et al. 2014). Therefore, the eventual contribution of interoception to body image remains poorly understood. The following sections provide a review of relevant empirical findings that point, directly or indirectly, to the relation between interoception and body image.

2. Evidence in support of an interoceptive role in body image

2.1 Body image disorders

Distorted body image and altered processing of internal visceral signals are key features of eating disorders and most notably of anorexia nervosa. Clinicians typically report that their anorexic patients perceive themselves as overweight despite a severe state of emaciation (i.e. body image disturbance) and report an absence of any hunger sensations in the face of severe malnutrition (i.e. interoceptive deficits). Numerous empirical studies support the presence of severe body image distortions in anorexia nervosa and other forms of eating disorders (Cash & Deagle, 1997; Fairburn & Harrison, 2003). By contrast, investigations of interoceptive functioning are less abundant. The reported findings highlight lower levels of IAcc and IAw in patients with severe body image disturbances, in relation to several stimuli (cardiac, food, hunger, and physical pain; Khalsa et al. 2015; Yoshikatsu &

Toshikiyo, 2001; Santel, et al. 2006), although, as explained below certain inconsistencies across studies are also present.

Specifically, Pollatos et al. (2008) observed lower interoception in anorexic patients than in healthy controls, measured through the heartbeat counting task that results in a IAcc score, and subjective self-report measures that evaluate levels of IAw. Pollatos et al. (2016) recently extended this former study, demonstrating a link between reduced IAcc and negative body image (i.e. higher body dissatisfaction) in anorexic patients. These results are in accordance with previous behavioural and neuroimaging evidence of deregulated interoceptive processing in eating disorders, in relation to hunger (e.g. Santel et al. 2006) or physical pain stimuli (e.g., Strigo et al. 2013). Some studies further propose that lower IAw may be predictive of the severity of anorexia nervosa (e.g. Bizeul et al. 2001; Gustafsson et al. 2010; Leon et al. 1995, see also Killen et al. 1994, 1996 for contradictory results). Similarly, such decreased trait-like sensitivity towards internal bodily signals has also been linked to overweight, obesity (Herbert & Pollatos, 2014), binge eating disorders (Holmes et al. 2015), recovered bulimia nervosa (Klabunde et al. 2013), chronic pain (see Tsay et al. 2015 for a review), suicidal (Forrest, Smith, White, & Joiner, 2015) and non-suicidal self-injury (e.g. Ross, Heat & Toste, 2009 see Bunderla & Kumperscak, 2015 for a review), somatoform disorders (Mussgay et al. 1999) and depression (Terhaar et al. 2012); these disorders all imply body image disturbances (e.g. Jackson et al. 2014; Martens et al. 2010; Muehlenkamp & Brausch, 2012). As a whole, these results may reflect dampened interoceptive perception and/or a top-down inhibition of interoceptive processing (Eshkevari at al. 2014a).

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However, the link between interoception and body image disturbances is not systematically reproduced (Eshkevari et al. 2014; Khalsa et al. 2015; Pollatos & Georgiou, 2016). For instance, a recent study failed to fully replicate the results of Pollatos et al. (2008, 2016). Eshkevari et al. (2014a) investigated IAcc and IAw capacities in a sample of 74 patients with mixed eating disorders (anorexia nervosa, bulimia, and eating disorder not otherwise specified) compared to 60 healthy controls, based on the self-report interoceptive deficit of the Eating Disorder Inventory (Garner et al., 1983) and a heart beat detection task (Whitehead et al. 1977). While the clinical sample consistently reported lower scores to the questionnaire measure (i.e. IAw), both groups showed similar results on the performance-based task (IAcc). Similar non-significant results have been reported by Goldzak-Kunik et al. (2012) in relation to cold pain responses investigated in adolescents with anorexia nervosa; instead these data revealed a trend for a greater sensitivity to cold temperature in the patient group. It is plausible that methodological limitations such as a small sample size (Goldzak-Kunik et al. 2012) and/or a low variance in the groups (Eshkevari et al. 2014a) have contributed to the divergent findings. For instance Eshkevari et al. (2014a) noted that each of their sample of participants scored below the chance threshold, revealing an eventual floor effect. Another explanation could stem in the presence of "state" factors that moderate the relationship between interoception and eating disorders. Khalsa et al. (2015) recently examined various facets of interoceptive capacities before and after a 1000-calorie meal in women diagnosed with anorexia nervosa, compared to healthy controls. Their evaluation of IAw involved the injection of low or high doses of isoproterenorol; a pharmacological agent eliciting rapid and transient changes in body arousal. In particular, Khalsa and colleagues (2015) assessed interoceptive detection thresholds, retrospective ratings of palpitation and dyspnea intensity (IAw) and the correlations between subjective moment-by-moment dial rating and observed heart rate responses (IAcc). While no differences were found for IAcc, altered IAw has been reported at low arousal levels, particularly during meal anticipation, which may be interpreted as a state variable (i.e. dependant of the context and not an intrinsic trait feature of the individual). To sum up, contrary to the author's expectations, the clinical sample showed similar detection rate of internal changes in higher degree of bodily arousal, independent of the state variable. Still, the heightened level of sensations reported by the clinical sample at lower body arousal in a pre-meal state is coherent with the imprecise estimation of heart rate during conditions of lower arousal observed by Pollatos et al. (2008).

From a neuroscientific perspective, studies that examine the cerebral responses to stimuli of one's own and of another's bodily appearance provide indirect yet valuable insights into the question of whether there is an association between body image and interoception. Such data mostly derive from clinical samples and typically support the role of the insula in body image distortions and particularly in its affective and perceptual components. For instance, Sachdev et al. (2008) describe that patients with anorexia nervosa show similar cerebral activity to controls when processing images of other's bodies while differences were observed in relation to self-body images, including a reduced activity in the insula. Furthermore, the data reviewed by Gaudio and Quattrocchi (2012), as previously described, indicate the relevance of a neural circuit that includes the insula for the affective component of body image. Facing evocative stimuli of aversive self-comparison or of desirable ideal body shape, the anorexic sample showed altered hyperactivation of the insula compared to healthy controls (e.g. Mohr et al. 2010, Friedrich et al. 2010). In Mohr et al.'s study, participants were presented with image of themselves with different degrees of body size distortion that they had to compare with their own ideal body image (affective body image component). They were further required to compare the same distorted stimuli with their own real body shape (perceptive body image component). The results notably demonstrated that anorexic patients displayed a higher activity of the left insula for the thin self-images during the task that primary involved the affective component of body image, in contrast to the thinner self-image during the perceptive task. The hyperactivity of the insula may be a consequence of a higher emotional valence of the thinner self-images. Another potential interpretation is that the difference of insular activation between the two groups is linked to a deficit in interoception and emotional processing in anorexia (i.e. compensatory brain activity).

Comparable results have been reported during performance in various forms of self-body image paradigms as well as in other clinical disorders, such as bulimia nervosa (Friederich et al. 2010; Mohr et al. 2010, 2011, Redgrave et al. 2008). Interestingly, van den Eynde et al. (2013) further suggests that abnormal insula functioning may specifically underpin body image concerns, but not other core features of eating disorders, such as the processing of food stimuli. Conversely, Nunn et al. (2008) suggest that these insular dysfunctions may play a pivotal role in explaining most of psychopathological and neuropsychological abnormalities present in anorexic patients.

2.2 Body image in non-clinical populations

So far, to our knowledge, there are only four studies that have directly examined the associations, in particular the correlations, between interoception and body image, in healthy participants recruited in the general population. A first study explored body image dissatisfaction, body mass index (BMI) and self-reported body awareness in relation to IAcc in a sample of 70 individuals (Emanuelsen et al. 2014). An inverse and moderate relationship between IAcc and body image dissatisfaction was evidenced, whereby individuals with lower IAcc report greater body image dissatisfaction. Secondly, Duschek et al. (2015) draw the attention towards the implication of interoception in experiencing a positive image of one's own body. They specifically hypothesized that individuals with higher IAcc, operationalized with performance in a heartbeat counting task, will report an increased satisfaction with bodily appearance, a greater confidence in physiological functions and more positive feelings related to the body. As expected, they observed that the group with higher IAcc (i.e. above

85% of correct detection, N=30) exhibited greater bodily satisfaction and identification, increased attention to physical appearance, reduced hypochondriac concerns and greater perceived bodily self-control and reduced sexual dissatisfaction; this sustains the implication of IAcc in a positive body image. Finally, the two last studies have been framed in relation to the self-objectification theory. Self-objectification broadly refers to a psychological mechanism describing the process through which individuals , and mainly women, tend to adopt a specific view of the self that is mostly focused on their body's appearance (e.g. attractiveness, sex appeal; see Fredrickson & Roberts, 1997). while the first study indicated that body dissatisfaction positively contributes to lower self-reported IAw (Holmes et al. 2015), another work observed a negative association between objective cardiac IAcc and self-objectification, whereby lower IAcc was correlated with greater self-objectification, implying that interoception may be a cause rather than an outcome of an increased proneness to see one's own body from a third perspective (Ainley & Tsakiris, 2013). Still, the cross-sectional and correlational designs shared by the four studies precludes any conclusive interpretation about the causal relation between interoception and body image. Nevertheless, it is noteworthy that all four studies found evidence for the hypothesised association between interoception and body-image in healthy individuals, suggesting that this relation is important not only for our understanding of disordered body-image, but also for the non-pathological, yet often troublesome, construction of a mental representation of how our body looks like. Taken together, these findings add new supporting direct and indirect evidence to suggest that body image processing and its deregulations could be intimately tied to interoceptive (dys)functioning.

3. Integrating the perception of the body from the outside and from within

As we described earlier, one of the most commonly used experimental paradigms to probe questions of body-ownership, and to a certain extent body-image (see Farmer et al. 2012), are multisensory bodily illusions. For example, the RHI (i.e. the previously mentioned "Rubber Hand Illusion"), has been established as one of the most important experimental paradigms that allows the controlled manipulation of the experience of body-ownership. However, as the body is not simply perceived exteroceptively - it is also felt interoceptively, interoceptive signals and their awareness may play an important role in body-ownership and body image as we argue here. In fact, any plausible model of embodiment should try to at least account for the integration of exteroceptive and interoceptive signals. Consider the experience of body-ownership during the RHI. The exteroceptive evidence suggests that what I am looking at (i.e. the rubber hand) is my hand. However, if this is my hand, then there are potential conflicts between interoceptive signals about how my true hand feels (i.e. the fact that I cannot feel the rubber hand interoceptively).

The first study that tested the potential link between exteroceptive and interoceptive awareness of the body measured and quantified IAcc and compared this measure with the change in body-ownership caused by multisensory stimulation, using the RHI as a paradigmatic case of the exteroceptive self. Tsakiris et al. (2011) observed a negative correlation between IAcc and RHI, such that people with lower IAcc showed a stronger RHI measured behaviourally and homeostatically (i.e. drop in skin temperature), suggesting that, in the absence of accurate interoceptive representations, one's model (i.e representation) of self is predominantly exteroceptive. This was a seminal finding that it could not be predicted by existing accounts of interoceptive awareness or models of the exteroceptive self, as it showed for the first time that both the experience of body-ownership and the same subsequent changes in homeostatic regulation are negatively correlated with levels of IAcc. These findings suggested an *antagonism* between interoceptive and exteroceptive cues in bodily self-awareness. Following that initial finding, the same negative correlation was observed in children aged 8 to 17 years (Schauder et al. 2015, and see also Aspell et al. 2013; Suzuki et al. 2013 for different manipulations of interoceptive processing), as well as in other multisensory bodily illusions (Tajadura-Jimenez & Tsakiris, 2014). Based on the findings of Pollatos et al. (2008) that showed reduced IAcc in anorexic patients, and in accordance with the negative relation between IAcc and RHI in Tsakiris et al (2014), it was hypothesized that patients with eating disorders may experience a stronger change in body-ownership during the RHI, possibly due to an over-reliance of such patients on exteroceptive information (e.g. vision) at the expense of interoceptive information. Indeed, Eshkevari et al (2014b) showed that patients with eating disorders experience a stronger RHI relative to controls and this was mainly attributed to heightened visual capture in these patients. Lastly, using another type of interoceptive stimulation, namely slow affective touch that activates C-Tactile afferents, Crucianelli et al. (2013), as well as van Stralen et al. (2014) demonstrated how this kind of stimulation enhances the experience of body-ownership in the RHI. Importantly, when slow affective touch was delivered in a group of anorexic patients (Crucianelli et al. 2016), the patients reported reduced perceived pleasantness of affective touch, relative to controls, suggestive of an impaired C tactile system in anorexia nervosa, an impairment that may be linked to their weakened interoceptive perception and distorted body representation. Body image disturbances could therefore be interpreted as an interoceptive/exteroceptive imbalance; an increased sensitivity to external visual information, in the form of visual capture, which overrides other internal inputs about or from the body, such as touch and proprioception (Eshkevari at al. 2014b).

The effects of multisensory stimulation on body-ownership and body-image have been recently interpreted in the context of predictive coding. Predictive coding attempts to provide a unifying theory of cortical function that underlies perception, action and interoception (Friston, 2010; Seth, 2013). According to the predictive coding theory, incoming sensory data is compared with internal models, that is with the brain's 'prediction' (best guess) about the environmental causes that affect the organism. 'Prediction errors" arise when predictions and data are incompatible. Given that biological organisms must maintain their bodies within a narrow range of states, the prediction errors *must be minimised*. Adapting the predictive coding framework to self-processing (Apps & Tsakiris, 2014) one's own body is processed in a probabilistic manner as the most likely to be "me" (see Limanowski & Blankenburg, 2015 for empirical support). Because of the hierarchical organisation of the self, signals and predictions from any modality may thus be brought to bear to resolve a conflict between cues in another, including higher-level, abstract and amodal predictions about one's own body. This framework (Apps & Tsakiris, 2014) and other predictive models of self-awareness (Seth, 2013) are important for understanding the dynamic relation between exteroceptive and interoceptive representations of the body. For example, in the experience of body-ownership during the RHI, the exteroceptive data suggests that what I am looking at (i.e. the rubber hand) is my hand. However, this experience is accompanied by interoceptive prediction errors to the extent that I may not feel interoceptively that I am looking at my hand. Such errors need to be explained away between how my true hand feels (i.e. the interoceptive prediction) and the prediction error caused by the fact that I cannot feel the rubber hand interoceptively. Therefore, exteroceptive and interoceptive streams must be in some way integrated for a body to be represented as "self". What determines the weighting of the different streams?

As Ainley et al. (2016) suggest in a predictive coding account of interoceptive awareness, both predictions and the incoming sensory data vary in the precision (i.e. reliability) of the information that they convey (e.g. how noisy they are). Precision is crucial when selecting information amongst various modalities because the brain preferentially weights signals that are the most precise in the given context. During the experience of body-ownership in the RHI, participants form a percept that the prosthetic hand is their own, by minimising prediction errors across all available sensory modalities. Importantly in this context, information from any sensory modality can be used to explain away prediction error in any other (Apps & Tsakiris, 2014). It is precision that dictates which part of the conflicting evidence is presumed to be reliable. If their interoceptive signals are precise, this would explain why individuals with higher IAcc experience a weaker body-ownership during the RHI by contrast with individuals with lower IAcc, as the visual or visuotactile information is not weighted sufficiently to minimize interoceptive prediction errors. For people with higher IAcc, the brain weights interoceptive predictions and prediction errors as more reliable compared to those with lower IAcc, making them more resistant to the exteroceptive evidence. Therefore, individual differences can be explained in terms of variations in the 'precision' with which interoceptive signals from within the body are represented (Ainley et al., 2016; Fotopoulou, 2013; Friston, 2009; Seth, 2013), and this precision-dependent account can also explain the effects that levels of IAcc may have on the exteroceptively-driven representation of the self. Of course, the overall environmental and physiological context affects the precision of interoceptive inferences. For example, as discussed by Ainley et al. (2016; see also Pelluzo, 2014), one's heartbeat or the recognition of one's hand may be fully predicted by the brain in contexts that have been regularly experienced. Contexts that elicit unexpected changes in heart functioning or in proprioception (e.g. one's hand falling asleep), may alter the precision of interoceptive inferences, require a response from the organism and are likely to reach awareness. Such a framework provides a plausible explanation of the often striking effects that have been reported in relation to bodily illusions over the last 20 years, as it explains how exteroceptive evidence can be used to minimize prediction errors during the construction of our body-awareness but also how exteroceptive with interoceptive information are integrated in this process. Interestingly, a similar but inverse relationship holds between interoception and *attitudes* towards one's own body. As we reviewed earlier, Ainley and Tsakiris (2013) showed that levels of IAcc are inversely correlated with self-objectification, and with body-image satisfaction (Emanuelsen et al. 2015). Taken together, these observations suggest that interoceptive influences extend from the basic levels of multisensory integration to the conscious (affective) *attitudes* that we hold about our body, highlighting the role that interoception may play across different hierarchical levels of body-representations. A predictive coding account of self-awareness (Apps & Tsakiris, 2014) based on the processing of interoceptive signals (Barrett & Simmons, 2015) and their subsequent mentalization (Fotopoulou, 2015) may be particularly important for understanding how the body's viscera influences the body's image, and possibly for other mental disorders (see for example Harshaw, 2015, for a comparable approach in depression).

4. Conclusion

The different lines of research that we reviewed here suggest that interoceptive processing and body image concerns may indeed be linked, possibly in a causal way, whereby reduced levels of interoceptive awareness may predispose individuals for greater body-image dissatisfaction in non-clinical populations and the development of eating disorders or the severity of body-image disturbances in clinical populations.

Specifically, the findings of the studies reviewed above converge to four key conclusions. First, there is a reduced performance-based and self-reported aptitude to perceive and recognize bodily signals in various disorders characterized by body image distortions, mostly discussed in the present review in relation to eating disorder samples. Second, brain areas, such as the insula, that have been shown to underpin the cortical representation of interoceptive signals and our awareness to become aware of those are also implicated in the representation of one's body image. Third, the function of the insular cortex is altered in psychopathologies with major body image disturbances. Lastly, a direct relationship between body image and interoceptive abilities exists also in non clinical samples. Nevertheless, while the data from non-clinical populations are consistent insofar lower cardiac IAcc correlates with greater body image concerns, the data from patients with anorexia nervosa are not always consistent across. It is important to consider such contradictory conflicting results in the light of often important methodological disparities in the way interoception and body image are measured across experiments or differences in the distinct aspects of body image components that are examined across studies. On the one hand, the way of assessment is important. Self-reported measures of IAw and objective measures of IAcc may operationalize independent components of interoception (e.g. Garfinkel et al. 2015). The results obtained through different tasks of cardiac accuracy are often used interchangeably despite the fact that they may have distinct correlates (Kleckner & Quigley, 2014). Altogether, these methodological issues are making the direct comparisons across studies challenging. Moreover, cross-sectional mean comparisons or correlational analyses are the most commonly used statistical approaches, and they are unable to unveil more complex relationships between the two constructs *and their* underlying causal relations. Lastly, indirect inferences have been common in this literature. For instance, because severe body image distortions co-occur with difficulties to attend to one's own internal bodily signals in several psychopathologies, an association between interoception and body image is deduced. Thus, we argue that a deeper understanding of the relation between interoception and body image question must entail methodological improvements. Beyond the scope of methodological issues, the existing data also lift the veil on some questions that remain open in the current literature and might represent promising future research avenues.

5. Future Directions

Numerous additional unanswered questions represent a timely opportunity for focused multidisciplinary research in the potentially causal links between interoceptive and body image concerns. Among others, acknowledging the idea that the extent to which one can attend to his internal bodily signals is, in some way, related to how people feel, think and behave about their own body, the distal/trait or proximal/state status of interoception arises as an important future research avenue, in a way analogous to the use of such dimensions in body-image research. Cash (2002) states the need to differentiate distal from proximal factors that influence body image components. Still, to date, whether we should assign to interoceptive awareness an early trait factor or a state proximal role in the developmental trajectory of body image has to be determined.

In favour of a trait status, it is likely that awareness of bodily signals may be rooted in an early intersubjective process analogous to that of others aspects of the self (e.g Orbach, 2004; Fotopoulou & Tsakiris, 2017) or the discovery of different internal invisible states (e.g. mental contents, Fonagy & Target, 1997). According to this hypothesis, the infant may gradually learn to attend, recognize and regulate one's bodily signals through repeated embodied interactions with a caregiver able to acknowledge and mirror the infant's bodily expressions. (see Bruch, 1961, 1962 or Shai & Belski, 2011 for the role of parental embodied mentalization in the subjective development, and Fotopoulou & Tsakiris, 2017). This literature sheds light on a potential developmental cascade concerning the association between interoception and body image. The disruption of this interactive process, due to innate factors or environmental failures may initially reduce the salience of bodily sensations as a trustworthy source of knowledge, which further prompts the person to turn one's own attention away from one's own visceral signals, sowing seeds of body experience disturbances, including body image distortions. Another non-mutually exclusive hypothesis argues that interoception could also represent a state-like feature, with a proximal role in the relationship with body image. In this case, the capacity to accurately detect one's own bodily internal signals would not entail an individual stable trait. It may rather show moment-by-moment variations. Physical (e.g. body mass index), psychological (e.g. stress) or situational factors may trigger a change of IAcc and moderate its relationship with body image.

An increased understanding of the relationship between interoception and body image does not only entail conceptual advances but also presents potentially substantial clinical implications. If future works consolidates the association between interoception and body image, individuals with body image concerns and distortions may benefit from evidence-based interventions that enhance their capacity to attend to and interpret correctly their internal bodily signals. Recent papers suggest that targeting interoceptive deficits in patients with body image disturbances might be promising as these capacities might be prone to change through specific therapeutic interventions, such as mindfulness-based treatment (Broneman & Singer, 2016; Sliverstein et al., 2011), and have been shown to be important for relapse prevention (Price & Smith-DiJulio, 2016). As a whole, future research on this field may inform early "interoception – based intervention and prevention programs" on detecting youths at risk of body image disturbances and their related psychological disorders.

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Studies with Clinical Populations

Reference	Samples	Interoceptive measures	Body image measures	Key relevant findings
Bizeul et al. (2001)	- REC AN (n=13f) - AN (n=13f)	▪ EDI		▪ IAw is associated with AN severity
Eshkevari et al. (2014a)	- HC (n=60f) - mixed ED (n=74f)	▪ Hearbeat detection task ▪ EDI-3		▪ Comparable IAcc in ED and HC ▪ Lower IAw in ED than HC ▪ In ED, association between IAw and body dissatisfaction
Eshkevari et al. (2014b)	- HC (n=61f); - REC ED (n=28f); - ED (n=78f)	▪ EDI 3	SOQ RHI	▪ Lower IAw in ED than REC ED ▪ Lower IAw in REC ED than HC ▪ Increased proprioceptive drift (RHI) in REC than HC but decreased than ED
Forrest et al. (2015) *Study 1*	- HC (n=27, 11f) - Suicide ideators (n=35, 13f) - Suicide planners (n=14, 9f) - Suicide attempters (n=30, 20f)	▪ EDI		▪ IAw is associated to the degree of suicidality
Forrest et al. (2015) *Study 2*	- Outpatients with previous attempts (n=459, 272f) - No previous attempt (n=136, 104f)	▪ EDI		▪ Lower IAw in attempters than in no attempters ▪ Lower IAw is associated more to recent attempts than to distant attempts

Goldzak-Kunik et al. (2012)	- Adolescent AN (n=15 : 14f) - Adolescent HC (n=15 : 14f)	▪ Gustatory tests (i.e. food and nonfood tastes) ▪ Cold pain test	Body-size evaluation.	▪ Better cold detection in AN than HC ▪ Similar other sensory functions in AN than HC
Herbert & Pollatos (2014)	- Overweighted and obese (n= 55f) - Normal weighted (n=55f)	▪ Schandry Task		▪ Lower IAcc in overweight and obese than normal weighted ▪ Negative association IAcc and BMI
Khalsa et al. (2015)	AN (n=15f) HC (n=15f)	▪ Bolus intravenous infusions of isoproterenol (before/after meal) ▪ Interoceptive detection thresholds ▪ Retrospective ratings of palpitation and dyspnea intencity ▪ Correlations between subjective ratings and observed heart rate responses		▪ Normal IAw in AN at high arousal ▪ Altered Iaw at low arousal, during meal anticipation ▪ No differences in IAcc
Killen et al. (1994)	- Community children tested at 3-year interval (n=939f)	▪ EDI		▪ Lower IAcc is associated with the onset of ED symptoms over the interval
Klabunde et al. (2013)	- REC BN (n=9f) - HC (n=10f)	▪ Schandry task		▪ Lower IAcc in BN than HC
Mussgay et al. (1998)	- Psychiatric patients assessed for psychosomatic disorders (n=546 ; 409f)	▪ Schandry Task		▪ Trend to decreased IAcc in psychosomatic patients
Pollatos et al. (2008)	- AN (n=28f) - HC (n=28f)	▪ Schandry Task ▪ EDI		▪ Decreased IAcc and IAw in AN

Pollatos & Georgiou (2016)	- BN (n=23f) - HC (n=23f)	▪ Schandry Task ▪ EDI		▪ Lower IAw, assessed with EDI, in BN than HC ▪ Comparable IAcc in BN and HC ▪ Negative correlation between IAcc and IAw in BN but not HC
Ross et al. (2009)	- Adolescents with NSSI (n=59) - Without NSSI (n=57)	▪ EDI		▪ Decreased IAw in the NSSI sample
Terhaar et al. (2012)	- DP (n=16, 13f) - HC (n=16, 12f)	▪ Schandry Task		▪ Lower IAcc in DP than HC

Studies focusing exclusively on Non- Clinical Populations

Ainley & Tsakiris (2013)	- Adults (n=50f)	▪ Schandry Task ▪ BCQ	SOQ	▪ Negative association between IAcc and self-objectification
Duschek et al. (2015)	- Higher IAcc (n=30; 20f) - Lower IAcc (n=30;20f)	▪ Schandry Task ▪ BCQ	BAI	▪ Higher IAcc showed more positive body image scores
Holmes et al. (2015)	- Adults (n=408f)	▪ EDI	EDEQ	▪ Lower IAw was associated to higher body dissatistfaction ▪ IAw mediated the relationship between body image and binge eating
Emanuelsen et al. (2015)	- High school students (n=82; 53f) - University students (n=70 ; 49f)	▪ Schandry Task ▪ BAQ	BIQ	▪ Negative association between IAcc and body dissatisfaction score ▪ No relation IAcc-IAw

Table 1 : Summary of the main behavioral results that inform the relation between interoception and body image. The table does not provide an exhaustive summary of measures and results reported in the studies, as often these studies included other tasks and depenedent variables that go beyond the scope of the present paper. Therefore, only results and measures relevant for the aims of the present paper were included. AN stands for Anorexia Nervosa, BN for Bulimia Nervosa, DP for depression, ED for

Eating Disorders, HC for Healthy Control, NSSI for Non-Suicidal Self-Injury, REC for recovered. BAI is for Body Appraisal Inventory, BAQ for Body Awareness Questionnaire, BCQ for Body Consciousness Questionnaire, BIQ for Body Image Ideals Questionnaire, EDI for Eating Disorder Inventory, EDEQ for Eating Disroder Examination Questionnaire, RHI for Rubber Hand Illusion, SOQ for Self-Objectification Questionnaire.