CiMeC
Center for Mind/Brain Sciences

UNIVERSITY
OF TRENTO - Italy
CIMeC - Center for Mind/Brain Sciences

BODY REPRESENTATIONS IN OBESITY

PhD Candidate

Sofia Tagini

Doctoral School in Cognitive and Brain Sciences (32nd Cycle)

CIMeC, Center for Mind/Brain Sciences,

Rovereto (TN)

University of Trento

Tutor: Prof. **Massimiliano Zampini**

TABLE OF CONTENTS

ABSTRACT

Body representation disorders have a key role in the characterization of obesity. So far, the literature consistently pointed to a negative attitudinal body image. Conversely, after reviewing the pertinent literature, it emerges that more incoherent results have been reported for the self-perceived body size. **Chapter 2** tries to clarify this issue by adopting a more innovative theoretical framework (i.e., the implicit/explicit model; Longo, 2015). For the first time, we probed the implicit representation underlying position sense in obesity, reporting a similar representation to healthy weight participants. Importantly, this result shows that not all components of body representation are affected by obesity. **Chapter 3** addresses another aspect of body representation that has been neglected in obesity, namely bodily self-consciousness. The Rubber Hand Illusion has been traditionally used to investigate the mechanisms underlying body awareness. Our results show that individuals with obesity have comparable subjective experience of the illusion, while the effect of the illusion on self-location is reduced. This dissociation can be interpreted as the result of a preserved visuo-tactile integration and an altered visuo-proprioceptive integration in obesity. However, in **Chapter 4** we reported that individuals with obesity have a reduced temporal resolution of visuo-tactile integration, meaning that they integrated stimuli over an extended range of asynchronies than healthy weight participants. In fact, this evidence predicts that in the RHI individuals with obesity might perceive more synchronously the asynchronous stimulation, showing a greater effect of the illusion also in this condition. Nevertheless, we failed to show this pattern of results in our study with an interval of asynchronous stimulation of 1000 ms (usually adopted in the RHI paradigm). We hypothesized that smaller time-lags, which are inside the temporal binding window of individuals with obesity and outside the temporal binding widow of healthy weight participants, might not be perceived by individuals with obesity but detected by healthy weight individuals. Accordingly, a dissimilar susceptibility to the illusion should be observed. **Chapter 5** investigates this issue by adopting a modified version of the RHI that enables a parametrical modulation of the timing of the stimulation. However, we could not replicate the RHI even in healthy weight participants. The possible methodological reasons for this failure are discussed.

Overall, this work tries to fill some gaps in the previous literature about body representation in obesity. Moreover, our findings provide an important clue about the possible cognitive mechanisms involved in body representation disorders in obesity. However, many questions still need an answer: due to the complexity of the domain a comprehensive knowledge of the topic might be challenging. A deep understanding of obesity is fundamental to develop multidisciplinary and efficacious rehabilitative protocols. Indeed, better treatments would significantly ameliorate individuals' well-being but also contribute to reduce the huge health costs related to obesity comorbidities.

THESIS OVERVIEW

Obesity is a complex clinical condition that has a major impact on people's quality of life, due to its **physical** consequences but also given its **social**, **psychopathological**, and **cognitive correlates**. These aspects are discussed in detail in the first section of the **Preliminary Introduction** (Chapter 1). In particular, the Preliminary Introduction aims to outline a general description of obesity and to get the reader acquainted with the key concepts necessary to contextualize the experimental works presented later. In the section 1.2, the topic of **body representation** is introduced focusing on the traditional distinction between **body image** and **body schema** (Berlucchi & Aglioti, 2010; de Vignemont, 2010) but also discussing an alternative taxonomy of body representations: the **implicit/explicit model** more recently proposed by Longo (2015). Importantly, Longo's model has been adopted to introduce the research questions of the first study presented (Chapter 2), which investigates the implicit self-perceived body size in obesity. Finally, the section 1.2 describes how individuals build coherent body representations, discussing the role of **multisensory integration** and, specifically, of the temporal resolution of this process. This information aims to provide the conceptual framework for the studies presented in Chapter 3, 4, and 5, which focus on the relationship between multisensory integration and body representation (specifically, bodily-self-consciousness) in obesity.

It is worth noting that the purpose of this section is not to discuss the whole knowledge gained so far on body representations; instead, it aims to provide the information essential to the understanding of both the previous investigation of **body representations** in **obesity** and the present work.

Body representation disorders have a crucial role in the characterization of this clinical condition (e.g., Schwartz & Brownell, 2004). The topic of **body dissatisfaction** (i.e., attitudinal body image), **body size estimation** (i.e., perceptual body image), and **body schema** in obesity are discussed in detail in the section 1.3 of the Preliminary Introduction. So far, the literature has consistently demonstrated a negative attitudinal body image in obesity (see e.g., Weinberger et al., 2016). On the other hand, studies on the perceptual body image reported more incoherent results (see e.g., Schwartz & Brownell, 2004, Tagni et al., in preparation). However, the previous works mainly referred to a dyadic taxonomy of body representations, which nevertheless has been criticized (Berlucchi & Aglioti, 2010; de Vignemont, 2010; see also section 1.2).

In **Chapter 2**, the adoption of a more innovative theoretical framework, i.e. the implicit/explicit model proposed by Longo (2015), is proposed to shed light on the investigation of the self-perceived body size in obesity. If this model is applied to the previous literature on body size estimation in obesity, it emerges that these individuals might have a distorted explicit representation of the body, mainly in the direction of an overestimation of body dimensions. On the other hand, the implicit representation has been rarely studied in obesity (Scarpina, Castelnuovo, & Molinari, 2014). In Chapter 2, the **implicit representation** of the body metric involved in position sense has been investigated in obesity and healthy weight participants with the **landmarks localization task** (see e.g., Longo and Haggard, 2010). The results are interpreted suggesting a possible dissociation between a similar implicit representation and a dissimilar explicit representation of the body among individuals with obesity and with healthy weight. The possible role of body dissatisfaction in this dissociation is suggested but it is still a speculative interpretation, which deserves further investigation. Furthermore, it is discussed how this first study might help in the understanding of the previous inconsistent findings about body size estimation in obesity.

Beyond the implicit representation, also other aspects of body representation in obesity have never been addressed or scarcely considered. **Chapter 3** focuses on **bodily self-consciousness**. As reported in the introductory chapter, body representations (Azañón et al., 2016; Maravita, Spence, & Driver, 2003; Pasqualotto, Dumitru, & Myachykov, 2016) and, specifically, bodily self-consciousness (Blanke, 2012; Ehrsson, 2012) ground on the integration of multisensory body-related stimuli. In the **Rubber Hand Illusion** (RHI), bodily self-consciousness is manipulated through *ad hoc* visuo-tactile stimulation of the real (hidden) hand and a rubber (visible) hand (Botvinick & Cohen, 1998). When the stimulation is synchronous, visuo-tactile-proprioceptive signals are integrated in the same perceptual event. As a consequence, the rubber hand *feels* like the real hand and the perceived location of the real hand is recalibrated in favour of the fake one (Botvinick & Cohen, 1998). As anticipated in the Preliminary

Introduction, temporal sensitivity (namely, the ability to discriminate between synchronous and asynchronous stimuli) is tightly related to multisensory integration since simultaneous stimuli have a higher probability to be bounded (Spence, 2007; Stein & Meredith, 1993; Wallace et al., 2004). The perception of multisensory simultaneity is thus crucial for the illusion to emerge.

This paradigm has been widely used to investigate the multisensory mechanisms supporting body representations in both typical (e.g., Botvinick & Cohen, 1998; Moseley et al., 2008; Pavani & Zampini, 2007; Rohde, Luca, & Ernst, 2011; Tsakiris & Haggard, 2005) and atypical populations (e.g., Cascio, Foss-Feig, Burnette, Heacock, & Cosby, 2012; Ding et al., 2017; Kaplan, Enticott, Hohwy, Castle, & Rossell, 2014; Nava, Steiger, & Roder, 2014; Thakkar, Nichols, McIntosh, & Park, 2011). Furthermore, multisensory integration anomalies have been linked to altered susceptibility to this bodily illusion (Cascio et al., 2012; Ding et al., 2017; Eshkevari, Rieger, Longo, Haggard, & Treasure, 2012; Kaplan et al., 2014; Keizer, Smeets, Postma, van Elburg, & Dijkerman, 2014; Nava et al., 2018; Paton, Hohwy, & Enticott, 2012; Thakkar et al., 2011). Interestingly, an altered processing of multisensory information has been reported in obesity (Scarpina et al., 2016; Wan, Spence, Mu, Zhou, & Ho, 2014). Consequently, one might hypothesize that bodily self-consciousness would be affected in obesity. In Chapter 3, the susceptibility to an adapted version of the RHI (i.e., using a real-size picture of the participant’s hand) has been compared between individuals with obesity and healthy weight participants. Both groups properly experience the illusion, as subjectively reported in a questionnaire. However, the illusion had no effect on the recalibration of the hand position towards the rubber hand (i.e., implicit measure) in obesity. As mentioned, the success of the illusion is strictly related to the multisensory integration of stimuli, which in turn is linked to the fact that these stimuli are delivered synchronously. When the stimulation is asynchronous, the sensory information cannot be merged and the illusion does not occur (Botvinick & Cohen, 1998; Ehrsson, 2012; Rohde et al., 2011). An altered processing of multisensory stimuli in obesity, thus, might explain our findings. Specifically, our results suggest that the processing of visuo-proprioceptive stimuli that supports the recalibration of position sense in the illusion (Rohde et al., 2011) might be altered in obesity, whereas the visuo-tactile integration that supports the explicit manipulation of bodily self-consciousness might be preserved. It can be speculated that visuo-tactile simultaneity was properly perceived (inducing the experience of the illusion), while visuo-proprioceptive temporal congruency was not detected (impeding the recalibration of position sense). The temporal resolution of visuo-tactile and visuo-proprioceptive integration has never been addressed in obesity. However, previous findings reported a reduced temporal sensitivity to audio-visual simultaneity (Scarpina et al., 2016). The authors hypothesized that this evidence might be related to the altered neural oscillatory activity found in obesity (Babiloni et al., 2011; Del Percio et al., 2013; Dubbelink et al., 2008). Moreover, also the atypical cerebral anatomy/metabolism in areas involved in multisensory integration (Maayan et al., 2011; Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Volkow et al., 2009; Weise et al., 2013; Willette & Kapogiannis, 2015; Yokum et al., 2012) might explain a reduced temporal sensitivity to multisensory simultaneity in obesity. However, these mechanisms would conceivably affect the whole process of integration, beyond the specific sensory modalities involved. On the contrary, our findings seem to suggest that the temporal sensitivity to visuo-tactile stimuli was preserved in obesity.

Chapter 4 aims to disentangle this issue, probing the **temporal resolution of visuo-tactile integration** in obesity through a **simultaneity judgment task** (Vroomen & Keetels, 2010; Zampini, Guest, Shore, & Spence, 2005). The results indicate a reduced temporal resolution of visuo-tactile integration in obesity, supporting the hypothesis of a cross-modal impairment. The apparent incongruency with the findings reported in the previous study are discussed in the light of the specific stimulus-onset asynchrony (SOA) used in the illusion paradigm. Stimuli have been delivered with 1 second delay that, according to the results of Chapter 4, should be properly detected by individuals with obesity despite the reduced temporal sensitivity. In other words, the different temporal sensitivity between individuals with obesity and healthy weight participants emerges with narrower visuo-tactile SOAs than the time lag used in Chapter 3. Therefore, we speculated that the subjective experience of the illusion might be differentiated between groups if small SOAs are adopted since the perception of simultaneity might be different in the two groups with these delays.

In **Chapter 5** we aimed to probe this hypothesis modulating parametrically the SOAs used in the administration of the RHI. A modified version of the RHI was adopted, enabling a precise timing of the stimulation (Costantini et al., 2016). According to the results of Chapter 4 different SOAs have been identified to maximize the difference between groups in the ability to detect visuo-tactile simultaneity and, possibly, to experience the illusion. Unfortunately, the data collection was interrupted since troubles were detected in inducing the illusion in the healthy weight population, even with the typical synchronous stimulation. The possible reasons of this inconvenient are discussed.

Finally, the last Chapter (i.e., **General Discussion**) aims to summarise and integrate the results of the five studies presented, highlighting the relevance of the present findings in the advancement of this research field. Furthermore, the open questions and the recommendable future studies are discussed.

1 PRELIMINARY INTRODUCTION [1]

1.1 OBESITY

Obesity is a medical condition characterized by an excessive accumulation of body fat, which is determined by an energy imbalance between calories consumed (e.g., increase intake of foods that are high in fat) and energy expenditure (WHO, 2019). Conventionally, obesity is measured by computing the Body Mass Index (BMI; i.e., weight in kilograms divided by height in meters squared; see e.g., WHO, 1995) Individuals with a BMI higher than 30 are considered clinically affected by obesity. Obesity afflicts the 19.5% of the worldwide population on average, with the lowest prevalence in Japan (3.7%) and the highest in the United States (38.2 %; OECD/EU, 2017). The number of people affected by obesity increased steadily in the last 30 years and, crucially, it is believed to keep on growing in both developed and underdeveloped countries (Dixon, 2010). Importantly, obesity is associated with a higher prevalence of severe pathological conditions, such as cardiovascular diseases, cancer, and diabetes (Lamarche, Lemieux, & Despres, 1999; Massie, 2002; Tchernof et al., 1996; Zimmet, Alberti, & Shaw, 2001). Thus, not surprisingly, it is related to an increased rate of mortality (Haslam & James, 2005). Furthermore, individuals with obesity often develop musculoskeletal disorders, osteoarthritis and several other physical disabilities which determine limbs pain and major mobility problems (e.g., Barofsky et al., 1997).

Physical comorbidities significantly impact on individuals' quality of life (Dixon, 2010), however, also the social consequences of being affected by obesity contribute to deteriorate people's well-being (Puhl & Heuer, 2009). In modern western societies, the value of a thin and lean body is strongly emphasized, favouring the development of a strong weight "anti-fat" stigma (Puhl & Brownell, 2001; Puhl & Heuer, 2009). The weight stigma determines negative attitudes towards individuals with obesity. Moreover, it

---

[1] Some of the contents reported in this Chapter are part of the work *"Body Size Estimation in Obesity: A Novel Insight from the Implicit/Explicit Model of Body Representations"* by Sofia Tagini, Federica Scarpina and Massimiliano Zampini, currently in preparation.

seems to be pervasive in the general population (Teachman, Gapinski, Brownell, Rawlins, & Jeyaram, 2003) and it has been reported even in health care professionals (Schwartz, Chambliss, Brownell, Blair, & Billington, 2003). People with obesity are stereotyped as lazy, weak-willed, sloppy and emotionally unstable. Furthermore, they are discriminated in crucial domains of life, including education, employment, health care and social interactions (Papadopoulos & Brennan, 2015; Puhl & Heuer, 2009). Notably, the weight stigma increases individuals' vulnerability, favouring the development of maladaptive weight-related behaviours (i.e., unhealthy eating behaviours, exercise avoidance) but also mood disorders and low self-esteem (Papadopoulos & Brennan, 2015; Puhl & Brownell, 2001; Puhl & Heuer, 2009).

Psychopathological comorbidities

Commonly, individuals with obesity are believed to suffer from a higher psychological distress when compared to healthy weight individuals. Nevertheless, previous studies investigating the prevalence of psychopathological conditions in obesity, specifically low self-esteem, depression, and anxiety, reported inconsistent results (Fabricatore & Wadden, 2004; Friedman, Reichmann, Costanzo, & Musante, 2002). Certain subgroups of people might be more vulnerable while others more resilient (Dixon, Dixon, & O'Brien, 2003; Wadden et al., 2006). Female sex, severe obesity, and binge eating comorbidity seem to be crucial risk factors for the development of psychopathologies (Fabricatore & Wadden, 2004; Friedman & Brownell, 1995). Furthermore, people who are actively seeking for treatments report higher psychological distress than "non-seeker" (Fabricatore & Wadden, 2004). Nevertheless, it is not clear whether being overweight causes such psychopathological burden, especially given the related social stigma and a poor quality of life, or *vice versa* whether psychopathological vulnerabilities precede obesity. Longitudinal studies reported that mood disorders forerun obesity in adolescents girls (but not in boys) and that, on the contrary, obesity was found to be predictive of later psychopathological disorders in adults (Carpenter, Hasin, Allison, & Faith, 2000; Istvan, Zavela, & Weidner, 1992). Finally, a negative body image has also been related to a higher prevalence of mood disorders in obesity (Friedman et al., 2002), as discussed later in this chapter.

Cognitive comorbidities

Obesity has been extensively linked to several cognitive deficits (Prickett, Brennan, & Stolwyk, 2015; Smith, Hay, Campbell, & Trollor, 2011; Wang, Chan, Ren, & Yan, 2016). The majority of experimental findings points consistently to an impairment of executive functions (Boeka & Lokken, 2008; Fagundo et al., 2012; Lokken, Boeka, Yellumahanthi, Wesley, & Clements, 2010; Nilsson & Nilsson, 2009; Roberts, Demetriou, Treasure, & Tchanturia, 2007; Wolf et al., 2007), including decision making and inhibition (Fagundo et al., 2012). However, evidence of cognitive disorders is also reported in other domains, such as memory (Gunstad, Paul, Cohen, Tate, & Gordon, 2006; Nilsson & Nilsson, 2009), attention (Etou et al., 1989; Fergenbaum et al., 2009), visuo-constructional abilities (Boeka & Lokken, 2008; Lokken et al., 2010), and language (Gunstad, Lhotsky, Wendell, Ferrucci, & Zonderman, 2010; Nilsson & Nilsson, 2009). Furthermore, several studies revealed that mid-life obesity is associated with a greater risk of developing later-life dementia (Kivipelto et al., 2005; Whitmer, Gunderson, Barrett-Connor, Quesenberry, & Yaffe, 2005). Importantly, lower cognitive performances were also shown in individuals affected by obesity after controlling for socioeconomic variables (Smith et al., 2011; Sørensen & Sonne-Holm, 1985). However, Prickett and colleagues (2015) pointed out that quite often studies investigating cognitive functioning in obesity did not control properly for all the possible confounding factors, such as the presence of cardiovascular diseases and mood disorders, which are associated with cognitive impairments independently from the presence of obesity. Therefore, more systematic and controlled investigations are needed to understand the link between obesity and the cognitive functions. Indeed, cognitive dysfunctions might also precede the onset of obesity, suggesting a bidirectional relationship. For instance, poor cognitive performances in healthy weight children seem to predict the later increase of the BMI (Smith et al., 2011).

Cognitive impairments in obesity might be related to the low-grade, chronic, and pervasive inflammation of the organism determined by the accumulation of lipids in the intracellular tissues (Miller & Spencer, 2014; Spyridaki, Avgoustinaki, & Margioris, 2016; Spyridaki et al., 2014). This low-grade pro-inflammatory status would spread from the periphery to the central nervous system, favouring the release of C-reactive protein and other inflammatory biomarkers (i.e., cytokines) that affect cerebral metabolism (Baune et al., 2008; Trollor et al., 2010), neurogenesis, and favour neurodegeneration (see, for a review Miller & Spencer, 2014). Indeed, obesity has been related to lower metabolic activity in the prefrontal cortex (Volkow et al., 2009), which is crucially involved the executive functioning (Denes & Pizzamiglio, 1999). Moreover, individuals with obesity often develop insulin resistance (e.g., Kahnz & Flier, 2000) that, in turn, has been related to the development of cognitive impairments (Kim & Feldman, 2015). Furthermore, neuro-inflammation is also associated with structural changes in brain anatomy (Satizabal, Zhu, Mazoyer, Dufouil, & Tzourio, 2012; Wilson, Finch, & Cohen, 2002). Previous studies reported atrophy of the frontal (Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Willette & Kapogiannis, 2015) and prefrontal cortex (Maayan, Hoogendoorn, Sweat, & Convit, 2011; Pannacciulli et al., 2006; Weise, Thiyyagura, Reiman, Chen, & Krakoff, 2013; Willette & Kapogiannis, 2015) in obesity that, conceivably, contributes to the executive impairments found in this population (Walther, Birdsill, Glisky, & Ryan, 2010). Structural anomalies in the brain of individuals with obesity have been also found in the temporal (Weise et al., 2013; Yokum et al., 2012) and occipital lobe (Pannacciulli et al., 2006), hippocampus, thalamus, anterior cingulate gyrus (Raji et al., 2010), post-central gyrus, putamen (Pannacciulli et al., 2006), insula (Pannacciulli et al., 2006; Weise et al., 2013), and cerebellum (Weise et al., 2013), with potential detrimental effects on several cognitive functions.

Crucially, cognitive deficits might adversely affect the compliance with weight loss treatments and the adherence to long-term weight management, especially considering the role of executive functions in the ability to control humans’ behaviour.

Finally, a key aspect that must be considered when dealing with obesity is that individuals often have a peculiar experience of the body, characterized by body representation anomalies (Schwartz & Brownell, 2004). Importantly, body representation disorders might have a significant impact on both people’s welfare and treatment outcomes.

1.2 BODY REPRESENTATIONS

Definition and taxonomy

The brain gathers and integrates the bodily information in the so-called *body representations* (Berlucchi & Aglioti, 2010; de Vignemont, 2010; Dijkerman & de Haan, 2007; Longo, 2017; Longo, Azañón, & Haggard, 2010), supporting our movements and interactions with the environment (Dijkerman & de Haan, 2007; Longo et al., 2010) and enabling us to recognize and distinguish our body from the others (Tsakiris, 2017). Body representation impairments may have deleterious effects on people's well-being, by generating extreme misperceptions of the body. For instance, after right-sided cerebral damages some patients deny that the controlesional paralyzed limb is their own, insisting that it belongs to someone else (*somatoparaphrenia*; Vallar & Ronchi, 2009). Otherwise, people affected by certain neurological and psychiatric conditions reported to "see" themselves and the surrounding world from an external perspective, outside the boundaries of the physical body (*out-of-body experiences*; Blanke, Landis, Spinelli, & Seeck, 2004; see, for more examples, Longo, 2017).

Traditionally, the mental representation of the body has been fractioned into two different cognitive components: the *body schema* and the *body image* (e.g., de Vignemont, 2010, for a review). The body schema consists of a dynamic, non-conscious, representation of the posture and spatial location of the body in action, which is continuously updated (Buxbaum & Coslett, 2001; Dijkerman & de Haan, 2007; Gallagher, 2005; Paillard, 1999; Schwoebel, Branch Coslett, & Coslett, 2005; Sedda & Scarpina, 2012). In contrast, the body image refers to stored perceptual, conceptual, and emotional representations of the body (Gallagher, 2005; Head & Holmes, 1911; Paillard, 1999) of which we are aware (Paillard, 1999). For example, when we pass through a doorway, we are not aware of the rapid update of the representation of the body in space necessary to perform the movement efficaciously (i.e., body schema), yet we can ask ourselves if we will fit through the door (i.e., body image). However, the terms "body schema" and "body image" have been often used inconsistently in the literature, frequently referring to vague concepts whose meanings differ from author to author (Berlucchi & Aglioti, 2010; de Vignemont, 2010). Moreover, this dyadic taxonomy of body representations fails to explain the whole experimental evidence and to categorize all the clinical observations into body schema/body image impairments (Berlucchi & Aglioti, 2010; de Vignemont, 2010). Consequently, additional partitions of body representation have been suggested (see de Vignemont, 2010, for a review), such as the *Body Structural Description* (i.e., a topological map of the body), and the *Semantic and Lexical Representation* (including the names of body parts and their functions; Schwoebel et al., 2005). Previous studies in obesity mainly referred to the traditional distinction between body image and body schema.

Alternatively, Longo (2015) theorized that several body representations can be identified by different levels of accuracy and three-dimensionality at each point of the same continuum (Longo & Haggard, 2010; 2011;2012a; 2012b; Longo, 2015; Mancini, Longo, Iannetti, & Haggard, 2011). At one end of the continuum, are located the primary somatosensory maps that represent the body as a rough bidimensional mosaic of body surfaces. It is well-known that in the primary somatosensory cortex the representation of the different parts of the body is not commensurate with their actual dimensions (Penfield & Boldrey, 1937). Thus, these representations are extremely imprecise.

The representations located in the middle of the continuum are shaped on the primary somatosensory maps (Longo & Haggard, 2010), explaining why they are still slightly imprecise (Linkenauger et al., 2015; Longo & Haggard, 2012a). Nevertheless, these representations are more accurate and three-dimensional (i.e., “2.5-dimensional”; Longo & Haggard, 2012a) since they constitute higher-level percepts of the body (somato*perception*), beyond the information delivered by the primary somatosensory system (somato*sensation*; Longo et al., 2010). These representations support high order somatosensory processes (Longo et al., 2010), such as the ability to localize (Mancini et al., 2011) and to estimate the size of tactile stimuli on the body (Longo & Haggard, 2011), and to self-localize our body in the space (Longo & Haggard, 2010) (see Chapter 2 for further details). During actions, the visual information might offset the residual biases of these representations (Longo & Haggard, 2010). As a result, we can accurately locate the body in the space and move properly. On the other hand, when vision is not available the accuracy of our movements decreases (e.g., Kuling, Brenner, & Smeets, 2013) and action trajectories are influenced accordingly to the distortions of the representations (Peviani & Bottini, 2018). Individuals use the information stored in these representations automatically: they are not aware to take advantage of it. These representations are, thus, called *implicit.*

The *explicit* representation lies at the opposite end of the continuum and consists of an accurate three-dimensional representation of the whole body. The explicit representation relies mainly on visual information and represents the body as a volumetric object (Longo, 2015; Longo, 2015b). This representation is recruited when individuals consciously think about a three-dimensional "picture of their body" or when they have to judge the body. For instance, when they have to decide whether a template is the same size as their own body (Longo & Haggard, 2012).

The distinction between implicit and explicit body representations might resemble the mentioned distinction between unconscious body schema supporting actions and conscious body image supporting perception (Dijkerman & de Haan, 2007; Gallagher, 2005; Kammers, de Vignemont, Verhagen, & Dijkerman, 2009). However, the idea of a continuum of body representations enables a more flexible taxonomy; indeed, it predicts a wider range of constructs defined, at each point, by different levels of accuracy and three-dimensionality. Moreover, since these body representations are part of the same continuum they can interact and individuals can recruit different hybrid combinations of implicit and explicit representations (Longo & Haggard, 2012b).

Interestingly, Longo and Haggard (2012b) applied the mentioned model to the investigation of body size estimation, providing an innovative interpretation of the body representations involved in the tasks used in this research field. The adoption of this theoretical framework may help to interpret the inconsistencies previously reported in the literature on body size estimation. With a view to the present dissertation, this approach may be specifically worthy in obesity since previous studies found high incoherent results. The state of art about body size estimation in obesity will be discussed in detail later in the present chapter. Furthermore, the potential relevance of Longo's model (2015) in the investigation of body representations in obesity will be highlighted in the first experimental study presented (Chapter 2).

How do we build body representations? The role of multisensory integration

All sensory modalities contribute to the development of body representations, including visual, tactile, proprioceptive, vestibular, and auditory signals (Azañón et al., 2016; Ehrsson, 2012; Maravita, Spence, & Driver, 2003). However, to build coherent representations of the body these multisensory body-related inputs must be integrated (e.g., Pasqualotto, Dumitru, & Myachykov, 2016).

Generally speaking, multisensory integration enables us to organize the sensory information into a meaningful way binding together the information that belongs to the same object or event and segregating unrelated incoming signals. Accordingly, the accuracy of our perception is significantly improved (Calvert et al., 2004). The same mechanism applies to the development of body representations.

How does the brain know which inputs should be bounded and which one should not? The *assumption of unity* states that if signals from different modalities share a-modal properties the brain more likely treats them as originating from a common source (Vroomen & Keetels, 2010). For instance, when multisensory stimuli originate from the same *location* in the space they are easily integrated (e.g., Bertelson & De Gelder, 2004; Wallace et al., 2004). *Temporal coincidence* has also been identified as a fundamental factor determining whether multisensory stimuli should be integrated (Spence, 2007; Stein & Meredith, 1993; Wallace et al., 2004). However, strict temporal overlap is not necessary. In fact, sensory signals have different physical properties, as well as dissimilar computational and transmission timings, meaning that simultaneous stimuli might be detected by the brain with a slight delay (e.g., Pöppel *et al*., 1990). The brain has learned to tolerate small asynchronies between sensory information, still perceiving them in synchrony and bounding them to the same percept. As a consequence, even stimuli that are *not* physically simultaneous might be perceived synchronously and thus integrated (Vroomen & Keetels, 2010). The psychophysical measure of the time lag tolerated by the brain in order to perceive two stimuli as synchronous is called *temporal binding window* (Stevenson & Wallace, 2013). The larger is the temporal binding window, the higher is the probability to merge stimuli that do not belong to the same environmental event, with significant consequences on the accuracy of multisensory perceptions. The perception of simultaneity across sensory modalities is thus strictly related to the efficiency of multisensory integration (Stevenson & Wallace, 2013; Vroomen & Keetels, 2010).

Temporal sensitivity to multisensory simultaneity has a crucial role also in the multisensory integration mechanisms that support body representations and, more specifically, bodily self-consciousness (Blanke, 2012; Ehrsson, 2012). In the Rubber Hand Illusion (RHI), the simultaneous stroking of a visible rubber hand and the real (hidden) hand generates the feeling that the fake hand is *our own* and it induces to perceive the real hand as being located closer to the rubber one (Botvinick & Cohen, 1998). The perceptual conflict between the visible and the proprioceptive location of the hand is resolved by attributing the tactile sensation to the rubber hand (Blanke, 2012; Ehrsson, 2012). Indeed, the RHI depends on the three-way integration of visual, tactile and proprioceptive body-related stimuli. However, the RHI occurs only when the real and the fake hand are stroked synchronously since asynchronous stimuli cannot be integrated.

This illusion highlights the crucial role of multisensory integration and, more specifically of the temporal aspects of integration, in supporting and generating individuals' body representations. This topic will be probed in detail in Chapter 3, 4, and 5.

1.3 BODY REPRESENTATIONS IN OBESITY

The attitudinal body image: body dissatisfaction in obesity

As previously mentioned, body image includes attitudes, feelings, and beliefs about one's body (Gallagher, 2005; Head & Holmes, 1911; Paillard, 1999). These components of body representation define the so-called attitudinal body image, including a subjective evaluation of the degree of body dis/satisfaction. In other words, the possible discrepancy between one's perception of the body (actual body image) and how she/he would like to be (ideal body image). The current sociocultural norms of beauty significantly impact on the level of body dis/satisfaction in obesity emphasizing the need for a thin and lean body (Schwartz & Brownell, 2004). Indeed, a recent meta-analysis on the topic demonstrated that individuals with obesity have significantly more body image concerns than healthy weight individuals (Weinberger et al., 2016). However, even though the degree of body dissatisfaction generally increases with the BMI, this relationship seems to be mediated by several factors (Friedman et al., 2002; Schwartz & Brownell, 2004; Weinberger et al., 2016). For instance, body uneasiness is usually higher in women than men with obesity (e.g., Feingold & Mazzella, 1998; Muth & Cash, 1997), without considering that also healthy weight women often report a "normative discontent" (i.e., a low, tolerable, level of body dissatisfaction; Rodin, Silberstein, & Striegel-Moore, 1984). On the contrary, men might identify heaviness with strength; consequently, they would be more comfortable with their bodies (Schwartz & Brownell, 2004). Moreover, also ethnicity seems to influence body dissatisfaction since Afro-American and Hispanic women with obesity are more satisfied with their bodies than Caucasian women. This phenomenon might be due to a different sociocultural standard of beauty, which includes a wider range of "acceptable" body weight (Altabe & O'Garo, 2002; Celio, Zabinski, & Wilfley, 2002; Rucker & Cash, 1992). Furthermore, the presence of binge eating seems to be associated with higher weight and shape concerns, independently from the actual weight (see, for a review, Schwartz & Brownell, 2004). A subjective experience of stigmatization and teasing also enhances body dissatisfaction (Milkewicz & Cash, 2000), especially in those individuals with binge eating comorbidity (Jackson, Grilo, & Masheb, 2002). Finally, people with obesity who are treatment- seeking are generally more disappointed about their body than individuals who do not attempt to lose weight (Weinberger et al., 2016). This observation contributed to the idea that a certain degree of discontent about the body might motivate people to lose weight (Heinberg, Thompson, & Matzon, 2001; Sarwer, Thompson, & Cash, 2005). Heinberg and colleagues (2001) attempted to disentangle this issue suggesting that the relationship between body dissatisfaction and weight loss might be U shaped. Individuals that feel totally comfortable with their body, despite obesity, might not be determined to lose weight while individuals who have moderate body dissatisfaction might be more motivated. On the opposite, an excessive level of body concerns might be deleterious, making people feel hopeless, worthless, depressed and, therefore, less motivated to lose weight. However, the relationship between body dissatisfaction and (excessive) body weight might be far more complicated. Body dissatisfaction positively benefits from weight loss and deteriorates when individuals regain weight (Chao, 2015; Sarwer et al., 2005). Furthermore, a decrease in body concerns during weight loss treatments leads to more favourable outcomes and predict long-term weight maintenance (Chao, 2015; Cooper & Fairburn, 2001; Palmeira et al., 2010). Friedman and colleagues (2002) demonstrated that body dissatisfaction mediates the relationship between BMI and depression/low self-esteem, directly contributing to the psychological distress in treatment-seeking individuals with obesity. Accordingly, a reduction in body dissatisfaction during weight loss might "release" additional, favourable, psychological resources leading to better compliance with the treatment (Palmeira et al., 2010). However, people's concerns about body appearance can improve also independently of weight loss, when promoting a healthier lifestyle and higher self-acceptance (e.g., Cash, 2002; Cash & Strachan, 2002). Moreover, a certain independence of body dissatisfaction from weight loss is evident in the so-called *"phantom fat"* phenomenon, which defines the presence of residual body image disorders/body dissatisfaction despite a significant weight loss (Guardia et al., 2013; Schwartz & Brownell, 2004). This phenomenon might be explained in light of the so-called *allocentric lock* hypothesis (Riva, 2011, 2012). The allocentric (i.e., from "others' perspective") body representation includes consolidated long-term beliefs and attitudes related to the body (Riva, 2011, 2012). The social and cultural pressure to "be thin" is internalized in the allocentric body representation, which in obesity leads to an extremely negative conceptualization of the body. On the other hand, the egocentric representation reflects the current somatosensory state of the body. Normally, the allocentric and egocentric representation of the body interplay, however, individuals affected by obesity would struggle to integrate them in a coherent representation (Riva, 2011, 2012). Consequently, in the presence of physical changes such as weight loss they would be "locked" in an allocentric negative body representation. Importantly, this would negatively affect clinical compliance and treatment outcomes.

Concluding, body dissatisfaction has a crucial role in the characterization and treatment of obesity. Moreover, it should be specifically addressed by the rehabilitative protocols since weight loss might not be sufficient to improve it.

The perceptual body image: body size estimation in obesity

Body image not only involves emotional factors, but also perceptual components (Gallagher, 2005). Notably, a negative attitudinal body image and body dissatisfaction might contribute to a distorted self-estimation of body size (McCabe, Ricciardelli, Sitaram, & Mikhail, 2006). In other words, since individuals with obesity have a negative attitudinal body image, they may be more inclined to perceive their body bigger than it is. However, previous studies assessing self-perceived body size in obesity have come to inconsistent conclusions, reporting either an overestimation, underestimation or accurate estimation of the body size (Schwartz & Brownell, 2004).

The self-perceived size of the body has been investigated using several experimental paradigms, which have been considered equivalent methods to measure the accuracy of the perceptual body image. *Metric* methods involve the estimation of the size of a target body part (e.g., hips, limbs, chest) by measuring it using a non-bodily reference. For example, adjusting the distance between two markers on a horizontal bar (Cleveland et al., 1962; Reitman & Cleveland, 1964), regulating the gap between the hands or fingers (i.e., *calliper task*; Kreitler & Chemerinski, 1990; Kreitler & Kreitler, 1988), or drawing a line (Keizer et al., 2013; Scarpina et al., 2017). On the other hand, *depictive* methods require participants to estimate the dimensions of their whole body by comparing it to a bodily template. For instance, manipulating the size of a body model or of a non-veridical picture of one's own body to a size that matches the actual or ideal body (namely, *distorting photograph technique*) or to choose among different alternatives the silhouette (Beebe, Holmbeck, & Grzeskiewicz, 1999) or the body model (see, for instance, Moussally et al., 2017a, 2017b) most representative of the body appearance.

Previous research using metric tasks in obesity showed contradictory results. Studies adopting the *calliper task* reported that both individuals with obesity and healthy weight individuals overestimate the size of their body parts (Cappon & Banks, 1968; Garner et al., 1976; Pearlson et al., 1981; Slade & Russell, 1973). When participants were asked to draw vertical lines matched in length to the horizontal width of the shoulders and pelvis, individuals affected by obesity underestimated and healthy weight participants overestimated their width (even though differences across groups were not significant; Scarpina et al., 2017). Two studies have required participants to estimate body size without visual feedback. Kreitler and Chemerinski (1990) asked blindfolded participants to indicate the horizontal width of the mouth, face, waist, and hips by adjusting the gap between their hands. Individuals affected by obesity and healthy weight participants underestimated the body size, although individuals with obesity underestimated the waist and the hips significantly more than healthy weight people. Valtolina (1998) asked participants to indicate the relative locations of target body parts on a wall as if they were reflected in a mirror and used the distance between pivotal body landmarks (e.g., left and right hip) to estimate implicitly the specific body part dimension. They reported that individuals affected by obesity underestimated the body size (i.e., head, torso, abdomen, and pelvis), while healthy weight individuals overestimated the abdominal and pelvic areas and accurately estimated the head and torso.

To sum up, individuals with obesity misperceive the size of the body using metric tasks, either underestimating (Kreitler & Chemerinski, 1990; Scarpina et al., 2017; Valtolina, 1998) or overestimating the real dimensions (Cappon & Banks, 1968; Garner et al., 1976; Pearlson et al., 1981; Slade & Russell, 1973) according to the different procedures used. However, also healthy weight individuals overestimate (Cappon & Banks, 1968; Garner et al., 1976; Pearlson et al., 1981; Slade & Russell, 1973) or underestimate (Kreitler & Chemerinski, 1990) the size of the body in these tasks. Thus, the biases found in obesity may be related to a general tendency to erroneously self-estimate the dimensions of different body parts. Nevertheless, previous findings reported also qualitative and quantitative dissimilarities between healthy weight individuals and obesity in metric tasks. Therefore, at least part of the distortion found might be attributed to factors specifically related to obesity.

In depictive tasks, participants with obesity overestimate their body size (Collins et al., 1987; Collins, McCabe, Jupp, & Sutton, 1983; Docteur, Urdapilleta, Defrance, & Raison, 2010; Gardner, Gallegos, Martinez, & Espinoza, 1989; Gardner, Martinez, & Sandoval, 1987; Garner et al., 1976; Thaler et al., 2018) proportionally to the severity of the disease (Collins et al., 1983; Docteur et al., 2010). Using the same task, healthy weight individuals estimate accurately the body (Collins et al., 1987; Docteur et al., 2010; Gardner et al., 1987), even though patterns of underestimation (Garner et al., 1976; Thaler et al.,

2018) and overestimation (Gardner et al., 1989) have been reported. Using the body silhouette technique, Bell and collaborators (1986) found that individuals affected by obesity tend to underestimate the body while healthy weight individuals provide accurate estimations. However, this study was conducted on participants aged between 11 and 24 years, whose bodies and body representations are extremely different and unstable (Bremner, Hill, Pratt, Rigato, & Spence, 2013; Kállai et al., 2017; Palomo et al., 2018). Thus, this uneven sample limits the interpretation of this research.

Therefore, in depictive task individuals with obesity show a more homogeneous behaviour, mainly overestimating the whole body size (Collins et al., 1987; Garner et al., 1976; Glucksman, Hirsch, McCully, Barron, & Knittle, 1968; Meyer & Tuchelt-Gallwitz, 1968), while healthy weight individuals estimate the body more accurately (Bell, Kirkpatrick, & Rinn, 1986; Collins et al., 1987; Docteur et al., 2010; Gardner et al., 1987). Crucially, the estimation bias found in obesity using depictive methods disappears when participants judge others' bodies (Thaler et al., 2018). This evidence suggests that these distortions are linked to individuals' own body, and are therefore associated with self-related factors, such as body dissatisfaction, instead representing a global cognitive difficulty in estimating dimensions (Garner et al., 1976). On the other hand, Pearlson and colleagues (1981) reported that in obesity the overestimation of the size of single body parts in metric methods was not related to participants' satisfaction with those parts of the body, suggesting a relatively weak relationship between the body size estimation in metric tasks and body dissatisfaction.

Concluding, the experimental evidence suggests that individuals with obesity misperceive the dimensions of their body, even though this behaviour is not consistent across different studies and, specifically, seems to be influenced by the paradigm used. Moreover, while body dissatisfaction might have a role in the erroneous estimation of the body dimensions when using depictive tasks, metric methods might be less affected by emotional factors.

Body schema in obesity

Research on body representation in obesity has primarily focused on body image (see Schwartz & Brownell, 2004, for a review). To the best of our knowledge, only one study has explicitly explored body schema in obesity (Scarpina et al., 2017). Individuals affected by obesity and healthy weight participants had to walk through doorways of different apertures, while the kinematic of their movements was recorded. The walking behaviour through a door grounds on the body schema, which processes the localization and the size of the body with respect to external objects (Keizer et al., 2013). Apertures were calibrated for each participant and ranged from the actual width of the pelvis to its double, by fixed increments. Narrower is the doorway, higher is the rotation of the body needed to pass. If individuals with obesity overestimate their size, they would rotate the body more than healthy weight participants at the same increment of aperture. For example, with apertures that are 10% wider than the pelvis, they will rotate more the body than healthy weight individuals. Otherwise, if they underestimate their body dimensions, they would rotate their body less. Individuals with obesity moved accordingly with their physical dimensions, suggesting an efficient and accurate underlying body schema (Scarpina et al., 2017). The body schema in obesity, thus, seems to be unaffected by the attitudinal and perceptual aspects of body image. However, further investigations are needed to corroborate this finding.

To sum up, obesity is a complex condition that has a major impact on people’s quality of life due to its physical consequences but also given its social, psychopathological, and cognitive correlates. Furthermore, body representation disorders have a key role in the characterization of obesity. Some aspects of this domain remain scarcely investigated. Nevertheless, a deeper understanding of obesity is desirable because fundamental to develop multidisciplinary and efficacious rehabilitative protocols, addressing the whole complexity of this condition beyond weight loss. Indeed, better treatments would significantly ameliorate individuals’ well-being but also contribute to reduce the huge health costs related to obesity comorbidities.

2 THE SELF-PERCEIVED BODY SIZE IN OBESITY: EVIDENCE FROM THE IMPLICIT REPRESENTATION OF THE HAND [2]

2.1 INTRODUCTION

As previously explained, the self-perceived size of the body has been investigated using *metric* and *depictive* methods. Metric tasks involve the estimation of a target body part by reporting its perceived size according to a non-bodily metric (e.g., adjusting the distance between two markers or drawing a line; Cleveland, 1962; Keizer et al., 2013; Reitman & Cleveland, 1964; Scarpina et al., 2017). Depictive methods require participants to estimate the dimensions of their body by comparing it to a bodily template (e.g., manipulating the size of a non-veridical picture of the body to match the perceived size or to choose among different body models the most realistic; Beebe, Holmbeck, & Grzeskiewicz, 1999; Moussally, Rochat, Posada, & Van Der Linden, 2017; Moussally, Grynberg, Goffinet, Simon, & Van der Linden, 2017).

Previous studies showed that both individuals with obesity and healthy weight individuals either underestimate (Kreitler & Chemerinski, 1990) or overestimate (Cappon & Banks, 1968; Garner et al., 1976; Pearlson et al., 1981; Slade & Russell, 1973) the dimension of the body using metric methods; in some cases the magnitude of this bias was higher in obesity (Cappon & Banks, 1968; Kreitler & Chemerinski, 1990; Pearlson et al., 1981). Only in a minority of works the error was *qualitatively* different since individuals with obesity underestimate the body and healthy weight participants overestimate it (Scarpina et al., 2017; Valtolina, 1998). When individuals with obesity judge the dimension of the body in depictive tasks they tend to overestimate (Collins et al., 1987, 1983; Docteur et al., 2010; Gardner et al., 1989, 1987; Garner et al., 1976; Thaler et al., 2018); on the contrary, healthy weight individuals are generally significantly more accurate in these tasks (Collins et al., 1987; Docteur et al., 2010; Gardner et al., 1987).

---

[2] Some of the contents reported in this Chapter are part of the work *"Body Size Estimation in Obesity: A Novel Insight from the Implicit/Explicit Model of Body Representations"* by Sofia Tagini, Federica Scarpina and Massimiliano Zampini, currently in preparation.

In light of the theoretical dualism between body image and body schema (de Vignemont, 2010; Dijkerman & de Haan, 2007; Gallagher, 2005; Schwoebel et al., 2005), previous studies employed both metric and depictive tasks purporting to investigate the perceptual component of body image (Farrell, Lee, & Shafran, 2005; Schwartz & Brownell, 2004). However, if these methods measured the same construct, they should provide congruent results.

An alternative explanation proposed by Longo and Haggard (2012b) is that metric and depictive methods measure different components of body representation. This interpretation grounds on the implicit/explicit model of body representations (Longo, 2015), in which several representations can be identified by different levels of accuracy and three-dimensionality at each point of the same continuum. *Implicit* body representations represent the body fractioned in several parts, with a lower level of accuracy and lacking in three-dimensionality (Longo, 2015a). On the other hand, the *explicit* representation is a visual "picture" that represents the body accurately as a three-dimensional object (Longo, 2015a, 2015b). Since body representations are part of the same continuum, hybrid combinations of implicit and explicit body representations are predicted by this model (Longo & Haggard, 2012a; see Chapter 1.2 for a more comprehensive description of this taxonomy). As mentioned in Chapter 1, explicit representations are recruited when people think about their body (Longo, 2015a), while implicit representations support high-level somatosensory processes (Longo, Azañón, & Haggard, 2010). For instance, the implicit representation supports the *position sense*, which enables us to know the location of our body in the space even without visual feedback. Somatosensory receptors located in the periphery inform the brain about the degree of flexion of the joints, skin lengthening and muscle contractions (Proske & Gandevia, 2012) contributing to define the postural configuration of the body (Burgess, Wei, Clark, & Simon, 1982). However, this is not enough to figure out the absolute position of the body in the space (Longo et al., 2010; Longo & Haggard, 2010). For example, to locate our hand (without seeing it) the information about the degree of flexion of the elbow must be combined with the specific length of the arm (Longo & Haggard, 2010; Longo, 2015a). This information is not provided by the somatosensory system. People must rely on stored information about body dimensions, which is delivered by an implicit body representation of body metric called *body* *model* (Longo & Haggard, 2010). Interestingly, Longo and Haggard (2010), developed an innovative task to investigate the *body model* underlying the position sense, which was not specifically addressed by the traditional experimental paradigms. In the **landmarks localization task** (e.g., Longo, 2014; Longo & Haggard, 2010; Mattioni & Longo, 2014) the participant hides the hand under a horizontal panel and locates repetitively the position of fingertips and knuckles using a baton. The perceived distance between each fingertip and knuckle is used to estimate the represented length of the fingers, while the perceived distance between the knuckle of the index and the little finger is used to estimate the represented hand width.

Healthy individuals systematically underestimate the length of the fingers and overestimate the width of the hand in this task, suggesting that the *body model* is slightly distorted (e.g., Coelho & Gonzalez, 2017; Longo, 2014; Longo & Haggard, 2010; Mancini et al., 2011). When healthy participants judge whether a visually-presented line is shorter or longer than a specific part of their hand (i.e., a metric task) they are also imprecise. Interestingly, these biases are qualitatively similar to the distortions of the *body model* but lower in magnitude (Longo & Haggard, 2012b), suggesting that this task relies on a little more accurate representation of the body. On the contrary, when participants have to pick the most representative image of their hand (i.e., a depictive task) they correctly evaluate its size (Longo & Haggard, 2010; 2012b).

These studies about the representation of the hand in the healthy population demonstrate, again, that metric and depictive methods provide dissimilar findings suggesting that the two tasks do not investigate the same construct. Which are, thus, the body representations involved in these paradigms? Longo and Haggard (2012b) suggested that metric methods evaluate a combination of explicit (accurate) and implicit (imprecise) representation; in other words, the biases of the implicit representation would be partially corrected by the accurate information led by the explicit one. On the other hand, they proposed that depictive methods investigate an explicit accurate representation of the body.

Applying this alternative interpretation to the investigation of self-perceived body size in obesity, previous findings indicate that: *i*) individuals with obesity have a distorted explicit representation since they tend to overestimate body dimensions in depictive tasks; *ii*) the misperceptions found using metric tasks in obesity may be due to distorted explicit and/or implicit body representations. The interpretation of the previous experimental evidence using metric tasks thus required to know both sides of the same coin. In obesity, the explicit representation seems distorted indeed, but almost nothing is known about the implicit one. To the best of our knowledge, only one study investigated the implicit representation in obesity, asking participants to estimate the size of tactile stimuli applied on the arm and the abdomen (Scarpina et al., 2014). When individuals have to estimate the size of tactile stimuli applied to the skin, the represented dimension of a specific body part is used as a reference (Longo et al., 2010; Serino & Haggard, 2010; Spitoni, Galati, Antonucci, Haggard, & Pizzamiglio, 2010). For instance, if one knows that a certain body segment is long *n*, and the stimulus is covering half of that surface, the size of the stimulus will be estimated as n/2. Therefore, any distortion in the estimation of the physical size of haptic stimuli can be interpreted as a distortion in the implicit representation (Longo, 2015a; Longo et al., 2010). Scarpina and colleagues (2014) reported that both healthy weight individuals and individuals affected by obesity implicitly overestimate the body, even though this overestimation in obesity was enhanced for the arm. On the contrary, healthy weight individuals showed no difference as a function of the body part estimated. Moreover, individuals with obesity overestimated the arm significantly more than healthy weight individuals. This finding suggests that individuals with obesity and healthy weight individuals might have a similar (distorted) implicit representation, even though in obesity this bias might be increased for specific body parts. Thus, although scarce, the experimental evidence supports the idea that the distortions found using metric tasks in obesity could be related also to biases of the implicit representation of the body that, however, are not specific to this clinical condition since similar misperceptions can be detected also in the healthy weight population. Obesity may only enhance such biases.

The aim of this study was to investigate the implicit body representation supporting the ability to locate the body in the space (i.e., the *body model*; Longo & Haggard, 2010) in individuals with obesity compared to healthy weight individuals. To this purpose, we used an adapted version of the landmarks localization task, which has been extensively used to investigate the implicit representation of the hand in both healthy individuals (e.g., Longo, 2014; Longo & Haggard, 2010; Mattioni & Longo, 2014) and clinical populations (Longo, Long, & Haggard, 2012). In line with the literature, we expected healthy weight individuals to underestimate the fingers length and overestimate the hand width (e.g., Longo, 2014; Longo & Haggard, 2010; Mattioni & Longo, 2014). According to Scarpina and colleagues' work (2014), we expected individuals with obesity to show qualitatively similar distortions of the implicit representation that however might be higher in magnitude.

The distortions of the *body model* of the hand might be related to the fact that tactile acuity is greater on the medio-lateral axis of the hand dorsum (which is overestimated) than on the proximo-distal axis (which is underestimated) (Cody, Garside, Lloyd, & Poliakoff, 2008; Longo & Haggard, 2010; Weber, 1996). Thus, a dissimilar tactile acuity between healthy weight and individuals with obesity (Bussolaro, Garcia, Zanella, & Ferreira, 2012; Miscio et al., 2005) might explain the possible differences between groups in the magnitude of the estimation errors. Tactile acuity was measured using a two-point discrimination task (Falling & Mani, 2016; Klein, 2001).

2.2 METHODS

Participants

Fifteen participants affected by obesity (i.e., BMI equal or higher than 30) (9 female) voluntarily took part in the study at the IRCCS Istituto Auxologico Italiano – Ospedale San Giuseppe (Piancavallo, Oggebbio, VCO, Italy), before attending a weight loss rehabilitative program. Nineteen healthy weight individuals (i.e., BMI lower than 30) (16 female) were recruited from the University of Trento or by experimenters' contact. Healthy weight individuals participated in return for academic credits or monetary compensation (7 euros). The number of participants was established according to the previous studies using the same experimental paradigm (Coelho & Gonzalez, 2018; Ganea & Longo, 2017; Longo, 2014; Longo & Haggard, 2010b, 2012b, 2012a; Longo, 2015a, 2015b). All participants were right-handed. The presence of any neurological, motor and/or sensory impairment was an exclusion criterion. All participants were naïve to the rationale of the experiment and gave their informed written consent. The demographics of the two groups are reported in Table 1. Independent samples *t*-tests revealed that the two groups had comparable age ($t_{(32)} = -0.752$, two-tailed $p = .458$, $d = 0.26$), while healthy weight participants had significantly longer education ($t_{(32)}$ = 2.521, two-tailed p = .017, d = 0.87). As expected, individuals with obesity had a significantly higher Body Mass Index (BMI) than healthy weight participants[3] ($t_{(32)}$ = - 11.64; two-tailed p = .001, d = 4.02). Moreover, the administration of the Body Uneasiness Test (BUT; Cuzzolaro, Vetrone, Marano, & Garfinkel, 2006; Marano et al., 2007)[4], showed that individuals with obesity had significantly higher concerns about their body appearance [*obesity* = 22.27; *healthy weight* = 13.74; (U = 71, z = - 2.41, two-tailed exact p = .012, r =*0*.41)].

The study was approved by the ethical committee of the IRCCS Istituto Auxologico Italiano and was performed in compliance with the ethical standards laid down in the 1964 Declaration of Helsinki (most recently amended in Fortaleza, 2013).

Table 1 Mean and standard deviation (in brackets) of *Age* in years, *Years of Education*, and *Body Mass Index* (BMI) in kg/m^2 of the obesity and healthy weight group.

	Age	Years of Education	BMI
Healthy Weight	43.58 (9.21)	13.79 (3.43)	23.98 (4.21)
Obesity	45.87 (8.27)	10.73 (3.61)	42.77 (5.21)

Task and procedure

Landmarks localization task. An adapted version of the task originally proposed by Longo and Haggard (2010) was administered. The participant was blindfolded and sat comfortably in front of a table

---

[3] Individuals with a BMI higher than 30 are considered clinically affected by obesity.

[4] The BUT is a self-report questionnaire used to evaluate the distress towards the body (Cuzzolaro et al., 2006; Marano et al., 2007). We specifically focused on the subscales relative to *Weight Phobia* and *Body Image Concerns*. We also computed the *Global Severity Index,* which evaluates the general level of body uneasiness (BUT-part A), and the *Positive Symptoms Distress Index* (BUT- part B), which evaluates the entity of worries about specific parts, features (e.g., smell) and functions (e.g., swearing) of the body.

where a 23-inch LCD touch-screen monitor (HP 2310ti) was placed horizontally, nestled in a polystyrene support. The polystyrene apparatus with the screen stands 12 cm over the table, held up by four wooden supports. The participant put the right hand under the screen on a velvet patch, palm down with the fingers spread in a comfortable position. The hand was located approximately 30 cm from the body, aligned with the body midline. The left hand was placed on the polystyrene apparatus on another velvet patch 10 cm to the left of the screen border, aligned with the shoulder. The velvet patch on the apparatus indicated the point where the participant had to return the hand after each trial (Figure 1A). The participant had to locate the fingertip and the knuckle (i.e. *metacarpophalangeal joints*) of each finger, touching the screen with the left index. More specifically, the participant was instructed to touch the screen where she/he perceived the target landmark under the apparatus. Before the task, the experimenter explicitly indicated each landmark by touching it, to ensure a proper understanding of the targets to locate. The indication of the landmark to pinpoint was given through headphones (e.g. “index fingertip”; “middle finger knuckle”). When the participant touched the screen, a sound signalled the recording of the location by the system, while not providing any feedback about the accuracy of the localization. The participant was encouraged to take her/his time trying to be as more precise as possible. The participant was also told to judge each landmark individually, avoiding any strategy to relate the following judgments. To favour so, the participant had to return the left hand to the starting position after each trial.

Each participant judged each landmark 10 times in a randomized order: the experiment included a total of 100 trials. The x-y pixel coordinates of each point were recorded using E-Prime 1.2 software (Psychology Software Tools, Pittsburgh, PA). For each participant, the mean of the x-y pixel coordinates relative to the same landmark, across the 10 repetitions, was computed. A spatial map of the reciprocal locations of each fingertip and knuckle was then obtained (Figure 1B). After that, the distances between the averaged pointed landmarks were converted from pixels to centimetres. The distance between each averaged pointed fingertip and the corresponding averaged pointed knuckle was used as an implicit measure of the represented finger length; the distance between the averaged pointed knuckles of the index and the little finger was used as an implicit measure of the represented hand width. In this way, an indirect measure of the metric of the implicit hand representation was obtained (Longo & Haggard, 2010; Longo, 2014; Longo & Haggard, 2012; Longo & Haggard, 2012; Mattioni & Longo, 2014).

Two-point discrimination task. Pairs of two-point tactile stimuli were delivered on the centre of the hand dorsum, perpendicularly to the proximodistal body axis, approximately one centimetre below the lowest knuckle of the middle finger. The participant had to say whether she/he perceived one point, two points or whether she/he was “unsure” (i.e., three-alternative forced-choice method; see e.g., Klein, 2001). Stimuli were delivered using the tips of a commercially available digital calliper (Falling & Mani, 2016). The inter-stimulus interval was nearly 5 seconds. Tactile acuity threshold was computed according to the psychophysical adaptive staircase method with an up-down tracking rule (Cornsweet, 1962; Ehrenstein & Ehrenstein, 1999) for a total of 12 reversals (Falling & Mani, 2016). According to Falling and Mani (2016), each correct answer (i.e., “two points”) was followed by a decrease of one increment of the distance between the stimuli; each incorrect answer (i.e., “one point”, “unsure”) was followed by an increase of two increments of the distance between the stimuli. In the first six reversals, a 5 mm increment was used. In the last six reversals was adopted a more sensitive increment of 2 mm to approach the threshold more accurately. The starting point was set at 30 mm since at this distance the calliper tips should be likely perceived as separated (Mancini et al., 2014).

The order of tasks was counterbalanced across participants.

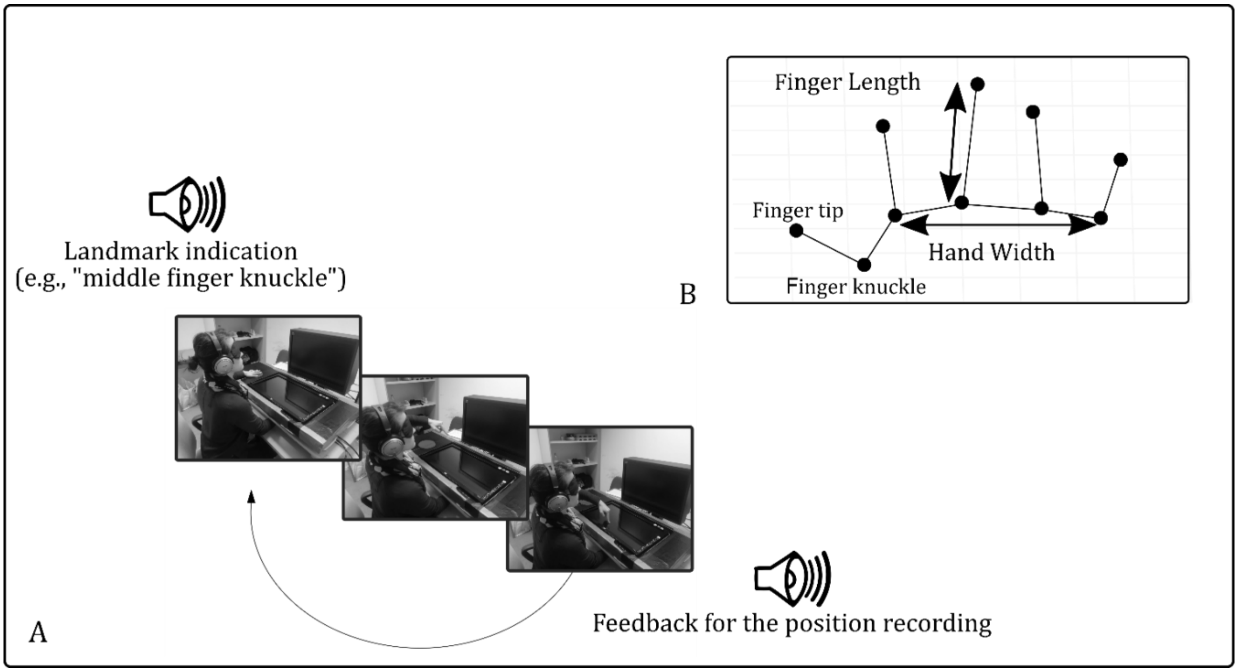

Figure 1. *Panel A***:** Illustration of the setting and the procedure of the landmarks localization task. *Panel B*: Example of the spatial map of the hand obtained for each participant.

Analysis

Landmarks localization task. The real dimensions of the participant's hand were measured with a ruler after the experiment. An *estimation error* was computed for each finger length and the hand width as the percentage of the difference between the real size and the estimated size weighted for the real one (i.e., *(real size – estimated size)/real size *100*). Negative values indicate an underestimation, while positive values indicate an overestimation. An estimation error equal to zero means that the estimated dimension corresponds to the real one. The estimation error for the five fingers were averaged into one single index (i.e., *fingers length*).

The estimation error for each finger, the average fingers length and the hand width were normally distributed in both groups (Shapiro Wilk test $p > .05$).

According to the literature (e.g., Longo, 2014; Longo & Haggard, 2010a, 2012b), in each group, the estimation errors for the fingers length and hand width were compared to zero (i.e., accurate estimation) using a one-sample *t*-test to probe whether the magnitude of the distortion observed was statistically significant. After that, two independent sample *t*-tests were adopted to compare the estimation error of the fingers length and the estimation error of hand width between healthy weight individuals and individuals affected by obesity.

Previous studies reported also a significant increase of the fingers length underestimation towards the radial-ulnar direction (i.e., from the thumb to the little finger) (e.g., Longo, 2014; Longo & Haggard, 2010a, 2012b). A least-squares regression was performed to estimate the increase in underestimation from the thumb to the little finger in each participant independently. The average regression coefficient in each group was compared to zero (i.e., no increment in underestimation across fingers). In the healthy weight group, a one-sample *t*-test was applied. In the obesity group, normality of the regression coefficient was violated (Shapiro Wilk test $p < .05$). Accordingly, the Wilcoxon signed-rank test was performed. The between groups comparison was performed using the Mann-Whitney U test.

Two-point discrimination task. The mean of the last six reversals was taken for each subject as measure of the tactile acuity threshold (Cornsweet, 1962; Ehrenstein & Ehrenstein, 1999; Falling & Mani, 2016). An independent sample *t*-test was adopted on normal distributed data (Shapiro Wilk test $p > 0.05$) to compare the tactile acuity threshold between healthy weight individuals and individuals affected by obesity.

2.3 RESULTS

Landmarks localization task. The within group one-sample *t*-test revealed that both groups significantly underestimated the fingers length [*healthy weight*: (M (SD) = - 21.39 (21.57); $t_{(18)} = -4.32$, two-tailed $p = .001$, $d = 0.99$); *obesity*: (M (SD) = - 17.12 (26.5); $t_{(14)} = -2.502$, two-tailed $p = .025$, $d = 0.65$)] and overestimated the hand width [*healthy weight*: (M (SD) = 66.06 (41.62); $t_{(18)} = 6.918$, two-tailed $p = .001$, $d = 1.59$); *obesity*: (M (SD) = 65.96 (42.04); $t_{(14)} = 6.076$, two-tailed $p = .001$, $d = -1.57$].

The independent sample *t*-test did not show any significant difference between groups in the estimation error of the fingers length (($t_{(32)} = -0.518$, two-tailed $p = .608$, $d = 0.18$) and in the estimation error of the hand width ($t_{(32)} = 0.007$, two-tailed $p = .96$, $d = 0.002$). Both individuals with obesity and healthy weight individuals equally underestimated the fingers length and overestimated the hand width.

These results provide evidence in support of the null hypothesis, i.e. the absence of any difference between the two groups in the implicit body representation. To probe further whether our data provide positive evidence against a possible effect of the group on the implicit body representation a Bayesian two-sided independent sample *t*-test was performed using JASP (JASP Team, 2019; JASP, Version 0.11.1). Given that this was the first study comparing healthy weight and individuals with obesity in the landmarks localization task no previous data were available to estimate the expected effect size, therefore, the default value for the prior was adopted, as settled by the software. The prior was described by a Cauchy distribution centred around zero with a width parameter of 0.707. This corresponds to a probability of 80% that the effect size is between -2 and 2. For the fingers length the analysis revealed a weak / nearly moderate support for the null hypothesis ($b_{01} = 2.727$; $b_{10} = 0.367$; Jeffreys, 1961). For the hand width the analysis indicated a moderate support for the null hypothesis ($b_{01}= 3.027$; $b_{10} = 0.33$; Jeffreys, 1961).

The least-squares regression analysis revealed that the underestimation of the fingers length increased from the thumb to the little finger in both groups (*obesity:* average b (SD) = - 1.34 (8.78) per finger; *healthy weight*: average b (SD) = -2.38 (5.46) per finger). However, this increment was not significantly different from zero in both groups (*obesity:* median b = -2.11, z = -1.36, two-tailed exact $p = 0.188$, $r = 0.35$; *healthy weight*: $t_{(18)} = -1.90$, two-tailed $p = .073$, $d = 0,44$). Furthermore, the increment in underestimation across fingers was comparable between groups, as showed by the Mann-Whitney U test (U = 127, z = -0.54, two-tailed exact $p = .607$, $r = 0.09$).

Two-point discrimination task. The independent sample *t*-test revealed that the tactile acuity threshold was not significantly different ($t_{(32)} = - 0.984$, two-tailed $p = .326$, $d = 0.34$) between healthy weight participants (M (SD) = 14.99 (5.07)) and individuals with obesity (M (SD) = 16.82 (5.62)). Both groups had comparable somatosensory sensitivity.

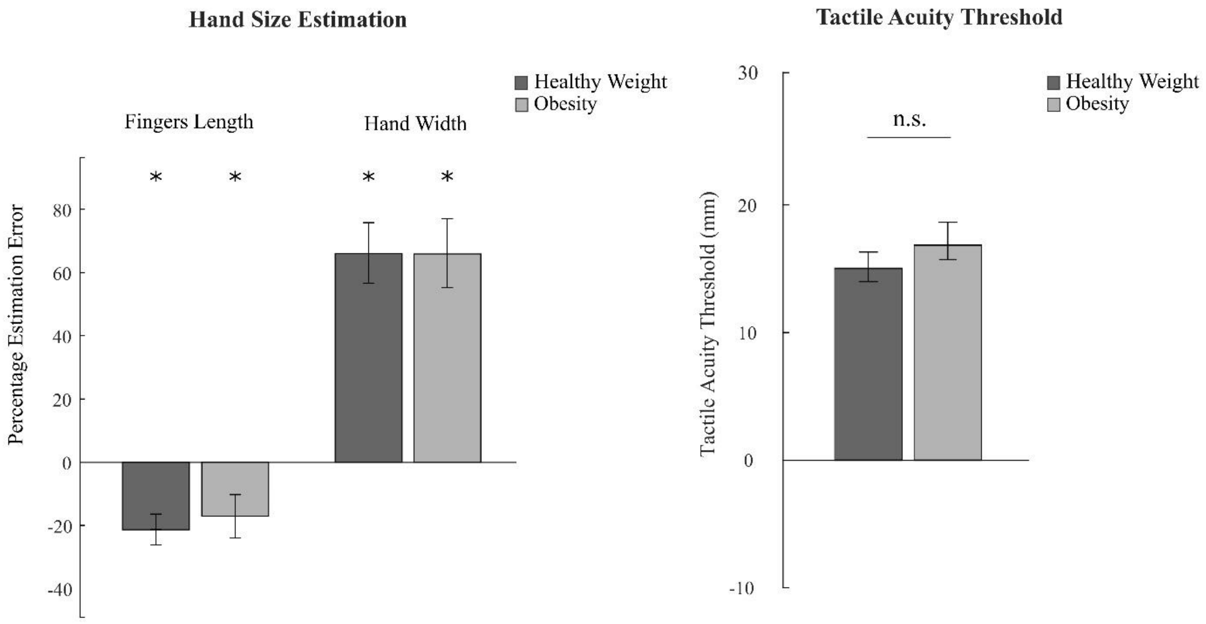

Figure 2. *Left panel*: the graph illustrates the mean and standard error of the percentage estimation errors of fingers length and hand width in healthy weight and in the obesity group. Positive values indicate an overestimation of the actual dimensions; negative values indicate an underestimation. Asterisks indicates that the magnitude of the error is significantly different from zero (i.e., accuracy level). *Right panel*: the graph illustrates the mean and standard error of the tactile acuity threshold in mm in healthy weight and in the obesity group.

2.4 DISCUSSION

Previous studies investigating the self-perceived body size in obesity provided incongruent results. In particular, they reported that individuals with obesity either overestimate (Cappon & Banks, 1968; Garner et al., 1976; Pearlson et al., 1981; Slade & Russell, 1973) or underestimate (Kreitler & Chemerinski, 1990; Scarpina et al., 2017; Valtolina, 1998) their own body size when adopting metric tasks and, mainly, overestimate it when using depictive techniques (Collins et al., 1987; Collins, McCabe, Jupp, & Sutton, 1983; Docteur, Urdapilleta, Defrance, & Raison, 2010; Gardner, Gallegos, Martinez, & Espinoza, 1989; Gardner, Martinez, & Sandoval, 1987; Garner et al., 1976; Thaler et al., 2018). Previous studies considered both metric and depictive tasks methods to investigate the perceptual component of the body image (i.e., the “visual picture” of the body) (Farrell et al., 2005; Schwartz & Brownell, 2004). However, if this was the case, they should have provided congruent results. A more innovative interpretation of the body representations that are recruited in the traditional estimation paradigms might help to clarify these findings. Adopting the interpretation proposed by Longo and Haggard (2012b), depictive methods would assess the explicit representation of the body, while metric methods would recruit a combination of both the implicit and explicit body representation. Consequently, the estimations provided by depictive methods can be easily interpreted. On the contrary, to interpret the results of metric methods, it is necessary to find out whether the distortions are related to the implicit or explicit representation. In healthy weight individuals, the explicit representation of the body is accurate (Collins et al., 1987; Gardner et al., 1987; Longo, 2015; Longo & Haggard, 2012). Consequently, the misperception of body dimensions in metric tasks should be related to the implicit representation that, indeed, is slightly distorted (e.g., Coelho and Gonzalez, 2017; Longo, 2014; Longo & Haggard, 2010; Mancini et al., 2011). In obesity, the explicit representation has been proven to be distorted (Collins et al., 1987, 1983; Docteur et al., 2010; Gardner et al., 1989, 1987; Garner et al., 1976; Mölbert et al., 2018), however, the implicit representation has not been systematically investigated.

We probed the implicit representation of the hand underlying position sense (i.e., the *body model*) in obesity and healthy weight individuals using an adapted version of the landmarks localization task (Longo & Haggard, 2010). According to Scarpina and colleagues’ work (2014), we expected individuals with obesity and healthy weight individuals to have a qualitatively similar (distorted) implicit representation. However, we also expected that the magnitude of the estimation bias might be higher in obesity. According to expectations, healthy weight individuals underestimated the fingers length and overestimated the hand width. This pattern of distortions has been extensively reported in the literature (e.g., Coelho & Gonzalez, 2017; Longo, 2014; Longo & Haggard, 2010; Mancini et al., 2011). Interestingly, our findings demonstrate that the same distortions are also present in obesity. However, contrary to expectations, the magnitude of the estimation errors was comparable across groups for both the fingers length and the hand width. The absence of any effect of the group on the implicit body representation was also suggested, even though weakly, by an additional Bayesian’s comparison between healthy weight and individuals with obesity. A larger number of participants, especially in the obesity group, could have increased the strength of our findings. However, it is well-known that the recruitment of clinical populations is often slowed down due to logistic and practical reasons.

In both groups the underestimation of the finger length increased from the thumb towards the little finger, although this increment was not significantly different from zero. This result contrasts with previous studies reporting a significant radial-ulnar gradient of fingers length underestimation (e.g., Longo, 2014; Longo & Haggard, 2010a, 2012b). In previous studies participants located the landmarks using a baton, we asked them to pinpoint with their index on the touch-screen monitor. Therefore, dissimilar results might be attributed to the adaptation of the original set-up adopted in the present study. The fact that the same pattern was reported in both groups supports this hypothesis. For instance, participants might have found easier to locate the landmarks directly with the index, minimizing the difference in underestimation across the fingers. Importantly, the radial-ulnar increment in underestimation of the fingers length was comparable between groups, despite the incongruency with the previous literature. This result agrees with the fact that the magnitude of the estimation errors was similar across groups for both the fingers length and hand width.

These findings suggest that the implicit representation of the hand in obesity is *physiologically* distorted as well as for the healthy weight population. Consequently, the distortions of the implicit *body model* reported in obesity should not be related to this pathological condition, but to the physiological mechanisms that support the development of the implicit representation of the body. These distortions have been related to the biases of the primary somatosensory maps of the body (i.e., in which the representation of the different parts of the body is not commensurate to their actual dimensions; Penfield & Boldrey, 1937) (Longo & Haggard, 2010; Longo, 2015). Moreover, the estimation biases reported reflect anisotropies in the tactile receptive fields of the hand dorsum (Longo & Haggard, 2010). In detail, these tactile receptive fields are oval-shaped, therefore, they are smaller on the medio-later axis than on the proximo-distal axis (Alloway, Rosenthal, & Burton, 1989; Brown, Fuchs, & Tapper, 1975). Consequently, the same portion of skin surface includes more receptive fields in the medio-lateral than in the proximo-distal axis, which might explain why the width of the hand is overestimated and the length of the fingers underestimated (Longo & Haggard, 2010).

Implicit biases of hand dimensions might also be related to the fact that the tactile acuity is greater on the medio-lateral than on the proximo-distal axis of the hand dorsum (Cody, Garside, Lloyd, & Poliakoff, 2008; Longo & Haggard, 2010; Weber, 1996). Thus, a dissimilar somatosensory sensitivity between healthy weight and individuals with obesity could have explained differences between groups in the magnitude of the estimation errors. In line with the fact that both groups estimated similarly the hand dimensions, the tactile acuity threshold was comparable across groups.

Our results agree with Scarpina and colleagues' work (2014), reporting a qualitatively similar distorted implicit representation of the body in obesity and healthy weight participants. However, we did not find a higher magnitude of distortions in obesity. Two explanations might be given for this inconsistency. First, the authors used a different paradigm (i.e., tactile distance estimation) involving an implicit representation of the body metric that is, at least partially, distinguished by the one underpinning position sense (Longo & Morcom, 2016). Indeed, these representations showed qualitatively similar distortions, namely an underestimation of the proximo-distal body axis and an overestimation of the medio-lateral one. However, the magnitude of the bias is significantly different and does not correlate between the two tasks (Longo & Morcom, 2016). Consequently, the evaluation of tactile distances and position sense likely rely on independent implicit representations. Secondly, we investigated the representation of the hand, while they focused on the abdomen and the arm. Since implicit representations represent the body as fractioned in multiple surfaces (Longo, 2015), differences between body parts might be expected (Longo & Haggard, 2012a). Given the role of somatosensation in the implicit representation (Longo, 2015), a dissimilar somatosensory sensitivity across different body parts (Cody et al., 2008; Mancini et al., 2014) might account for this finding.

To sum up, our results point to a similar (distorted) implicit representation of the body in healthy weight participants and obesity, while previous findings reported a less accurate explicit representation of the body (i.e., using depictive task) (see for review, Schwartz & Brownell, 2004).

It is worth discussing why the explicit representation of body dimensions is altered in obesity while the implicit might be not. Explicit misperceptions of body dimensions disappear when participants with obesity judge others' bodies (Thaler et al., 2018). Therefore, the source of these biases must be linked to self-related factors, such as body dissatisfaction and emotional attitudes towards the body. Perceptual processes ground on sensory bottom-up input, but are also influenced by cognitive top-down information (Mechelli, Price, Friston, & Ishai, 2004). Individuals with obesity have an extremely negative body image characterized by a high level of body dissatisfaction and adverse feelings towards the body (see Schwartz & Brownell, 2004; Weinberger et al., 2016, for reviews). This emotional component of body representation might negatively affect body size estimation (Cash & Deagle, 1997; McCabe et al., 2006; Mölbert et al., 2017; Smeets et al., 1999). In other words, a negative emotional conceptualization of the body might boost a deleterious perception of the body dimensions, which in turn would be perceived larger than reality. In accordance, studies probing the explicit representation of body size in obesity more consistently reported an overestimation of the body (Collins et al., 1987, 1983; Docteur et al., 2010; Gardner et al., 1989, 1987; Garner et al., 1976; Mölbert et al., 2018) than an underestimation (Bell et al., 1986). Nevertheless, the current experimental evidence does not rule out the possibility that a distorted perception of the body dimensions increases body dissatisfaction; further studies are needed to clarify this relationship. On the other hand, we speculate that emotional factors might not affect the implicit representation of the body. In accordance, participants with obesity in our sample had significantly higher concerns about their body appearance, but we did not find any differences in the implicit representation across groups. It must be pointed out that the hand has not a high emotional salience (Keizer et al., 2011; Sarwer, Wadden, & Foster, 1998), therefore its implicit representation might be insensitive to body dissatisfaction. However, Scarpina and colleagues (2014) found similar implicit estimation of the abdomen in healthy weight participants and individuals with obesity, despite this body part is considered one of the most unsatisfying (Keizer et al., 2011; Sarwer et al., 1998). Future studies might extend the investigation of implicit body representations in obesity to other body parts to clarify whether the previous considerations can be generalized. After all, while individuals are aware of judging their body when referring to the explicit body representation, they recruit their implicit representation of the body unconsciously (Longo, 2015). Therefore, it is plausible that emotional factors influence body estimation only when individuals explicitly think about their body. Futures studies might probe this hypothesis by investigating, in a systematic way, whether body dissatisfaction correlates with the estimation biases of the explicit representation and does not correlate with the misperceptions of the implicit one. Further studies are also recommended to probe our hypothesis of a preserved implicit body representation in obesity. In fact, in the present work a specific implicit body representation was tested, which is involved in position sense. As previously mentioned, Scarpina and colleagues (2014) investigated the implicit body representation involved in the estimation of the size of tactile stimuli. However, the experimental evidence available is too scarce to draw strong conclusions on the topic. Moreover, other implicit body representations have never been investigated in obesity, such as the representation of the body that supports the ability to *localize* the tactile stimuli on the skin (e.g., Mancini et al., 2011). Therefore, a more systematic investigation is desirable, aiming to probe deeper the different implicit body representations, possibly in the same sample of participants. Speaking of which, also a direct comparison (i.e., among the same individuals) between implicit and explicit representations (e.g., tested with depictive task) in obesity would be highly recommended. In this way, the dissociation between implicit and explicit body representation in obesity may be tested, strengthening the speculation made in this work.

Importantly, our results improve the understanding of previous findings about body size estimation in obesity. Since individuals with obesity have a distorted implicit representation of the body size, estimation errors reported in metric tasks can be attributed to these biases. The same scenario seems true for healthy weight individuals, who also showed distortions in metric tasks. However, some studies reported that the estimation biases found in metric tasks were higher in magnitude (Cappon & Banks, 1968; Kreitler & Chemerinski, 1990; Pearlson et al., 1981) or incongruent (i.e., underestimation instead overestimation; Scarpina et al., 2017; Valtolina, 1998) in individuals with obesity than in healthy weight individuals. Metric tasks also involved the explicit representation, which is misperceived in obesity (but not in healthy weight individuals). Therefore, the distortions of the explicit representation found in obesity would represent an additional source of bias to the misevaluations of the implicit representation that are common to healthy weight individuals.

Our findings significantly contribute to the investigation of a relatively neglected domain of body representation in obesity, suggesting that implicit and explicit components can be differently modulated by this clinical condition. The characterization of body representation in obesity indeed might be more complex than expected, going beyond the well-known emotional aspects. Furthermore, to the best of our knowledge, other important constituents of body representation have never been investigated in obesity. This is the case of bodily self-consciousness: Chapter 3 will address this issue.

3 THE VIRTUAL HAND ILLUSION IN OBESITY: DISSOCIATION BETWEEN MULTISENSORY INTERACTIONS SUPPORTING ILLUSORY EXPERIENCE AND SELF-LOCATION RECALIBRATION [5]

3.1 INTRODUCTION

Bodily self- consciousness is a somatic form of self-knowledge that describes the current state of one's body (Bermúdez, 1998; Legrand, 2006; Riva, Gutiérrez-Maldonado, & Wiederhold, 2016). It is a multidimensional construct, including experiences of body *ownership, agency*, and *self-location* (Longo et al., 2008*;* Serino et al., 2013) and it is attained by the multisensory integration of body-related stimuli (Blanke, 2012; Blanke et al., 2015; Ehrsson, 2012; Makin et al., 2008).

In the Rubber Hand Illusion (RHI), the concurrent stroking of a visible rubber hand and the real (hidden) hand induces most people to feel that the fake hand is *their own* and to perceive the real hand as being located closer to the rubber one (Botvinick & Cohen, 1998). The manipulation of body ownership and self-location in the RHI has been used widely to investigate the mechanisms that support bodily self-consciousness (Blanke, 2012; Ehrsson, 2012). The RHI depends on the three-way integration of vision, touch, and proprioception. The perceptual conflict between the visible and the proprioceptive location of the hand is resolved by interpreting the somatosensory and visual stimuli belonging to the same event (Blanke, 2012; Ehrsson, 2012). The RHI occurs only when the real and the fake hand are stroked synchronously (with stimulus-onset asynchronies shorter than 300 ms; Bekrater-Bodmann et al., 2014; Shimada, Suzuki, Yoda, & Hayashi, 2014) since asynchronous stimuli cannot be integrated. The multisensory integration of body-related stimuli is then necessary to experience the RHI (Blanke, 2012; Costantini et al., 2016; Ehrsson, 2012).

---

[5] Some of the contents reported in this Chapter are part of the work "*The Virtual Hand Illusion in Obesity: Dissociation between Multisensory Interactions supporting Illusory Experience and Self-location Recalibration"* by Sofia Tagini, Federica Scarpina, Francesca Bruni, Massimo Scacchi, Alessandro Mauro and Massimiliano Zampini (2019). *Multisensory Research,* 1 (aop), 1-25.

Altered multisensory integration processes have been related to an atypical susceptibility to the RHI in autism spectrum disorders (Cascio et al., 2012; Paton et al., 2012), schizophrenia (Thakkar et al., 2011), body dysmorphic disorder (Kaplan et al., 2014), eating disorders (Eshkevari et al., 2012; Keizer et al., 2014), multiple sclerosis (Nava et al., 2018), and Parkinson's disease (Ding et al., 2017). Anomalous processing of multisensory information has also been reported in obesity (Scarpina et al., 2016; Wan et al., 2014). Consequently, one might hypothesize that bodily self-consciousness would be affected by obesity, especially since this condition is characterized by disturbed bodily experiences (see Chapter 1). No previous study probed RHI susceptibility in obesity. Nevertheless, the investigation of this topic might be particularly relevant. It has been suggested that multisensory full-body illusions might be used to manipulate body representation in rehabilitative protocols, for example, increasing body satisfaction by a self-identification with a thinner body (Riva, Wiederhold, & Mantovani, 2019; Serino & Dakanalis, 2017). As explained in detail in Chapter 1, the decrease of body dissatisfaction during weight loss protocols has been related to higher adherence to those protocols and to a lower risk of regaining weight (Palmeira et al., 2010; Schwartz & Brownell, 2004). This approach thus seems promising, however, a deep understanding of patients' responsiveness to these illusions is required before developing and testing the efficacy of *ad hoc* treatments. The RHI focused only on a small portion of the body, nevertheless, the cognitive mechanisms underlying full-body illusions are the same (Olivé & Berthoz, 2012).

The aim of this study was to determine whether the manipulation of bodily self-consciousness evoked by the RHI differs between individuals affected by obesity and healthy weight individuals. The similarity between the appearance of the real hand and the rubber hand is a fundamental constraint to the onset of the illusion (Tsakiris & Haggard, 2005). Pavani and Zampini (2007) demonstrated that the illusion disappears when individuals see an image of a hand that is smaller than the real one. Physical dimensions are generally enlarged in obesity. Consequently, a standard-size prosthetic hand would be smaller and of a different shape than participants' real hand, possibly preventing the onset of the illusion. Taking this into consideration, a full-size picture of the participants' hand instead of a rubber hand was used in the present study (Ijsselsteijn & De Kort, 2006; Pavani & Zampini, 2007; Tsakiris et al., 2005) to guarantee anatomical coherence between the participants' hand and the fake hand. Following synchronous and asynchronous visuo-tactile stimulations, we considered two possible outcomes of the RHI. First, we adopted a self-report questionnaire (adapted from Pavani & Zampini, 2007) to investigate the typical perceptual effects associated with the experience of the illusion, providing a subjective explicit measure of the RHI (Botvinick & Cohen, 1998; Ehrsson, 2012; Tsakiris & Haggard, 2005). Furthermore, we measured the mislocation of the real hand towards the virtual one (i.e., the proprioceptive drift; Botvinick & Cohen, 1998; Ehrsson, 2012; Tsakiris & Haggard, 2005), that is generally considered an objective implicit measure of the illusion (Botvinick & Cohen, 1998; Ehrsson, 2012; Tsakiris & Haggard, 2005).

In healthy weight individuals, the sensory susceptibility to fake sensations was found to be positively correlated with the subjective strength of the illusion (Marotta et al., 2016). Accordingly, possible differences in RHI susceptibility between our groups might be explained by a general dissimilar propensity to experience counterfeit sensory sensations rather than being strictly task-dependent. We used the Sensory Susceptibility Scale (Gheorghiu & Huebner, 1992) to compare the propensity of healthy weight individuals and individuals with obesity to experience counterfeit sensory perceptions.

3.2 METHODS

Participants

Twenty-one participants (11 female) affected by obesity (i.e., BMI equal or higher than 30) voluntarily took part in the study at the IRCCS Istituto Auxologico Italiano – Ospedale San Giuseppe (Piancavallo, Oggebbio, VCO, Italy), just before starting a weight loss rehabilitative program. Twenty healthy weight (i.e., BMI lower than 30) individuals (13 female) were recruited from the University of Trento or by experimenters' contact and participated in return for academic credits or monetary compensation (7 euros) (see Table 2 for demographic information on the two groups). The number of participants was established according to the previous administrations of the RHI in different clinical populations (Cascio et al., 2012; Ding et al., 2017; Kaplan et al., 2014; Paton et al., 2012; Thakkar et al., 2011). All participants were right-handed. A non-parametric Mann-Whitney U test revealed that the two groups had comparable age (*U* =158, *z* = -1.36, two-tailed exact *p* =.18, *r* = 0.21), while healthy weight participants had significantly more years of education (*U* = 78.5, *z* = -3.58, two-tailed exact *p* =.001, *r* = 0.56). Moreover, as expected, a *t*-test revealed that the average Body Mass Index (BMI) was significantly higher in the obesity group than in healthy weight participants ($t_{(27.64)}$ = -14.77, two-tailed *p* =.001, *d* = 4.4). The presence of any neurological, motor and/or sensory impairment was an exclusion criterion.

All participants were naïve to the rationale of the experiment and gave their informed written consent. The study was approved by the ethical committee of the IRCCS Istituto Auxologico Italiano and was performed in compliance with the ethical standards laid down in the 1964 Declaration of Helsinki (most recently amended in Fortaleza, 2013).

Table 2. Demographic information of the two samples: mean and standard deviation (in brackets) of *Age* in years, *Years of Education* and *Body Mass Index* (BMI) in kg/m^2.

Healthy Weight	36.75	(7.69)	16.55	(2.39)	22.10	(2.82)
Obesity	38.67	(12.45)	12.90	(3.03)	45.33	(6.46)

Materials

The Rubber Hand Illusion paradigm. An adapted version of Pavani and Zampini’s task (2007) was used. Before the task, for each participant, the left hand was photographed on a black opaque paper background using a digital camera and a tripod. The camera was mounted 50 cm in parallel over the table. Each picture was processed with Adobe Photoshop CC 2017 (version 20161130.r.29 x64, © 1996-2016 Adobe System Incorporated) to isolate the hand against a homogeneous black background and eliminate any contextual references. Each image was resized (as a percentage of the dimension in pixel of the original picture) using Microsoft Paint (version 1607, © 2016 Microsoft Corporation) to match the real dimension. Before data collection, the experimenter worked on a hand template-picture to identify the specific amount of reshaping necessary to reproduce the picture on the screen in real-size, given a specific distance of the camera from the table, a fixed focal length and the screen resolution. The length and width of the hand template were taken and then compared with the dimensions of the image on the screen.

During the task the participant sat comfortably in front of a table where a wooden box (20.5 cm x 100 cm x 41 cm) was placed. The box had a removable lid (108 cm x 49 cm) and contained a Dell 1907FPt monitor (34 cm x 40 cm) placed horizontally; the real-size picture of the participant's left hand was shown on the screen. A small platform (21 cm x 30 cm x 5.5 cm) near the screen indicated the specific location of the participant's middle finger and aid the vertical alignment of the hand with the screen surface.

The task involved two sessions of stimulation during which the real hand and the virtual hand were stroked synchronously and asynchronously, in a counterbalanced order across participants. During each stimulation session, the lid was removed and a vertical wooden panel (40 cm x 22.5 cm) was placed between the platform and the screen to hide the real hand (see Figure 3A). The participant's body midline was aligned with the centre of the monitor and the left hand was placed inside the box on the platform. The virtual middle finger was located approximately 28 cm from the real middle finger. The participant's right hand was hidden under the table, resting on the legs. The participant wore a black cloak from the shoulders to the screen edge to create the impression of continuity between the physical body and the virtual hand. The RHI paradigm was induced according to previous studies (see Botvinick & Cohen, 1998; Kammers et al., 2009; Pavani & Zampini, 2007). In the *synchronous* condition, the real and the virtual middle fingers were stroked at the same time in a proximo-distal direction with two paintbrushes. The experimenter stroked the hands approximately every second. The *asynchronous* condition was identical to the previous one, except that the real and virtual fingers were stroked alternately, approximately every second. The experimenter set the cadence of the stroking according to a digital chronometer. Each stimulation session lasted 3 minutes during which the participant was required to focus on the image of the hand and the tactile sensation.

After each stimulation session the subjective experience of the illusion was assessed by the Illusion Questionnaire (see Table 3), adapted from Pavani and Zampini (2007). The questionnaire probes the visual capture of hand position (questions 1 to 3) and the visual capture of touch (questions 4 and 5). Moreover, it includes two questions that do not specifically investigate any visual capture phenomena but are used as control (questions 6 and 7). The participant rated each question using a seven-point Likert scale from 1 "Total disagreement" (i.e., weak illusion) to 7 "Total agreement" (i.e., strong illusion). The mean ratings about the visual capture of hand position and touch were averaged to compute the *Test Questions* index in each stimulation session, while the average of control questions provided the *Control Questions* index. The *Test Questions* index is expected to be higher in the synchronous stimulation than in the asynchronous one. Moreover, the *Test Questions* index is expected to be higher than the *Control Questions* index in the synchronous stimulation but not in the asynchronous one.

Table 3. Illusion Questionnaire

Visual Capture of Hand Position	1. Did you have the feeling that your left hand was where you saw the image of your hand? 2. Did you have the feeling that your left hand was drifting towards the image of your hand? 3. Did you have, suddenly, the feeling that your left hand got the position of the image of your hand?
Visual Capture of Touch	4. Did you have the feeling that the touch you felt was provoked by the brush that was stroking the image of your hand? 5. Did you have the feeling that the touch of the brush come halfway between your left hand and the image of your hand?
Control Questions	6. Did you feel like having two left hands? 7. Did you have the feeling that the image of your hand was moving towards the location of your left hand?

Proprioceptive judgment task. To evaluate the mislocation of the real hand towards the virtual hand, a proprioceptive judgment task (Kammers et al., 2009; Scarpina et al., 2015) was administered before (*pre-test*) and after (*post-test*) the synchronous and the asynchronous stimulation. The participant placed the left hand inside the wooden box. The lid of the box impeded the sight of both the real and the virtual hand (see Figure 3B). The experimenter moved a needle on the edge of the box opposite to the participant. The participant had to stop it when she/he perceived the needle to be aligned with the left middle finger.

The experimenter slid the needle at a constant rate, starting from left or right in a randomized order. Each participant made ten proprioceptive judgments before and after each stimulation session: after each judgment the experimenter recorded the participant's answer according to a paper meter fixed on the box edge. Smaller values on the meter indicated a shift towards the virtual image of the hand. The participant was encouraged to make each judgment according to the current perception of the hand location, avoiding using any strategy or external reference points. A shift of the perceived location of the real hand towards the virtual hand (i.e., proprioceptive drift) is considered a behavioural objective measure of the RHI (see Ehrsson, 2012 for a review). Therefore, according to the previous literature (Botvinick & Cohen, 1998; Kammers et al., 2009; Longo et al., 2008; Tsakiris & Haggard, 2005), the proprioceptive drift is expected to be significantly greater in the synchronous than in the asynchronous condition, as a consequence of an effective RHI.

Sensory Susceptibility Scale (Gheorghiu & Huebner, 1992)**.** This test consists of fourteen exercises in which the experimenter induces tactile, visual, auditory, and taste sensations in the participant, through *ad hoc* stimulations and verbal suggestions. In ten exercises out of fourteen, sensations are not physiologically plausible (*Experimental Exercises).* For example, the experimenter emphasizes that the stimulation of different parts of the tongue elicits different tastes (sweet or salty). Then the experimenter asks the participant to stroke the side and the tip of the tongue against the teeth and ask to rate how intense was the (fake) taste perceived. On the contrary, in the *Control Exercises* sensations are physiologically determined, such as hearing a rustle when plugging the ears with the hands. After each exercise, the participant rates the vividness of the sensation on a five-point Likert scale from zero "No sensation" to four "Intense sensation". Two indices were computed: the average rating of the *Experimental Exercises* and the average rating of the *Control Exercises*. Individuals who are more sensory-suggestible, i.e. inclined to perceive fake perceptions, are expected to rate the *Experimental Exercises* higher than low sensory-suggestible people. All individuals are expected to rate *Control Exercises* high.

Procedure

First, the experimenter took the photograph of the participant's left hand and processed the image as previously described. The participant was instructed to put the left hand inside the covered wooden box on the platform and to keep it motionless until further warning while performing the pre-test proprioceptive judgment task. The participant was then asked to close the eyes; the lid of the box was removed, and the vertical wooden panel placed between the real hand and the screen. The participant was asked to open the eyes and the RHI paradigm was performed. After 3 minutes of stimulation, the participant closed the eyes again until the box was readied to perform the post-test proprioceptive judgment task. After, the participant was encouraged to move the hand, while completing the Illusion Questionnaire.

Finally, the Sensory Susceptibility Scale (Gheorghiu & Huebner, 1992) was performed to avoid any possible confounding effect on the illusion susceptibility.

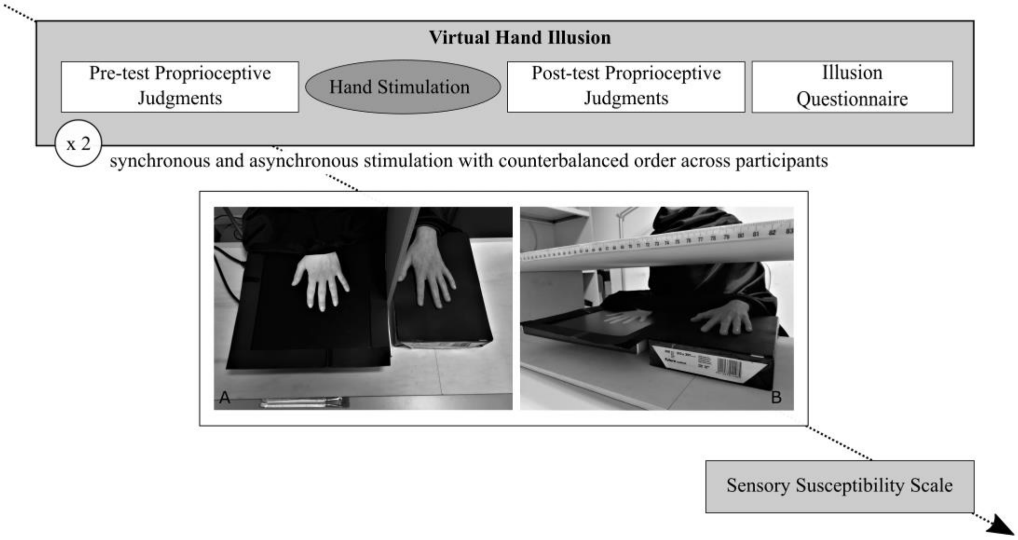

Figure 3. Illustration of the experimental procedure and of the experimental setting during the synchronous and asynchronous stimulation of the real and the virtual hand (panel A) and during the pre and post-test proprioceptive judgments of hand location (panel B).

3.3 RESULTS

The Rubber Hand Illusion paradigm

Illusion Questionnaire. To investigate the strength of the illusion within each group, the *Test Questions* index was compared between the synchronous and asynchronous conditions. Moreover, *Test* and *Control Questions* indices were compared in each condition. Given that variables are ordinal, and most of their distributions were not symmetrical, data were analysed using non-parametric exact sign tests. In the healthy weight group, the median rating of *Test Questions* in the synchronous condition (median = 2.9) was significantly higher than in the asynchronous condition (median = 1.6) (two-tailed exact p = .008, PS_{dep} = 0.8). The median rating of *Test Questions* in the synchronous condition (median = 2.9) was significantly higher than that of *Control Questions* (median = 1) (two-tailed exact p = .001 PS_{dep} = 0.85). Contrary to expectations, the median rating of *Test Questions* (median = 1.6) was higher than *Control Questions* (median = 1) also in the asynchronous condition (two-tailed exact p = .004, PS_{dep} = 0.8).

Therefore, among healthy weight participants, the subjective experience of the illusion was higher after the synchronous than the asynchronous stimulation, as expected. However, a slighter effect of the illusion was detected also after the asynchronous stimulation.

In the group affected by obesity the median rating of *Test Questions* in the synchronous condition (median = 1.6) was significantly higher than in the asynchronous condition (median = 1) (two-tailed exact p = .022, PS_{dep} = 0.71). Furthermore, in the synchronous condition the median rating of *Test Questions* (median = 1.6) was significantly higher than *Control Questions* (median = 1) (two-tailed exact p = .003, PS_{dep} = 0.76), while no difference (two-tailed exact p =.55) was found in the median rating of *Test Questions* (median = 1) and *Control Questions* (median = 1) in the asynchronous condition. Therefore, among individuals affected by obesity, the synchronous stimulation evoked a significantly higher subjective experience of the RHI than in the asynchronous stimulation.

To compare the subjective experience of the illusion between the healthy weight and individuals affected by obesity, the *Test Questions* index was compared across groups for each condition of stimulation independently. Ordinal data were analysed using the Mann-Whitney U test. This analysis revealed that the median differences between groups in the rating of *Test Questions* were not statistically significant in both the synchronous and asynchronous conditions [synchronous condition: *Test Questions* (U = 128.5, z = -1.73, two-tailed exact $p = .084$, $r = 0.27$); asynchronous condition: *Test Questions* (U = 139.5, z = -1.46, two-tailed exact $p = .146$, $r = 0.22$)]. Therefore, individuals with obesity and healthy weight individuals had a comparable subjective experience of the illusion in both conditions of stimulation.

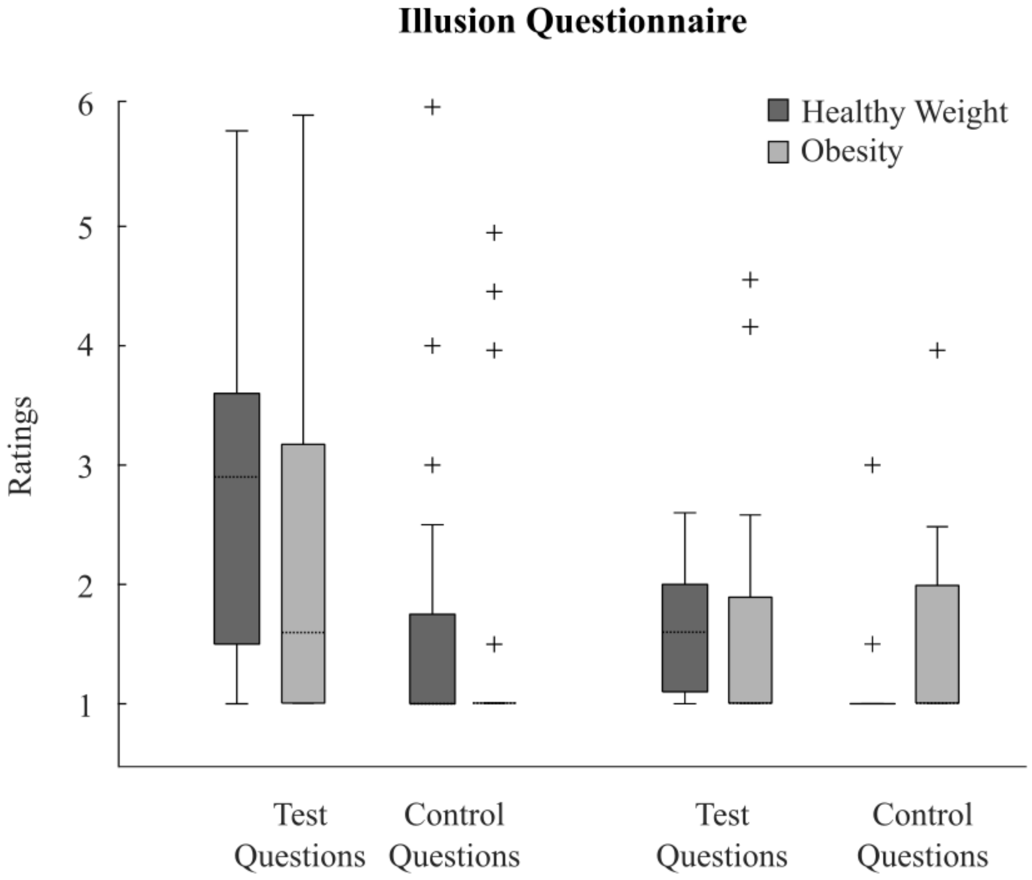

Figure 4. Box plots illustrate the *Test Questions* and *Control Questions* ratings in the Illusion Questionnaire, according to *Group* and *Condition* of stimulation. Dashed lines indicate the medians. Crosses indicate outliers; given that w is the maximum whisker length (+/–2.7σ), and q1 and q3 are the 25th and 75th percentiles of the sample data, values higher than q3 + w × (q3 – q1) or less than q1 – w × (q3 – q1) were considered outliers.

Proprioceptive Drift. Single pre-test and post-test proprioceptive judgments in both synchronous and asynchronous condition were analysed to detect possible outliers. Outliers were defined as values higher or lower by twice the standard deviation than the participant's average proprioceptive judgment relative to each specific session (pre-test and post-test) and condition of stimulation. On average, the percentage of proprioceptive judgment removed was 1.9 % in the obesity group and 0.88 % in the healthy weight group. The *Proprioceptive Judgment Error* was computed subtracting the perceived position of the hand from its real position at each point (pre-test and post-test) and in each condition (synchronous and asynchronous) of stimulation. An error close to zero indicates that the hand was perceived almost in its real position. A positive error indicates a mislocation of the real hand towards the virtual hand and *vice versa* (Pavani & Zampini, 2007; Tsakiris & Haggard, 2005). To monitor the basic ability to locate the body in the space across groups, one-sample *t*-tests were performed to compare the pre-test and post-test Proprioceptive Judgment Error in both synchronous and asynchronous conditions to zero. In obesity the pre-test and post-test Proprioceptive Judgment Error in both conditions was not significantly different from zero [synchronous stimulation: *pre-test* (M (SD) = 0.52 (2.97), $t_{(20)}$ = 0.81, two-tailed *p* = .429, *d* = - 0.18); post-test (M (SD) = 1.01 (2.97), $t_{(20)}$ = 1.56, two-tailed *p* = .133, *d* = - 0.34); asynchronous condition: *pre-test* (M(SD) = 0.50 (2.47), $t_{(20)}$ = 0.93, two-tailed *p* = .365, *d* = - 0.2); *post-test* (M (SD) = 0.20 (2.44), $t_{(20)}$ = 0.37, two-tailed *p* = .715, *d* = - 0.08)]. On the other hand, in healthy weight participants the Proprioceptive Judgment Error was always significantly different from zero [synchronous condition: *pre-test* (M (SD) = 1.04 (2.01), $t_{(19)}$ = 2.30, two-tailed *p* = .033, *d* = - 0.5); *post-test* (M (SD)= 2.88 (2.8), $t_{(19)}$ = 4.60, two-tailed *p* = .001, *d* = - 1.03; asynchronous condition: *pre-test* (M (SD) = 1.72 (2.71), ($t_{(19)}$ = 2.84, two-tailed *p* = .01, *d* = - 0.63; *post-test* (M (SD) =2.24 (2.79), $t_{(19)}$ = 3.58, two-tailed *p* = .002, *d* = - 0.8)]. However, if Bonferroni's correction for multiple comparisons is applied (α = .0125) the pre-test Proprioceptive Judgment Error in the synchronous stimulation becomes not significantly different from zero. To sum up, individuals with obesity were quite accurate in estimating the hand position at each point and in each condition of stimulation, whereas healthy weight individuals always tended to mislocate the position of the hand towards the virtual hand.

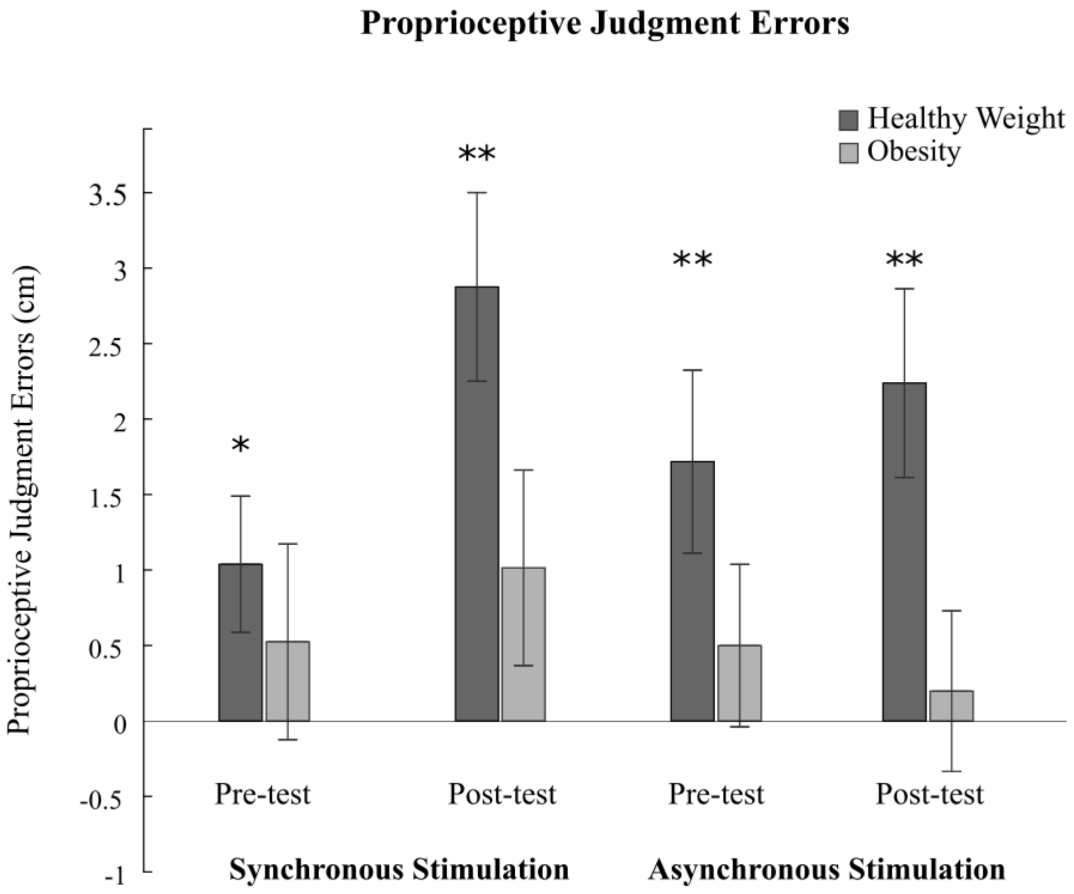

Figure 5. The graph illustrates the *Proprioceptive Judgment Error* at each point and in each condition of stimulation in healthy weight participants and individuals with obesity.

To probe the effect of the illusion on self-location the *Proprioceptive Drift* was computed subtracting the pre-test Proprioceptive Judgment Error from the post-test Proprioceptive Judgment Error in each condition of stimulation (Tsakiris & Haggard, 2005). A positive value indicates that the mislocation of the hand towards the virtual hand was higher after the stimulation than before the stimulation. The higher is the (positive) Proprioceptive Drift, the greater is the mislocation of the real hand towards the virtual hand after the stimulation. Therefore, a higher (positive) Proprioceptive Drift is expected after the synchronous than after the asynchronous stimulation, because of the illusion.

Data were normally distributed (Shapiro-Wilk test $p > .05$). The Proprioceptive Drift was entered in a 2x2 mixed ANOVA, with *Condition* (*synchronous* vs *asynchronous*) as within-subjects factor and

Group (*obesity* vs *healthy weight*) as between-subjects factor. The analysis revealed a main effect of *Condition* ($F_{1,\,39}$ = 7.47, p =.009, η^2 = 0.16), indicating that the mislocation of the real hand towards the virtual hand was higher after the synchronous stimulation (marginal mean (SE) = 1.16 (0.27)) than the asynchronous one (marginal mean (SE) = 0.11 (0.23)), regardless of the group. Furthermore, the analysis showed a main effect of *Group* ($F_{1,\,39}$ = 11.69, p =.001, η^2 = 0.23), suggesting that the mislocation of the hand towards the virtual hand was higher in healthy weight participants (marginal mean (SE) = 1.18 (0.23)) than individuals with obesity (marginal mean (SE) = 0.09 (0.22)), regardless of the condition of stimulation. The *Condition*Group* interaction effect was not significant ($F_{1,\,39}$ = 0.46, p =.50, η^2 = 0.01).

Differences between groups were probed further by independent sample *t*-tests. Means and standard deviations of the Proprioceptive Drift after each condition of stimulation are reported in Table 4. The analysis revealed that the Proprioceptive Drift after the synchronous stimulation was significantly higher in healthy weight participants than in individuals with obesity ($t_{(39)}$ = 2.48, two-tailed p = .018, d = 0.77). On the contrary, the Proprioceptive Drift was comparable across groups after the asynchronous stimulation ($t_{(39)}$ = 1.82, two-tailed p = .076, d = 0.57). Taken together, these findings suggest that even though the illusion generated a recalibration of position sense in both groups, in individuals with obesity the effect of the illusion was weaker than in healthy weight participants.

Table 4. Mean and standard deviation (in brackets) of the *Proprioceptive Drift* in individuals with obesity and healthy weight individuals after the synchronous and asynchronous stimulation.

	Synchronous		**Asynchronous**	
Healthy Weight	1.84	(1.74)	0.52	(0.98)
Obesity	0.49	(1.74)	-0.30	(1.77)

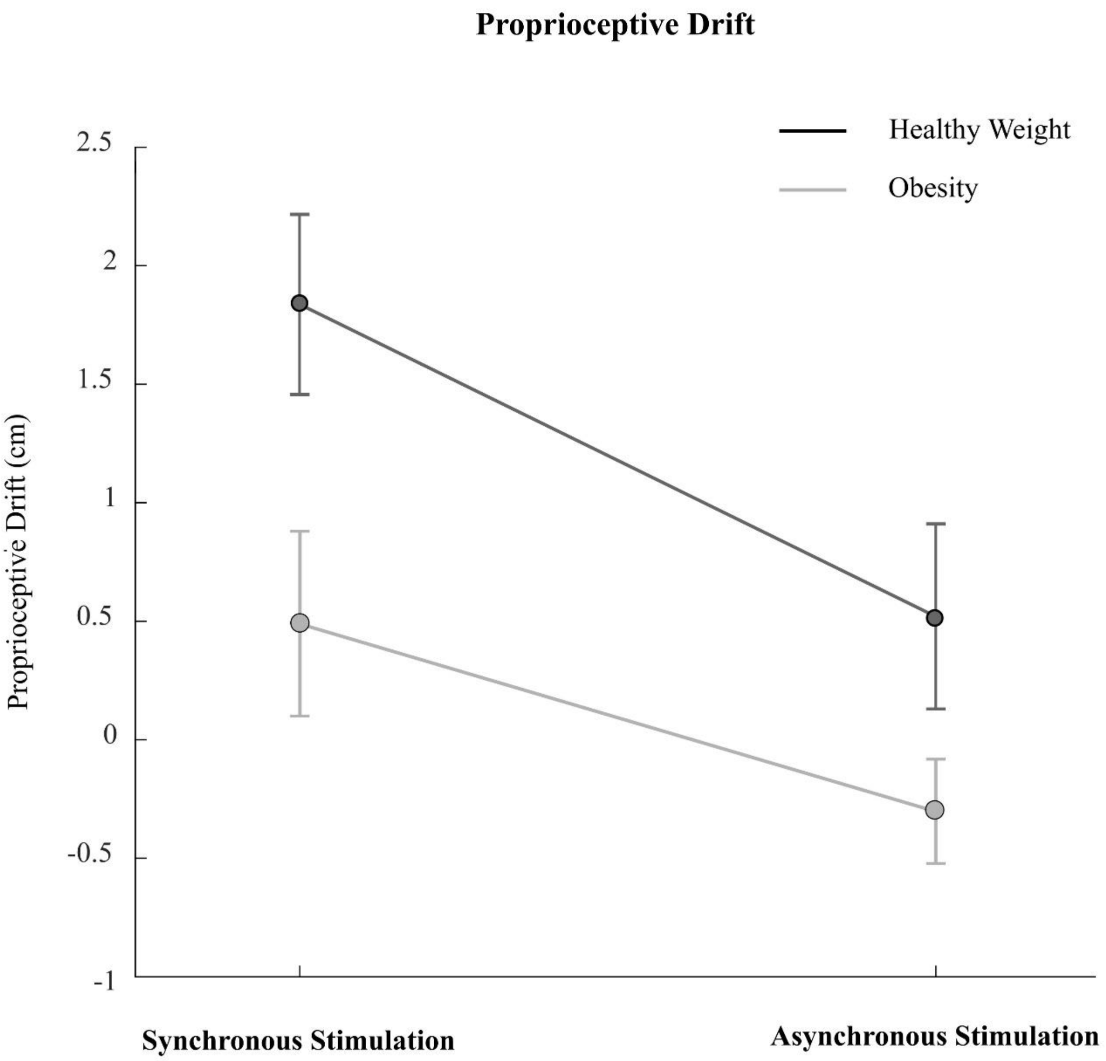

Figure 6. The graph illustrates the *Proprioceptive Drift* after the synchronous and asynchronous stimulation of the hand in healthy weight participants and individuals with obesity.

Sensory Susceptibility Scale

To detect significant differences in the tendency to experience counterfeit sensory perceptions between healthy weight and individuals affected by obesity ordinal data were analysed with the Mann-Whitney U test. The median rating of the C*ontrols Exercises* was significantly higher in the healthy weight group (median = 1.75) than among individuals affected by obesity (median = 1.5; U =129.5, z = -2.12, r = 0.33). The median rating of the *Experimental Exercises* was comparable between healthy weight (median

= 1.04) and individuals affected by obesity (median = 0.6; *U* = 144, *z* = -1.72, *r* = 0.27). Therefore, the two groups had a comparable propensity to experience counterfeit sensory stimuli, even though individuals affected by obesity were less susceptible to real sensory experiences.

Correlations

To investigate the role of individual differences on RHI susceptibility, Spearman's *r* coefficients of correlation were computed in each group independently, comparing *Years of Education, BMI,* and the Sensory Susceptibility Scale - *Experimental Exercises* score with the score of *Test Questions* in the Illusion Questionnaire and the *Proprioceptive Drift* in both conditions of stimulation. Bonferroni's correction for multiple comparisons was applied (α = 0.0042). No significant correlation was found in either group (see Table 5). Interestingly, the absence of any correlation suggests that neither the scholastic level nor participants' weight or sensory susceptibility influenced participants' behaviour in the RHI.

Table 5. Spearman's r coefficients of correlation and *p* values (in brackets) between years of education, BMI, Sensory Susceptibility Scale (SSS) – Experimental Exercises, the Illusion Questionnaire - Test Questions scores and Proprioceptive Drift, in both synchronous and asynchronous condition in each group. Bonferroni's correction for multiple comparisons was applied (α= 0.0042).

	Test Questions		**Proprioceptive Drift**	
	Synchronous	Asynchronous	Synchronous	Asynchronous
	Healthy Weight Group			
BMI	-0.25 (0.29)	-0.01 (0.96)	0.02 (0.94)	-0.06 (0.81)
Years of education	-0.19 (0.43)	-0.32 (0.13)	0.12 (0.62)	0.47 (0.04)
SSS - Experimental Exercises	0.12 (0.62)	-0.04 (0.88)	-0.07 (0.79)	-0.20 (0.40)
	Obesity Group			
BMI	0.03 (0.89)	-0.18 (0.43)	-0.15 (0.51)	0.26 (0.25)
Years of education	0.20 (0.38)	0.45 (0.04)	-0.03 (0.90)	-0.22 (0.34)
SSS - Experimental Exercises	0.58 (0.01)	0.43 (0.05)	0.20 (0.38)	0.10 (0.68)

3.4 DISCUSSION

The aim of the present work was to investigate whether the multisensory manipulation of bodily self-consciousness induced by the RHI differed between individuals affected by obesity and healthy weight individuals. A deeper understanding of this domain is indeed desirable since *ad hoc* multisensory illusions might be used in the clinical setting to improve body representation in obesity, determining better outcomes (Riva, 2011; Riva et al., 2019; Serino & Dakanalis, 2017).

According to the Illusion Questionnaire, both participants with obesity and healthy weight participants reported a comparable subjective experience of the illusion, which was significantly greater after the synchronous than the asynchronous stimulation.

The effect of the illusion in terms of a higher mislocation of the hand towards the virtual hand after the synchronous stimulation than the asynchronous one (Botvinick & Cohen, 1998; Pavani & Zampini, 2007) was observed regardless of the group. However, further analyses revealed that the Proprioceptive Drift after the synchronous stimulation was significantly higher in healthy weight participants than in individuals with obesity. Thus, the synchronous stimulation of the hand evoked a weaker recalibration of hand position towards the virtual hand in the group with obesity than in the healthy weight group.

Importantly, the effect reported in the Proprioceptive Drift was task-dependent, and not related to a global diminished propensity to experience counterfeit sensations. Indeed, both participants with obesity and healthy weight participants reported a comparable propensity to experience counterfeit sensory perceptions, when assessed by the Sensory Susceptibility Scale (Gheorghiu & Huebner, 1992).

On the other hand, *a priori* dissimilarities in the ability to locate the body in the space (i.e., Proprioceptive Judgment Error) were found. Individuals with obesity located the hand accurately at each point (pre-test and post-test) and in each condition of stimulation. Conversely, healthy weight individuals always biased the position of their hand towards the virtual hand. We might speculate that participants with obesity were more focused on their body since they were about to begin a weight loss rehabilitative program. Future studies might probe this issue. Anyway, the Proprioceptive Drift index was computed as the *difference* between pre-test and post-test Proprioceptive Judgment Error *within* each group. The Proprioceptive Judgment Error in obesity was lower than healthy weight participants but at each point (pre-test and post-test) and in each condition of stimulation, thus, this dissimilarity *between* groups should not affect the *difference* between pre-test and post-test Proprioceptive Judgment Error (i.e., Proprioceptive Drift) in both synchronous and asynchronous stimulation.

The RHI was studied in several clinical conditions as a tool to investigate body representation (such as in autism spectrum disorder; Cascio et al., 2012; Paton et al., 2012; schizophrenia; Thakkar et al., 2011; body dysmorphic disorder; Kaplan et al., 2014, and eating disorders; Eshkevari et al., 2012; Keizer et al., 2014), but no previous study administered it in obesity. Our findings, though not conclusive, demonstrate that some components of body representation in individuals affected by obesity can be manipulated, although to a lesser extent than healthy individuals. Nevertheless, the dissimilar effect of the RHI found on the subjective experience of the illusion and self-location might not be surprising. Indeed, it is well-know that these components can be differently modulated by the RHI in both healthy individuals (Abdulkarim & Ehrsson, 2016; Holle et al., 2011; Rohde, et al., 2011) and clinical populations (Kaplan et al., 2014; Keizer et al., 2014). Furthermore, they rely on dissimilar neural networks (Ehrsson, 2005; Ehrsson, Spence, & Passingham, 2004; Ionta et al., 2011; Kammers et al., 2009; Petkova, Zetterberg, & Ehrsson, 2012).

Thus, which is the novelty of our results? As previously mentioned, the traditional interpretation of the RHI states that the illusion relies on a three-way interaction of vision, touch, and proprioception (Blanke, 2012; Botvinick & Cohen, 1998). Altered multisensory integration processes have been related to an atypical susceptibility in several clinical populations (e.g., autism spectrum disorders; Cascio et al., 2012; Paton et al., 2012; schizophrenia; Thakkar et al., 2011; body dysmorphic disorder; Kaplan et al., 2014; and eating disorders; Eshkevari et al., 2012; Keizer et al., 2014). Multisensory integration has been scarcely investigated in obesity, nevertheless, preliminary evidence pointed to anomalies in this domain (Scarpina et al., 2016; Wan et al., 2014). Specifically, Scarpina and colleagues (2016) reported a lower audio-visual temporal resolution in obesity compared to healthy weight individuals. This means that individuals with obesity integrated visuo-tactile stimuli over an extended range of stimulus-onset asynchronies. Wan and colleagues (2014) measured the ability to detect and discriminate tactile stimuli in the presence or not of an auditory stimulus, observing that individuals with obesity differently benefit from multisensory stimulations (compared to unisensory stimulations) respect to healthy weight participants. Thus, an altered multisensory integration might explain our findings. In the classical view, both the subjective experience of the illusion and the proprioceptive drift rely on the same multisensory integration mechanisms (Blanke, 2012; Costantini et al., 2016; Ehrsson, 2012). Accordingly, if individuals with obesity were not able to integrate properly visual, tactile and proprioceptive stimuli, they should show a similar modulation of bodily self-consciousness in both the subjective (i.e., perceptual effects measured by the questionnaire) and objective (i.e., proprioceptive drift) components of the RHI.

A different line of interpretation of the multisensory integration mechanisms involved in the RHI was proposed by Rohde and colleagues (2011). The authors reported that the proprioceptive drift was higher after the synchronous than asynchronous stimulation, but they also observed a comparable proprioceptive drift even when participants looked at the rubber hand, in absence of any tactile stimulation. On the other hand, the modulation of the subjective illusory experience (i.e., questionnaire) arose only in the presence of synchronous stimulation between the real and the rubber hand. Previously, Holmes and colleagues (2006) also demonstrated that viewing a prosthetic hand towards a mirror (in absence of any tactile stimulation) biased the perceived limb position, without inducing a feeling of ownership towards the fake hand. Rohde and colleagues (2011) concluded that visuo-proprioceptive integration might be enough to induce a recalibration of proprioception in favour of vision, while the subjective experience of the illusion relies on visuo-tactile integration mechanisms. In other words, while the visuo-tactile integration seems necessary to manipulate the subjective experience of the illusion, it does not have an additive effect on the visuo-proprioceptive integration that induces the recalibration of self-location. Rohde and colleagues (2011), proposed that the prolonged asynchronous stimulation interferes with the visuo-proprioceptive integration, *reducing* the proprioceptive drift. More recently, Costantini and colleagues (2016) observed that when the interval between the visual and tactile stimuli in the RHI was slightly out of individuals' temporal binding window, the subjective experience of the illusion was abolished, while participants had a significant proprioceptive drift both during synchronous and asynchronous stimulation. Therefore, a slight asynchrony might not be enough powerful to interfere with the visuo-proprioceptive integration that causes the proprioceptive drift, similarly to what has been reported by Rohde and colleagues (2011) with discontinuous asynchronous stimulations. According to Rhode and colleagues' (2011), our findings might be explained by altered visuo-proprioceptive integration mechanisms and preserved visuo-tactile integration processes in obesity. This would explain why in obesity the RHI has a negligible effect on self-location and a typical effect on the subjective experience of the illusion.

In the presence of multisensory stimuli, individuals tend to integrate them according to their reliability (Alais & Burr, 2004; Ernst & Banks, 2002; van Beers, Wolpert, & Haggard, 2002; Welch, Widawski, Harrington, & Warren, 1979). The proprioceptive drift that usually emerges in the RHI illusion demonstrates that the precision of the proprioceptive information can be lowered in favour of the visual information (i.e., regarding the position of the fake or, in our study, the virtual hand) in situations characterized by conflictual sensory perceptions. However, the reliability assigned to visual and proprioceptive information can vary across individuals (Boulinguez & Rouhana, 2008; Coello, Milleville-Pennel, & Orliaguet, 2004). If individuals with obesity weighted higher the proprioceptive information than the visual one, the visual capture that induces the proprioceptive drift might not occur. For instance, the stronger tendency to focus on proprioceptive information in case of multisensory conflict has been related to a delayed proprioceptive recalibration of the hand position in the RHI in children affected by autism spectrum disorders (Cascio et al., 2012).

But, why should they consider the proprioceptive information more reliable than healthy individuals? One possibility is that individuals with obesity have either a more efficient proprioception or a less efficient visual perception, or both. Few studies investigated proprioceptive abilities in obesity, yet reporting a *reduced* proprioceptive accuracy of the knee joint (Moravveji, Ghanbari, & Kamali, 2017; Saleh & El-Nabie, 2017; Wang, Li, Xu, & Hong, 2008). Proprioceptive difficulties in obesity have been considered a consequence of the excessive body weight, which induces an anomalous and prolonged load on the knee joint, altering the physiological function of mechanoreceptors (Moravveji et al., 2017; Saleh & El-Nabie, 2017; Wang et al., 2008). However, the body mass does not lean directly and persistently against the hand, thus a similar scenario is unlikely for this body part. Furthermore, in our sample individuals with obesity were even more accurate than healthy weight individuals in the localization of the hand.

On the other hand, primary visual perception has never been investigated in obesity (Prickett et al., 2015). Visuo-constructional anomalies have been reported in this medical condition (see, for instance, Roberts, Demetriou, Treasure, & Tchanturia, 2007; Sargénius, Lydersen, & Hestad, 2017 and Prickett et al., 2015, for a review), suggesting that individuals might rely on more analytic than global visual processing, focusing more on the scene details than on the gestalt. However, it is not clear how this tendency might affect visuo-proprioceptive integration. To sum up, previous experimental evidence together with our results are not enough to clarify whether individuals with obesity are more anchored to proprioception than vision due to either more efficient proprioception accuracy or less efficient visual perception, or both. Future lines of research might deepen this issue.

A further speculation might be that visual capture does not occur because visual and proprioceptive information are not integrated at all, rather than because proprioception prevails on vision. It was proposed that an atypical oscillatory neural activity might determine aberrant multisensory integration in obesity (Scarpina et al., 2016), which might affect the RHI experience. This topic will be more extensively discussed in the following chapters. Furthermore, functional connectivity in resting-state has been recently related to the temporal resolution of multisensory integration processes (Ferri et al., 2017), which in turn has been associated with anomalous susceptibility to multisensory illusions (Ferri, Venskus, Fotia, Cooke, & Romei, 2018). Preliminary experimental evidence, although very scarce, suggests that functional connectivity (Ochner, Green, Jason Van Steenburgh, Kounios, & Lowe, 2009) during resting-state might be anomalous in obesity.

To the best of our knowledge, visuo-proprioceptive integration in obesity has never been investigated. Furthermore, also visuo-tactile integration has never been probed in this clinical population, thus, we cannot be sure that this process is actually preserved. In fact, previous evidence points to altered audio-visual and audio-tactile multisensory processing in obesity (Scarpina et al., 2016; Wan et al., 2014); therefore, one might expect that the whole multisensory integration mechanism might be impaired. The following chapter focuses on the temporal resolution of visuo-tactile integration in obesity, which was addressed first than visuo-proprioceptive integration since the immediate availability of the experimental material in our lab. Indeed, visuo-proprioceptive integration is slightly more difficult to investigate, since the traditional tasks used in the investigation of multisensory integration (e.g., the Temporal Order

Judgment and the Simultaneity Judgment Task) might not fit the purpose. Proprioceptive information is indeed more peculiar than visual, auditory, and tactile cues since its administration is hardly controlled with high precision. The *mirror illusion* (Holmes & Spence, 2005; Holmes, Crozier, & Spence, 2004; Snijders, Holmes, & Spence, 2007) might be a suitable alternative paradigm. When one hand is hidden behind a parasagittal mirror and the other one is put so that it is reflected in the mirror, the reflection resembles the hidden hand. In this scenario, the visual exposure to a fake position of the (hidden) hand induces participants to perceive the hand where they see it in the mirror and to move it accordingly to the counterfeit location (Holmes, Snjders, & Spence, 2006; Holmes, Crozier, & Spence, 2004). These results support the idea that the perceived position of the hand depends on the integration of visuo-proprioceptive information. It may be interesting to perform the same task in obesity, to probe whether a proper visuo-proprioceptive integration occurs. According to the results reported in this chapter, one might expect the visual capture of hand position to be reduced in obesity, similarly to what happened for the Proprioceptive Drift in the illusion.

4 REDUCED TEMPORAL RESOLUTION OF VISUO-TACTILE INTEGRATION IN OBESITY: EVIDENCE FROM A SIMULTANEITY JUDGMENT TASK [6]

4.1 INTRODUCTION

Our brain is often exposed to several sensory inputs. To build a coherent cognitive representation of the world, stimuli of different sensory modalities must be organized in a meaningful way, binding together the information that originates from the same object or source and segregating unrelated incoming signals. Temporal coincidence is one of the most important factor determining whether multisensory stimuli should be integrated in a unique perceptual event (Spence, 2007; Stein & Meredith, 1993; Wallace et al., 2004), improving the accuracy of our perception (Calvert et al., 2004). However, a strict temporal overlap is not necessary. In fact, sensory signals have different physical properties, as well as dissimilar computational and transmission timings, meaning that simultaneous stimuli might be detected by the brain with a slight delay (e.g., Pöppel et al., 1990). The brain has adaptively learned to tolerate small asynchronies between sensory information, still perceiving them in synchrony and bounding them to the same percept. As a consequence, even stimuli that are *not* physically simultaneous might be perceived in synchrony and thus integrated (Vroomen & Keetels, 2010). The temporal binding window is a psychophysical measure of the time lag tolerated by the brain in order to perceive two stimuli as synchronous (Stevenson & Wallace, 2013). In other words, it measures individuals' temporal sensitivity to multisensory simultaneity. The larger the temporal binding window, the higher the probability of merging stimuli that do not belong to the same environmental event, with significant consequences on the accuracy of our perception. The perception of simultaneity across sensory modalities is thus strictly related to the efficiency of multisensory integration (Stevenson & Wallace, 2013; Vroomen & Keetels, 2010).

.

---

[6] Some of the contents reported in this Chapter are part of the work *"Reduced Temporal Sensitivity in Obesity: Evidence from a Simultaneity Judgment Task"* by Sofia Tagini, Federica Scarpina, Massimo Scacchi, Alessandro Mauro and Massimiliano Zampini currently under review in *Multisensory Research.*

The simultaneity judgment task (SJT) is a traditional method to measure the temporal binding window. In this task, pairs of multisensory stimuli are delivered at a range of different stimulus-onset asynchronies (SOAs) using the method of constant stimuli (Vroomen & Keetels, 2010; Zampini et al., 2005). Participants have to judge whether the stimuli are presented simultaneously or successively. The percentage of "synchronous" judgments is plotted as a function of SOAs and fitted to a Gaussian curve. Conventionally the standard deviation (i.e., the width) of the curve is taken as a measure of the temporal binding window, since it represents the range of SOAs at which the two stimuli have a high probability (i.e., about the 68%) to be perceived in synchrony (Vroomen & Keetels, 2010). Alternatively, temporal sensitivity can be measured with a temporal order judgment (TOJ) task in which participants must judge which of two stimuli come first. This task provides a measure of the smallest interval the observer can reliably notice (i.e., the just noticeable difference, JND). The smaller is the just noticeable difference, the higher is the temporal sensitivity (Vroomen & Keetels, 2010).

Scarpina and colleagues (2016) used the SJT and the TOJ task to evaluate the temporal sensitivity to audio-visual simultaneity in obesity. They demonstrated that individuals with obesity had a larger temporal binding window in the SJT and a higher just noticeable difference in the TOJ task compared to healthy weight individuals. Temporal sensitivity to audio-visual asynchrony seems thus reduced in obesity. Obesity has been extensively related to several cognitive impairments (see Chapter 1). On the other hand, despite its relevance, the domain of multisensory perception has been scarcely investigated. Indeed, except for the mentioned work by Scarpina and colleagues (2016), to the best of our knowledge, only another study probed this issue. Wan and colleagues (2014), measured the ability to detect and discriminate tactile stimuli in the presence or not of an auditory stimulus, reporting that individuals with obesity benefit less from multisensory stimulations (compared to unisensory stimulations) respect to healthy weight participants. Nevertheless, the authors did not specifically consider the temporal sensitivity to multisensory simultaneity, limiting the comparison with Scarpina and colleagues' work.

Previous studies showed atypical oscillatory patterns of alpha-band rhythms in obesity (Babiloni et al., 2011; Del Percio et al., 2013; Dubbelink et al., 2008). In turn, the neural oscillatory activity in the brain has been related to the discrimination between stimuli synchrony/asynchrony (Keil & Senkowski, 2017; Kösem, Gramfort, & van Wassenhove, 2014; Yuan, Li, Liu, Yuan, & Huang, 2016). Accordingly, Scarpina and colleagues (2016) argued that an anomalous oscillatory neural activity might affect the temporal sensitivity to multisensory simultaneity in obesity, eventually influencing the mechanism of multisensory integration.

Additionally, a reduced volume of the grey matter (Maayan et al., 2011; Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Weise et al., 2013; Willette & Kapogiannis, 2015; Yokum et al., 2012) and a lower cerebral metabolism (Volkow et al., 2009) have been reported in obesity in areas related to the ability to discriminate between synchrony/asynchrony of stimuli (Binder 2015; Bushara et al. 2001; Love *et al*. 2018). Thus, the altered cerebral anatomy/metabolism might also affect the perception of multisensory simultaneity in obesity and, eventually, the process of multisensory integration.

Both these factors (i.e., an altered neural oscillatory activity and the anomalous cerebral anatomy/metabolism) would conceivably affect the perception of synchrony across *several* parings of sensory modalities rather being limited to specific combination of sensory inputs. However, in our previous study (see Chapter 3) individuals with obesity properly experienced the illusion, suggesting that they perceived the stimuli (visuo-tactile) simultaneity. Thus, a crucial issue is whether the atypical temporal sensitivity to multisensory stimuli found in the audio-visual domain (Scarpina et al., 2016) extends to other parings of sensory modalities (according to the mechanisms that might explain altered multisensory perception in obesity) or not, as suggested by the results of Chapter 3. Thus, the aim of this work was to extend the previous preliminary evidence probing the temporal sensitivity to visuo-tactile simultaneity in obesity through a SJT task. If individuals with obesity had an enlarged visuo-tactile temporal binding window (as previously reported with audio-visual stimuli; Scarpina et al. 2016), the hypothesis of a reduced temporal sensitivity that goes beyond the specific sensory modalities considered will be strengthened. Importantly, this might determine a lower efficiency of the whole multisensory integration processing. On the contrary, if individuals with obesity had a comparable temporal sensitivity to visuo-tactile simultaneity, the speculation made in Chapter 3 of a preserved perception of visuo-tactile simultaneity will be supported.

In this case, alternative sources for the altered temporal sensitivity previously reported in obesity may be figured out.

4.2 METHODS

Participants

Eighteen participants (12 female) affected by obesity (i.e., BMI equal or higher than 30) voluntarily took part in the study at the IRCCS Istituto Auxologico Italiano – Ospedale San Giuseppe (Piancavallo, Oggebbio, VCO, Italy), just before starting a weight loss rehabilitative program. Eighteen healthy weight (i.e., BMI lower than 30) individuals (14 female) were recruited from the University of Trento or by experimenters' contact and participated in return for academic credits or monetary compensation (4 euros). Sample size was established according to the previous study investigating audio-visual temporal sensitivity in obesity (Scarpina et al., 2016). Table 6 illustrates the demographic information of the two groups. All participants were right-handed. Non-parametric Mann-Whitney U tests on non-normal data (Shapiro-Wilk test $p < .05$) revealed that the two groups were comparable about age ($U = 161.5$, $z = 0.016$, two-tailed exact $p = .988$, $r = 0.003$), while healthy weight participants had significantly more years of education ($U = 58$, $z = 3.498$, two-tailed exact $p = .001$, $r = 0.583$). Moreover, as expected, the BMI was significantly higher among participants with obesity than in healthy weight participants ($U = 0.000$; $z = 5.110$; two-tailed exact $p < .001$, $r = 0.852$). The presence of any neurological, motor and/or sensory impairment was an exclusion criterion. All participants were naïve to the rationale of the experiment and gave their informed written consent. The study was approved by the ethical committee of the IRCCS Istituto Auxologico Italiano and was performed in compliance with the ethical standards laid down in the 1964 Declaration of Helsinki (most recently amended in Fortaleza, 2013).

Materials and procedure

A visuo-tactile simultaneity judgment task was adopted according to the procedure previously used by Costantini and colleagues (2016) in healthy participants. Pairs of stimuli were delivered by the Heijo

Box (Heijo Research Electronics, UK). Tactile stimuli were produced using solenoid actuators with embedded cylinder plastic tips and were delivered on the dorsal surface of the middle phalanx of the right or left middle finger. Thus, the participant could keep the stimulated fingers motionless, easily responding with the index fingers. Visual stimuli consisted of red light-emitting diodes (LEDs; diameter about 3 mm). The participant sat in front of a table, wearing earplugs and earmuffs to cancel the noise made by the solenoids. Participant's hands were located on a keyboard on the top of which a black paper mask isolated the answer keys ('m' and 'z'). Each hand was placed in its homonymous hemispace. The two red LEDs were placed between the hands on the keyboard, 4 cm left and right to a fixation cross that was aligned with the participant's body midline. Stimuli were 42 cm distant from the participant's body (see Figure 7). The participant was instructed to fixate towards the fixation cross during the whole experiment. The task was to judge whether the stimuli were simultaneous or not, pressing the corresponding answer key on the keyboard with the index fingers. The participant was encouraged to respond as fast as possible. When the tactile stimulus was delivered on the left hand, the visual stimulus was projected in the right visual hemispace (right to the fixation cross). When the tactile stimulus was delivered on the right hand, the visual stimulus was projected in the left visual hemispace (left to the fixation cross). Both visual and tactile stimuli lasted 30 ms (Costantini et al., 2016; Scarpina et al., 2016) and the duration of the intertrial interval was 2000 ms. Stimuli were presented at a range of twelve different SOAs: ± 350, ± 200, ± 120, ± 70, ± 40, ± 25 ms (negative SOAs indicate that the visual stimulus was presented first, whereas positive values indicate that the tactile stimulus was presented first) (see Costantini et al., 2016). Pairings of visuo-tactile stimuli were delivered 32 times at each SOAs, for a total of 384 trials, divided into three blocks (two self-paced breaks were introduced to cope with the participant's fatigability). The four possible stimulus configurations (*i)* first visual stimulus left, second tactile stimulus right; *ii)* first visual stimulus right, second tactile stimulus left; *iii)* first tactile stimulus left, second visual stimulus right; *iv)* first tactile stimulus right, second visual stimulus left) occurred with equal probability. Trials were delivered to all participants in a pseudo-randomized order, with no more than three consecutive presentations of the same trial. The response key for "simultaneous" and "not simultaneous" were counterbalanced across participants. The stimulation delivery and recording of participants' answers were performed by a Dell PC running Psychtoolbox-3 (Kleiner et al., 2007) in MATLAB. For each pair of stimuli, the participant's judgment and the reaction time in milliseconds were recorded.

Analysis

For each participant, trials with a reaction time higher or lower than two standard deviations from the individual's average reaction time (i.e., invalid trials) were removed before the analysis as indicative of anticipation and lack of attention respectively (Ratcliff, 1993). On average, we removed the 2.73 % of trials in the group of individuals with obesity and the 3.53 % of trials in the healthy weight group for each participant. The percentage of trials removed for each SOA was comparable across groups (Mann-Whitney U test, $p > .05$).

The temporal binding window was computed for each participant (see Scarpina et al. 2016). First, we computed the percentage of "simultaneous" answers across all SOAs. Then, the MATLAB built-in function *fit* was used to fit the observed distribution of responses of each single participant to a Gaussian function[7] (Stein & Meredith, 1993; Vroomen & Keetels, 2010). The standard deviation (i.e., the width) of the curve was taken as a measure of the participant's temporal binding window. Participants' temporal binding windows were averaged in each group independently.

Spearman's coefficient of correlation has been computed between participants BMI and the temporal binding window to probe whether temporal sensitivity was related to body mass. To increase the

---

[7] To perform the fitting the following function was used: F(x) = a * exp (- ((x - b) ^ 2) / 2(c ^ 2)) as representative of a Gaussian distribution. The parameter *a* represents the curve's *peak*; *b* is the x value (i.e., the SOA) corresponding to the peak (i.e., the *point of subjective simultaneity – PSS*); *c* is the standard deviation (i.e., the *temporal binding window*). The *peak* and *PSS* of the two groups are reported in the Appendix. The bounds of coefficients [*a b c*] have been specified in the fitting options: [0 -500 0] for the lower bound and [1 500 1000] for the upper bound.

number of observations and the range of BMI, the analysis was performed merging all participants in one single group.

4.3 RESULTS

One healthy weight participant was discarded since the observed responses did not fit well the Gaussian function ($r^2 < 0.80$). Data were not normally distributed in both groups (Shapiro-Wilk test $p < .05$); thus, a non-parametric Mann-Whitney U Test was performed to compare the temporal binding window between healthy weight individuals and individuals affected by obesity. The analysis revealed that individuals with obesity had a larger temporal binding window (median =114.41 ms) than healthy weight individuals (median = 86.03 ms) ($U = 73$; $z = 2.80$; two-tailed exact $p = .004$; $r = 0.47$) (see Figure 8). Means and standard deviations are reported in Table 6.

Table 6. Mean and standard deviation (in brackets) of *Age* in years, *Years of Education*, *Body Mass Index* (BMI) in kg/m^2 and *Temporal Binding Window* in milliseconds among individuals with obesity and healthy weight individuals.

	Age		Years of Education		BMI		Temporal Binding Window	
Healthy Weight	36.11	(15.53)	15.28	(2.97)	21.36	(2.70)	99.61	(38.76)
Obesity	36.33	(12.62)	11.33	(2.63)	43.16	(7.10)	142.97	(75.92)

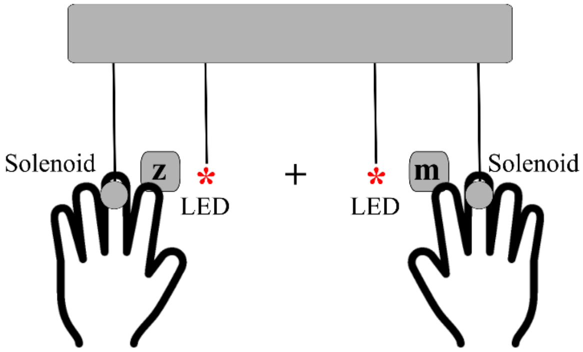

Figure 7. Experimental set-up

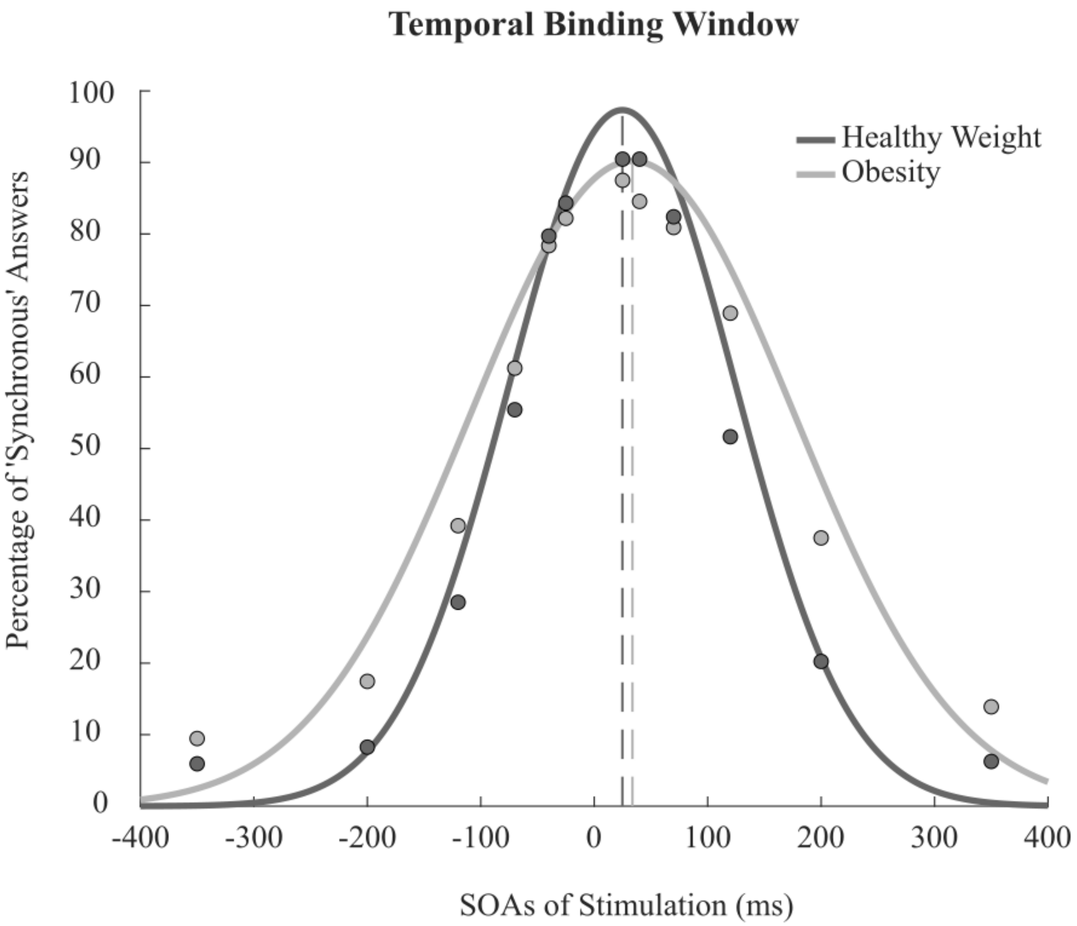

Figure 8. Gaussian fitting to the observed distribution of responses in healthy weight participants and participants with obesity. Dots represent raw unfitted data (i.e., the average percentage of "synchronous" answers for each SOA in each group)

Finally, we found a positive correlation between the BMI and the temporal binding window across all participants (Spearman's r = 0.46, *p* = .005), suggesting that as the body mass increases the visuo-tactile temporal sensitivity decreases.

4.4 DISCUSSION

The temporal binding window measures the time lag tolerated by the brain in order to perceive two stimuli as synchronous. In other words, it represents individuals' temporal sensitivity to sensory simultaneity.

Preliminary evidence reported a higher audio-visual temporal binding window (i.e., lower temporal sensitivity) in obesity (Scarpina et al., 2016). An altered neural oscillatory activity and an anomalous cerebral anatomy/metabolism might underpin this atypical temporal sensitivity. However, both these factors likely affect temporal sensitivity beyond the specific sensory modalities considered and, eventually, the *whole* process of multisensory integration. Nevertheless, the evidence reported in Chapter 3 supports the hypothesis of an efficient perception of visuo-tactile simultaneity in obesity. Up to date, it is unknown whether the reduced temporal resolution found in obesity is specific for audio-visual stimuli or extends to other multisensory pairings. Indeed, while other domains of the cognitive functioning have been extensively investigated in this population (such as executive functions, attention, and memory; see Prickett et al., 2015 for a review) this topic has been almost neglected. In the present study, the investigation of the temporal sensitivity to multisensory simultaneity in obesity has been extended to the visuo-tactile domain, comparing individuals with obesity and healthy weight individuals in a SJT. The results showed that individuals with obesity have a larger visuo-tactile temporal binding window, meaning that they perceived as simultaneous visuo-tactile stimuli with larger onset asynchronies compared to healthy weight participants. Importantly, temporal sensitivity has been found to decrease as much as the body mass increases, suggesting that the differences found between groups might be specifically related to obesity.

Therefore, our results contrast with the findings of our previous study (see Chapter 3), which suggest a preserved perception visuo-tactile simultaneity in obesity. In turn, one might expect that given the larger temporal binding window, individuals with obesity should be more inclined to bind together perceptual conflicting information and, thus, to experience the RHI even at larger temporal discrepancy (e.g., asynchronous stimulation). However, individuals with obesity and healthy weight participants had a comparable subjective experience of the RHI (see Chapter 3), which should be more susceptible to visuo-tactile integration anomalies than the proprioceptive drift (Rohde et al., 2011). The SOA used in the RHI (approximately 1000 ms) might explain this result. Indeed, even if individuals with obesity integrate stimuli over an extended range of SOAs than healthy weight individuals, a 1000 ms SOA is considerably out of their temporal binding window. Consequently, they might have not integrated the visuo-tactile information, the same as healthy weight participants. In accordance, asynchronous RHI susceptibility in a different clinical population with wider temporal binding window (i.e., children with autism spectrum disorder) was found using shorter SOAs (Cascio et al., 2012), which might be more difficult to detect. A parametrical modulation of SOAs may disentangle this issue, probing whether SOAs closer to individuals' temporal binding window could affect the experience of the illusion in obesity. Chapter 5 will pursue this aim.

To sum up, our results, support the hypothesis that the reduced temporal sensitivity to stimuli asynchrony reported in obesity extends to multiple parings of sensory modalities. This finding is indeed in agreement with the previous investigation in the audio-visual domain (Scarpina et al., 2016). When multisensory stimuli are perceived simultaneously they are likely integrated into the same perceptual event (Stevenson & Wallace, 2013). Therefore, temporal sensitivity and multisensory integration are strictly related. The larger is the temporal binding window, the higher is the probability to merge stimuli that do not belong to the same environmental event. Accordingly, the wider temporal binding window reported in obesity might lower the efficiency of multisensory integration in this population. Whether and how this anomalous perception of simultaneity across sensory modalities might influence higher-level multisensory perception in obesity should be probed further. Experimental paradigms in which the behaviour of participants is known to depend on the integration of multisensory stimuli might suit the purpose. For instance, in the RHI we reported that, individuals with obesity properly perceived and integrated the visuo-tactile stimuli that generate the experience of the illusion (at least with 1 second SOA). Similarly, a preliminary evidence showed that a full body illusion successfully induced the identification with a thinner body in an individual affected by severe obesity, improving body satisfaction (Serino et al., 2016).

Alternatively, one's might adopt the McGurk effect (Mcgurk & Macdonald, 1976) and the flash-beeps illusion (Shams, Kamitani, & Shimojo, 2002).

As previously mentioned, an altered multisensory temporal resolution in obesity might be related to an anomalous oscillatory neural activity in the brain (Scarpina et al., 2016). Indeed, it has been proposed that neural oscillations have a crucial role in multisensory integration (Keil & Senkowski, 2017; Mercier et al., 2015; Senkowski et al., 2007), since they lead the exchange of information between different sensory areas (Fries, 2015). In brief, when the excitatory states of different areas are synchronized (i.e., the phases of oscillations are aligned) the interactions between these areas are facilitated. Furthermore, the perception of multisensory simultaneity is related to the brain oscillatory activity, especially in the alpha-band frequency: two stimuli are more likely perceived in synchrony and integrated when they fall in the same phase of the oscillation (Keil & Senkowski, 2017; Kösem et al., 2014; Yuan et al., 2016). Consequently, it has been proposed that neural oscillations might tune the duration of the temporal biding window, i.e. the lower is the frequency of the oscillations the larger is the temporal binding window (Cecere et al., 2015; Cooke et al. 2019; Keil & Senkowski 2017). Previous studies showed atypical synchronization/desynchronization of alpha-band rhythms in obesity (Babiloni et al., 2011; Del Percio et al., 2013; Dubbelink et al., 2008), which might affect the sensitivity to stimuli simultaneity and then multisensory integration. Additionally, a reduced volume of the grey matter, including the insula (Weise et al., 2013), temporal cortex (Weise et al. 2013; Yokum et al., 2012), prefrontal cortex (Maayan et al., 2011; Pannacciulli et al., 2006; Weise et al., 2013; Willette & Kapogiannis, 2015) frontal cortex (Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Willette & Kapogiannis, 2015), and parietal cortex (Pannacciulli et al., 2006) has been reported in obesity. A lower metabolic activity was also observed in the prefrontal cortex (Volkow et al., 2009). Crucially, these areas have been related to the ability to discriminate between synchrony/asynchrony of stimuli (Binder 2015; Bushara et al. 2001; Love et al. 2018). According to our and previous (Scarpina et al., 2026) results, these mechanisms would conceivably affect the temporal sensitivity to multisensory simultaneity beyond the specific sensory modalities involved and the task used.

Future studies might probe this hypothesis, investigating systematically this issue using other pairings of sensory modalities and different tasks. In fact, in the present work we administered only a SJT for the sake of participants' fatigability. However, as previously mentioned, temporal sensitivity to multisensory stimuli can be measured also with a TOJ task, in which participants must judge which of two stimuli come first (e.g., "light first" or "tactile first"; e.g., Scarpina et al. 2016). The percentage of a given answer, for example "light first", is plotted as a function of SOAs and, in this case, fitted to a sigmoid function. Half of the difference between the SOAs corresponding to the 25% and 75% points on the vertical axis defines the just noticeable difference (i.e., the smallest interval the observer can reliably notice). The temporal binding window and the just noticeable difference cannot be considered equivalent indices, since the SJT and the TOJ task rely (at least partially) on different cognitive mechanisms (Zampini et al., 2003). However, both the measures are considered representative of the ability to discriminate multisensory stimuli simultaneity (Vroomen & Keetels, 2010). Further investigations might consider also the spatial aspects of multisensory integration in obesity, since spatial coincidence also favours the integration process (Wallace et al., 2004). Evidence of anomalies across several sensory modalities and multiple tasks as well as in the spatial resolution of integration would provide a strong evidence in favour of a generalized altered processing of multisensory stimuli in obesity.

A deeper understanding of this domain in obesity is indeed desirable, at least for two reasons. It is well-known that *ad hoc* multisensory stimulation can induced full body illusions during which people temporary identify themselves with another (dissimilar) body (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Petkova & Ehrsson, 2008). These paradigms might be used in clinical setting to promote positive rehabilitative outcomes (Riva, 2011; Serino & Dakanalis, 2017), for instance favouring a higher body satisfaction (Serino et al., 2016). The decrease of body dissatisfaction during weight-loss protocols has been related to a higher adherence to weight-loss treatments and to a lower risk of regaining weight (Palmeira et al., 2010; Schwartz & Brownell, 2004). This approach thus seems very interesting and promising for clinical and rehabilitative purposes. Nevertheless, it implies that the multisensory integration mechanisms on which these illusions ground (Ehrsson, 2007; Lenggenhager et al., 2007; Petkova &

Ehrsson, 2008) are functionally preserved. Importantly, the perception of multisensory synchrony has a specific role in the integration mechanisms involved in these bodily illusions (Botvinick & Cohen 1998; Ehrsson 2007; Lenggenhager et al. 2007). Furthermore, multisensory integration has a crucial role in the perception of food flavour and palatability; consequently, on food intake (Etou et al., 1989; French, 1999; Spence, 2015; Zandstra, De Graaf, Mela, & Van Staveren, 2000). Thus, multisensory integration anomalies in obesity might lead to dissimilar perception of food, encouraging overeating behaviours.

Finally, it is necessary to mention that our findings might be suitable for alternative interpretations. For instance, the cognitive difficulties reported in obesity (see Prickett, Brennan & Stolwyk 2015, for a review) might affect individuals' performance. Specifically, impairments in attention and executive functions (above all inhibition; Fagundo et al., 2012) might have affected patients' ability to cope with the task. Future studies might assess participants' cognitive profile to clarify whether the performance in these kinds of tasks is affected by possible cognitive impairments or by a truly altered processing of multisensory stimuli.

To conclude, multisensory integration is a fundamental cognitive process, which supports several brain functions (Hari et al., 2000) and enables individuals to implement adaptive behaviours (Calvert et al. 2004; Stevenson & Wallace 2013). Consequently, its alteration might have extremely relevant effects on individuals' cognition and daily activities. Our results suggest that a fundamental prerequisite of multisensory integration is altered in obesity. Future studies might deepen this issue since multisensory integration has a crucial role in key aspects of obesity, namely the perception of both the body and food.

APPENDIX

Table - Appendix. Mean and standard deviation (in brackets) of *peak* and *point of subjective simultaneity* (PSS) in healthy weight participants and individuals with obesity in the SJT.

	Peak		**PSS**	
Healthy Weight	0.97	(0.04)	24.81	(15.88)
Obesity	0.90	(0.12)	33.69	(21.5)

5 SUSCEPTIBILITY TO THE VIRTUAL HAND ILLUSION AND TEMPORAL RESOLUTION OF VISUO-TACTILE INTEGRATION IN OBESITY: PRELIMINARY RESULTS

5.1 INTRODUCTION

As explained in Chapter 3, the RHI illusion grounds on the integration between visual, tactile, and proprioceptive stimuli (Blanke, 2012; Ehrsson, 2012). According to Rohde and colleagues (2011), the subjective experience of the illusion specifically relies on a visuo-tactile integration, whereas the proprioceptive mislocation of the hand is related to the integration of visuo-proprioceptive inputs. The previous study (Chapter 4) demonstrated that individuals with obesity have a larger temporal binding window with visuo-tactile stimuli, meaning that they tend to integrate these signals over a more extended range of SOAs than healthy weight participants. Accordingly, individuals with obesity should bind together the perceptual conflicting information generating the RHI even at larger temporal discrepancy. Thus, they might experience the illusion also during the asynchronous stimulation. However, in Chapter 3 we reported that individuals with obesity and healthy weight participants had a comparable illusory experience (assessed by the Illusion Questionnaire) that, as usual, was higher in the synchronous than in the asynchronous stimulation.

As briefly mentioned in Chapter 4, the reason for this counterintuitive result might be that the SOA used in the asynchronous stimulation (1000 ms) is indeed far outside the temporal binding window of both participants with obesity and healthy weight individuals. Consequently, both might have segregated properly the inputs, preventing the illusion. We speculate that this scenario could change using SOAs that fall inside the temporal binding window of individuals with obesity but outside the temporal binding window of healthy weight individuals. At these time-lags, a dissimilar integration/segregation behaviour between the two groups is expected. Consequently, individuals with obesity should experience the illusion while healthy weight individuals should not.

The traditional RHI paradigm, however, does not enable the experimenter to control precisely for the timing of the multisensory stimulation. On the contrary, the adapted version of the RHI proposed by

Costantini and colleagues (2016) fits well this purpose. In their study, the visuo-tactile stimulation was delivered combing a small led located on the rubber hand and a solenoid placed on the participant's real hand. The stimuli delivery was controlled by a PC with precise timing. Using this method authors successfully induced the illusion of ownership towards a rubber hand in healthy participants; furthermore, they demonstrated that RHI susceptibility was strictly related to the individuals' temporal binding window measured by a SJT (Costantini et al., 2016).

The aim of the present study was to use this adapted version of the RHI to verify whether the effect of the illusion might be differentiated between healthy weight individuals and individuals with obesity as a function of the dissimilar temporal resolution of multisensory integration. If so, our results will add strong evidence in favour of the link between the temporal resolution of visuo-tactile integration (measured by the temporal binding window) and the RHI susceptibility (Costantini et al., 2016). Moreover, this investigation would improve our interpretation of the findings reported in Chapter 3, since visuo-tactile integration is a fundamental mechanism involved in the RHI. As for the study described in Chapter 3, a real-size picture of the participant's left hand was used to guarantee the highest similarity between the real hand and the virtual hand. We assessed both the subjective experience of the illusion (i.e., using a questionnaire) and the proprioceptive mislocation of the hand, even though according to Rohde and colleagues (2011) visuo-tactile integration should not affect the proprioceptive drift as much as the illusory experience. The findings reported in Chapter 4 led the definition of the range of SOAs to use in the experiment. Specifically, given the temporal binding windows found in the previous study in each group, we defined those SOAs at which stimuli should be integrated by both groups (i.e., < of the temporal binding windows of both groups), and those at which stimuli should be segregated by healthy weight individuals (i.e., > of the group's temporal binding window) and integrated by participants with obesity (i.e., < of the group's temporal binding window).

It must be anticipated that data collection was suspended since after a few subjects we realized that the typical effect of the illusion could not be replicated in the healthy weight population, even with the classical synchronous stimulation. The following sections describe the methods and partial results. The possible causes of this unexpected finding are argued in the discussion.

5.2 METHODS

Participants

Eight participants (3 female; age: M (SD) = 45.88 (9.08) years; education: M (SD) =12.38 (3.20) years; BMI: M (SD) = 45.97 (7.05) kg/m^2) affected by obesity (i.e., BMI equal or higher than 30) voluntarily took part in the study at the IRCCS Istituto Auxologico Italiano – Ospedale San Giuseppe (Piancavallo, Oggebbio, VCO, Italy), just before starting a weight loss rehabilitative program. Six healthy weight (i.e., BMI lower than 30) individuals (5 female; age: M (SD) = 37 (13.67) years; education: M (SD) = 15.67 (2.50) years; BMI: M(SD) = 25.11 (4.03) kg/m^2) were recruited from the University of Trento or by experimenters' personal contact and participated in return for academic credits or monetary compensation (10 euros). All participants were right-handed. Non-parametric Mann-Whitney U tests (given the small sample size) revealed that the two groups had comparable age (U = 14, z = - 1.294, two-tailed exact p = 0.213, r = 0.35), while healthy weight participants underwent significantly more years of education (U = 9.5, z = - 2.004, two-tailed exact p = .043, r = 0.54). Moreover, as expected, the average BMI was significantly higher in the obesity group than in healthy weight participants (U = 0.001, z = -3.098, two-tailed exact p = .001, r = 0.82). The presence of any neurological, motor and/or sensory impairment was an exclusion criterion. All participants were naïve to the rationale of the experiment and gave their informed written consent. The study was approved by the ethical committee of the IRCCS Istituto Auxologico Italiano and was performed in compliance with the ethical standards laid down in the 1964 Declaration of Helsinki (most recently amended in Fortaleza, 2013).

Materials and procedure

The Rubber Hand Illusion paradigm. After being introduced to the experimental procedure, the participant read and signed the informed consent. The picture of the participant's left hand was taken with the very same technique described in Chapter 3. During the task the participant sat comfortably in front of a black plastic box (60 cm x 45cm x 25cm) placed on a table. The right side of the box was uncovered and contained a horizontal Dell 1907FPt monitor (34 cm x 40 cm) where the image of the hand was shown. The image of the hand was aligned with the participant's body midline. The left part of the box was covered by a lid for all the duration of the experiment and contained a small platform where the participant put the left hand to be vertically aligned with the screen surface. The right hand was hidden under the table, resting on the legs. The participant could not see the real hands during the whole administration of the task. A black cloak was fixed from the shoulders to the edges of the box and of the screen to create the impression of continuity between the physical body and the virtual hand.

According to Costantini and colleagues (2016), the RHI was induced by pairings of visuo-tactile stimuli delivered on the virtual and the real hand, respectively. Visual stimuli were produced by small red light-emitting diodes (LEDs; diameter about 3 mm) placed on the middle phalanx of the left virtual middle fingers. Tactile stimuli were produced using a solenoid actuator with an embedded cylinder plastic tip that was fixed with paper tape on the middle phalanx of the left real middle finger. Stimuli were delivered by the Heijo Box (Heijo Research Electronics, UK).

Five conditions of stimulation were performed, with the following visuo-tactile SOAs: 0 ms, 100 ms, 150 ms, 200 ms, and 1000 ms. The order of conditions of stimulation was randomized across participants according to a balanced latin-square. 0 ms and 1000 ms represented the traditional conditions of synchronous and asynchronous stimulation (Botvinick & Cohen, 1998). According to the temporal binding windows measured in the previous study [temporal binding windows reported in Chapter 4; *healthy weight:* M (SD) = 99.61 (38.76) ms; *obesity*: M (SD) = 142.97 (75.92) ms], we hypothesized that stimuli with 100 ms SOA should be integrated by both groups, whereas with 150 ms and 200 ms SOAs stimuli might be segregated by healthy weight individuals and integrated by participants with obesity. In asynchronous conditions of stimulation, the visual stimulus preceded the tactile one in half of the trials and *vice versa*. The order of visual first and tactile first pairs was pseudo-randomized with a maximum of three consecutive repetitions of the same couple (i.e., visual first or tactile first). The interval between consecutive pairs of stimuli was 2000 ms. Each session of stimulation lasted 2 minutes during which the participant was asked to keep the hand motionless and to focus on the image of the hand and the tactile sensation.

Before and after each condition of stimulation the participant performed a proprioceptive judgment task (Kammers et al., 2009; Scarpina et al., 2015) to evaluate the mislocation of the real hand towards the virtual hand induced by the illusion. This procedure was explained in detail in Chapter 3. Each participant made ten proprioceptive judgments about the location of the middle finger before and after each condition of stimulation. During this task, the screen was switched off to prevent any possible confounding effects related to the sight of the virtual hand. In each condition of stimulation, the experimenter aligned the participant's middle finger to one of three different positions (i.e., at 24 cm, 27 cm, and 30 cm from the real middle finger) to avoid any effect of learning across subsequent sessions. The order of the positions was pseudo-randomized across participants and conditions, with no repetition in successive stimulation. A *Proprioceptive Judgment Error* was computed by subtracting the perceived location of the hand from its real position before (*pre-test*) and after (*post-test*) the stimulation. After that, we computed the *Proprioceptive Drift* subtracting the pre-test Proprioceptive Judgment Error from the post-test Proprioceptive Judgment Error to estimate the effect of the illusion on the mislocation of the hand towards the virtual hand. Positive values indicate a higher recalibration of the position sense in the direction of the virtual hand after the hand stimulation than before. Negative values indicate the opposite. A Proprioceptive Drift equal to zero indicates that the stimulation of the hand did not affect proprioception. A significant Proprioceptive Drift towards the virtual hand should be expected with synchronous (real or perceived) stimulations, suggesting the presence of an effective RHI.

Finally, after each condition of stimulation the subjective experience of the illusion was assessed by a questionnaire probing the typical perceptual experiences induced by the RHI (Botvinick & Cohen, 1998). Our adaptation of the Illusion Questionnaire used by Costantini and colleagues (2016) includes eight statements (see Table 7), probing the visual capture of touch (statements 1 and 2), the feeling of ownership towards the virtual hand (statement 3), and the visual capture of hand position (statements 4 and 5). Statements from 6 to 8 were control statements. The participant rated each statement using a seven-point

Likert scale from – 3 meaning "Total disagreement" (i.e., weak illusion) to + 3 meaning "Total agreement" (i.e., strong illusion). In each condition of stimulation, the ratings of questions from 1 to 5 were averaged to compute the *Test Statements* index. Participants are expected to strongly agree with the *Test Statements* when they experience the illusion in the synchronous (real or perceived) conditions of stimulation and to disagree or have a neutral experience in the asynchronous ones.

Table 7. Illusion Questionnaire

Visual Capture of Touch	1. It seemed like I was feeling the touch in the location where I saw the virtual hand being lit, instead on my real hand 2. It seemed like the touch I felt was caused by the light on the virtual hand
Ownership	3. It seemed like the virtual hand has become my real hand
Visual Capture of Hand Position	4. It seemed that my real hand was where I saw the virtual hand 5. It seemed like my real hand was moving towards the virtual hand
Control Statements	6. It seemed like I had three hands 7. It seemed as if the touch I was feeling came from somewhere between my own hand and the virtual hand 8. It seemed like the virtual hand was moving towards my real hand

5.3 RESULTS

Given the small sample size, all the analyses have been performed with non-parametric tests. After collecting a few data, we became doubtful about the efficacy of the procedure used, thus, we first wanted to test whether the experiment successfully induced the illusion in healthy weight participants.

Table 8. Mean and standard deviation (in brackets) of the Illusion Questionnaire - *Test Statements* ratings and *Proprioceptive Drift* in each condition of stimulation in healthy weight participants.

SOAs	**Test Statements**	**Proprioceptive Drift**
0 ms	-2.50 (0.91)	0.30 (0.53)
100 ms	-2.21 (1.27)	0.48 (1.32)
150 ms	-2.29 (1.17)	1.18 (1.16)
200 ms	-2.46 (1.21)	-0.29 (1.54)
1000 ms	-2.58 (1.02)	0.56 (1.69)

To probe the subjective experience of the illusion, one-sample Wilcoxon signed-rank tests have been used to verify whether the mean rating of *Test Statements* in each condition of stimulation significantly differed from the central point of the Liker scale. This value (i.e., zero) indicates that participants neither agree nor disagree with the statements. Ratings significantly higher than zero were expected in the real and perceived synchronous conditions, suggesting that participants properly experienced the illusion. On the contrary, values significantly lower than zero would indicate that participants strongly disagree with the questionnaire statements, suggesting that they did not experience the illusion. Negative ratings were expected with asynchronous stimulations. The analysis revealed that the mean ratings of the *Test Statements* were significantly *lower* than zero in the condition of stimulation with 0 ms (Median = -3; z = -2.26, two-tailed exact p = .031, r = 0.92) and 1000 ms (Median = -3, z = -2.33, two-tailed exact p =.031, r = 0.95) SOAs. In other words, participants strongly *disagree* with the questionnaire statements in these conditions. In the remaining conditions of stimulation the mean ratings of the *Test Statements* did not significantly differ from zero, suggesting that participants had a neutral experience [*100 ms*: median = -2.75, z = -2.01, two-tailed exact p = .063, r = 0.82; *150 ms*: median = -2.75, z = -2.06, two-tailed exact p = .063, r = 0.84; *200 ms*: median = -3, z = -2.12, two-tailed exact p = .063, r = 0.87]. To sum up, healthy weight participants did not experience the illusion not even with the classic synchronous stimulation. Means and standard deviations of the *Test Statements* ratings in each condition of stimulation are reported in Table 8 and illustrated in Figure 9. Importantly, the graph illustrates that only one subject reported *Test Statements* ratings higher than zero, yet only slightly positive.

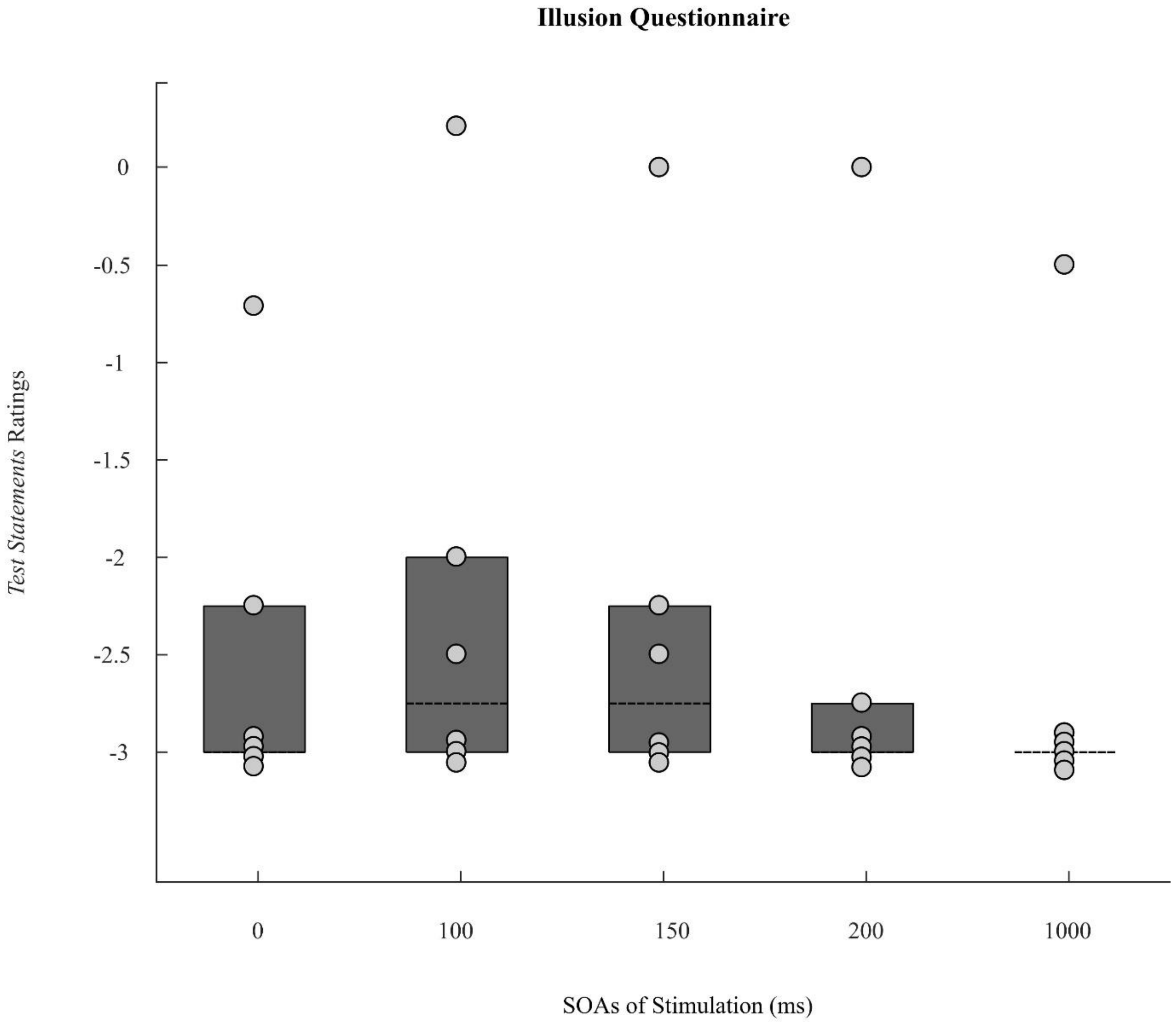

Figure 9. Box plots illustrate the *Test Statements* ratings of the Illusion Questionnaire in healthy weight participants, in each condition of stimulation. Dashed lines indicate the medians. Dots represent the ratings of each participant: overlapped dots indicate equal ratings.

As regards the Proprioceptive Drift, one-sample Wilcoxon signed-rank tests have been used to compare the mislocation of the hand respect to zero (meaning no recalibration of hand position). The analysis revealed that in all the conditions of stimulation the Proprioceptive Drift was not significantly different from zero [*0ms*: median = 0.26, *z* = 0.94, two-tailed exact *p* = .345, *r* = 0.38; *100 ms*: median = 0.33, *z* ,= 0.73 two-tailed exact *p* = .463, *r* = 0.30; *150 ms*: median = 0.77, *z* = 1.99, two-tailed exact *p* = .046, *r* = 0.81; *200 ms*: median = 0.08, *z* = 0.92, two-tailed exact *p* = .917, *r* = 0.38; *1000 ms*: median = 0.86, *z* = 0.94 two-tailed exact *p* = .345, *r* = 0.38]. In other words, the hand was perceived in the same position before and after the stimulation, suggesting that the illusion did not work in any of the conditions of stimulation delivered. Means and standard deviations of the Proprioceptive Drift in each condition of stimulation are reported in Table 8 and illustrated in Figure 10.

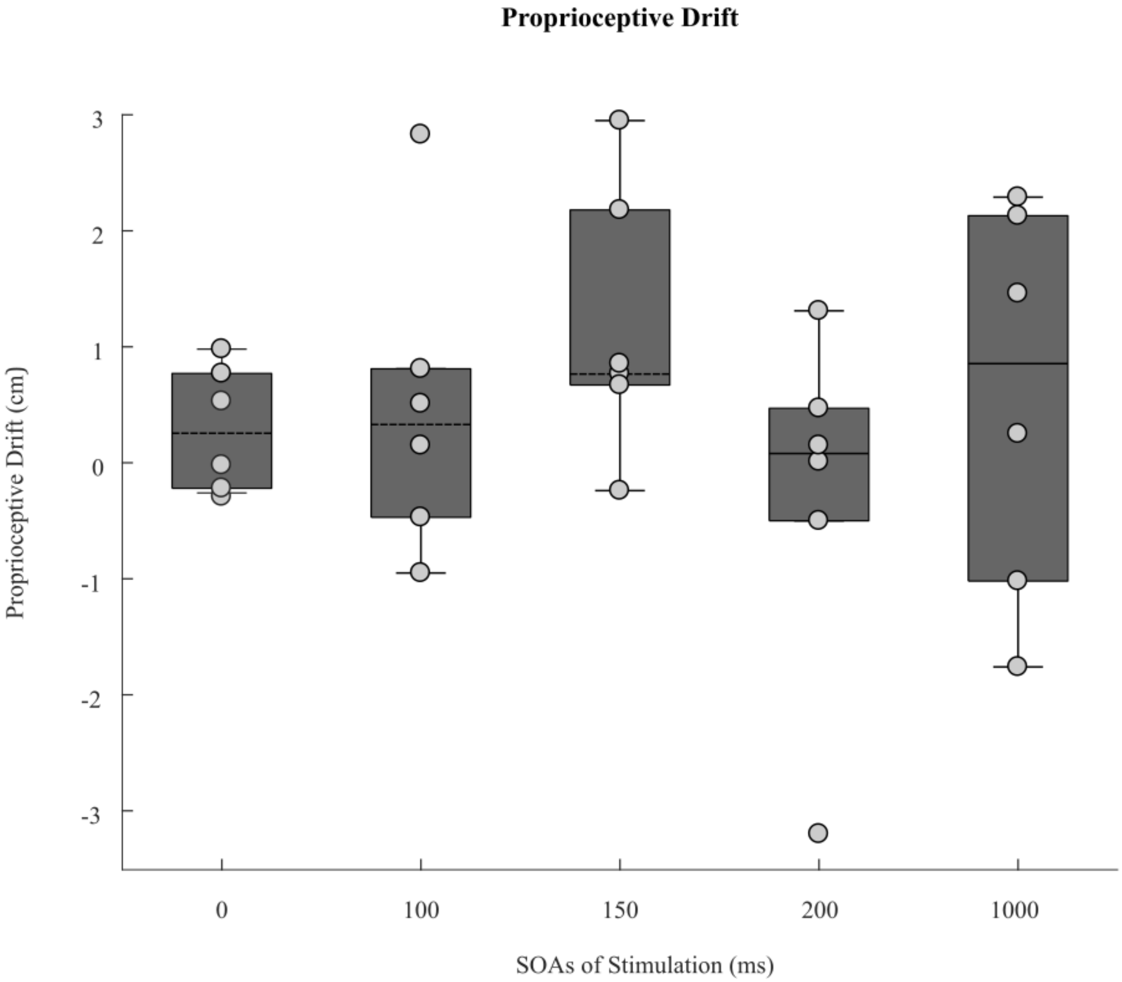

Figure 10. Box plots illustrate the *Proprioceptive Drift* in healthy weight participants, in each condition of stimulation. Dashed lines indicate the medians. Dots represent the *Proprioceptive Drift* of each subject.

To sum up, the preliminary investigation on the efficacy of the procedure used to induce the RHI demonstrated that the classic effects of the illusion on both the subjective experience (i.e., the Illusion Questionnaire) and the mislocation of the hand towards the virtual one (i.e., the Proprioceptive Drift) was not replicated in our control sample. Consequently, in our opinion, the data collected on individuals with obesity have no experimental value, as well as any comparisons between groups. For the sake of completeness, qualitative data in the eight individuals with obesity tested so far are reported in Table 9. In light of these considerations, data collection was suspended to understand the reasons that lead to such a null result. The possible causes of this scenario are discussed in the following section.

Table 9. Mean and standard deviation (in brackets) of the Illusion Questionnaire - *Test Questions* ratings and *Proprioceptive Drift* in each condition of stimulation in participants with obesity.

SOAs	**Test Statements**	**Proprioceptive Drift**
0 ms	-2.44 (1.59)	0.05 (0.90)
100 ms	-2.52 (1.37)	0.27 (0.78)
150 ms	-2.59 (1.15)	0.08 (1.06)
200 ms	-2.94 (0.17)	0.81 (1.29)
1000 ms	-2.67 (0.93)	0.54 (0.70)

5.4 DISCUSSION

The fact that individuals with obesity tend to integrate visuo-tactile stimuli over a larger range of SOAs (compared to healthy weight people) leads to the prediction that they might experience the RHI also when the visuo-tactile stimulation of the real and the virtual hand is asynchronous. However, in Chapter 3 our findings demonstrated that individuals with obesity and healthy weight participants had a comparable experience of the illusion when visuo-tactile stimuli were delivered with an SOA of 1000 ms. This time-lag is far larger than individuals' temporal binding windows in both groups (see Chapter 4). Consequently, all participants might have segregated correctly the signals, preventing the illusion to arise. We hypothesized that RHI susceptibility might be differentiated between the two groups using SOAs at which individuals with obesity integrate the stimuli (i.e., SOAs inside their temporal binding window) and healthy weight participants do not (i.e., SOAs outside their temporal binding window). To this purpose, we administered an adapted version of the RHI that enables a parametrical control of the timing of the visuo-tactile stimulation (Costantini et al., 2016).

After collecting a few data, we realized that the procedure was not working as expected, not even with healthy weight participants. Therefore, the data collection was suspended and the preliminary data in the control group were analysed. The results in the healthy population clearly showed that none of the conditions of stimulation, neither the synchronous one, evoked the typical perceptual experiences related to the illusion nor altered the proprioceptive localization of the hand.

How could we explain this finding? First, the RHI susceptibility is significantly reduced in middle adulthood (Marotta, Zampini, Tinazzi, & Fiorio, 2018). The participants we tested belong to this age-range, whereas Costantini and colleagues (2016) tested younger participants. Furthermore, the effect of the RHI is lower when a virtual representation of the hand is used instead of a rubber hand (IJsselsteijn et al., 2006). However, in Chapter 3 we successfully induced the RHI in healthy weight participants of about the same age and using the images of their hands. These aspects, thus, might have reduced the effect of the RHI but an additional factor related to this version of the task should be identified to explain the total absence of the illusion. A personal communication from the research group that firstly administered the experiment clarified this issue. It came up that, in the published work, they did not specify that participants underwent a preliminary training to *learn* the causality between a light and a tactile stimulation *before* the RHI. In the traditional version of the paradigm, the causal association between the stroking felt and the sight of a congruent object (i.e., a paintbrush) is immediate and derives from the participants' previous experience of the world. On the contrary, a causal link between a small light and a vibration is not taken for granted. Thus, the integration might not have happened because the visuo-tactile stimuli were not judged conceivably related, even though simultaneous. Accordingly, the impossibility to integrate the signals in a unique perceptual event prevented the manifestation of the RHI. Future studies with this version of the RHI should consider this crucial aspect. We speculate that, with proper training, participants should experience the illusion, at least healthy weight individuals. This is indeed a crucial prerequisite to probe potential differences between groups in the RHI susceptibility. Our purpose is to collect new experimental data, introducing a preliminary training phase before running the paradigm.

6 GENERAL DISCUSSION

The topic of body dissatisfaction has been extensively investigated in obesity, leading to the conclusion that negative emotions and attitudes towards the body have a crucial role in the characterization of this clinical condition and, importantly, they might have significant effects on treatment outcomes and individuals' well-being (Weinberger et al., 2016). On the contrary, other domains of body representation have been so far partially explored - or very neglected - and thus deserve further investigations.

For instance, it remains unclear whether individuals with obesity overestimate, underestimate or accurately estimate the body dimensions. Indeed, previous results about the self-perceived body size in obesity (see e.g., Docteur et al., 2010; Schwartz & Brownell, 2004; Thaler et al., 2018) are quite controversial and seem to be task-dependent (Tagini et al., in preparation). Moreover, the possible relationship between body dissatisfaction and the (mis)perception of the body dimension is far from being properly understood. The adoption of a more recent theoretical framework, namely the implicit/explicit model (Longo, 2015) of body representations, might help to guide new investigations. In the present work, it has been pointed out that the previous incoherent findings about body size estimation in obesity might become more intelligible if we consider that the traditional methods (i.e., metric and depictive tasks) actually measure the distortion of different body representations, rather than evaluating the same vaguely defined perceptual body image (Longo & Haggard, 2012). If previous findings are interpreted in the light of the implicit/explicit model, it seems that individuals with obesity have a significantly more distorted explicit representation (in the direction of overestimation) than healthy weight individuals (i.e., measured with depictive tasks; Collins et al., 1987, 1983; Docteur et al., 2010; Gardner et al., 1989, 1987; Garner et al., 1976; Mölbert et al., 2018). To the best of our knowledge, only one study probed the implicit representation (involved in the *tactile estimation* of stimuli) in obesity, reporting that patients and healthy weight individuals might have a qualitatively similar (distorted) implicit representation (Scarpina et al., 2014). However, the author showed that in obesity the estimation biases found for certain body parts seem to be higher.

In Chapter 2, the implicit representation of the body (i.e., the hand) involved in *position sense* has been investigated with the **landmarks localization task** (e.g., Longo, 2014; Longo & Haggard, 2010; Mattioni & Longo, 2014) in healthy weight participants and individuals with obesity. As previously reported in literature (e.g., Coelho & Gonzalez, 2017; Longo, 2014; Longo & Haggard, 2010; Mancini et al., 2011), healthy weight individuals underestimated the length of the fingers and overestimated the width of the hand. Interestingly, participants with obesity reported the same pattern and magnitude of distortions. Therefore, these biases should not be attributed to obesity, since they are present also in the healthy weight population. In fact, these estimation errors are likely related to the somatosensory origin of the implicit representation (Longo, 2015; Longo & Haggard, 2010). To sum up, it seems that in obesity the explicit representation is affected, while the implicit is not. We speculated that the high level of body concerns reported in obesity might affect the explicit representation of the body but not the implicit one. More generally, these results suggest that some aspects of body representation might not be altered in obesity while others might be more affected.

Chapter 3 focused on another component of body representation that has been neglected in obesity: the bodily self-consciousness. The **Rubber Hand Illusion** (RHI) is an experimental paradigm often used to investigate the mechanisms underpinning this domain (Blanke, 2012; Ehrsson, 2012). In this body illusion, the concurrent stroking of a visible rubber hand and the real (hidden) hand induces most people to feel that the fake hand is their own and to perceive their real hand as being located closer to the rubber one (i.e., *proprioceptive drift*; Botvinick & Cohen, 1998). In the present work, the susceptibility to an adapted version of the RHI illusion has been compared between healthy weight participants and individuals with obesity. Both groups showed a comparable subjective experience of the illusion, whereas the Proprioceptive Drift was significantly reduced in participants with obesity. In other words, participants with obesity properly embodied the virtual hand in their body representation, however, the illusion did not affect the awareness about the location of the body in the space. Therefore, some components of bodily self-consciousness might be less malleable in this clinical population than in healthy weight individuals. As mentioned, this information is crucial for clinical purposes since multisensory bodily illusions might be used in obesity to increase body satisfaction, improving the rehabilitative outcomes (Riva, 2011; Serino & Dakanalis, 2017).

An anomalous functionality of the multisensory integration processes involved in the RHI (Rohde et al., 2011) might explain our findings. More specifically, an atypical temporal sensitivity to visuo-proprioceptive simultaneity could have reduced any possible multisensory integration of the stimuli, explaining the reduced Proprioceptive Drift. On the contrary, our results point to a preserved perception of visuo-tactile simultaneity, explaining why the subjective experience of the illusion was properly manipulated. Thus, the results illustrated in Chapter 3 provided a crucial clue about the possible cognitive mechanisms that might underpin the altered bodily experience in obesity.

The subjective experience of the illusion is driven by top-down processes and it is determined by the fact that the fake hand is embodied in a *conscious* representation of the body (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Tsakiris & Haggard, 2005). Therefore, if we refer to the implicit/explicit model (Longo, 2015) we can speculate that this aspect of the illusion grounds on the explicit representation. On the other hand, since the implicit representation supports the position sense (Longo, 2015; Longo & Haggard, 2010) we can speculate that this representation is more involved in the mechanisms that lead to the proprioceptive drift.

Interestingly, thus, this result points again to a dissociation between implicit and explicit components of body representation (i.e., body self-consciousness) in obesity. However, in this case, differences between the two groups have been detected for the implicit component rather than the explicit one. To sum up, considering the results of the first two studies, it can be speculated that the implicit representation of the body in the space might be equally distorted in healthy weight participants and individuals with obesity, even though in obesity this representation might be less malleable.

On the other hand, previous findings suggest that the explicit representation in obesity delivers a more distorted “picture” of the body than in the healthy weight population. Emotional aspects related to the body might have a role in the distortions found in this representation. Conversely, taking a broad view of our findings, the explicit representation in obesity might be more flexible than the implicit one and as malleable as in healthy controls, at least under certain circumstances (i.e., experimental manipulation like the RHI). However, some individuals with obesity experience the impossibility to update the explicit representation of their body dimensions after a significant weight loss (i.e., *"phantom fat"* phenomenon; Guardia et al., 2013; Schwartz & Brownell, 2004). It can be speculated that the reduced cognitive flexibility often reported in obesity (Perpiñá, Segura, & Sánchez-Reales, 2017; Prickett et al., 2015) might also account for the lower malleability of body representations.

The aim of Chapter 4 was to probe the temporal resolution of visuo-tactile integration in obesity, to test whether this cognitive process is preserved in obesity, as suggested by the results of Chapter 3. A **visuo-tactile SJT** was administered to measure the temporal sensitivity to visuo-tactile simultaneity (i.e., the temporal binding window; Vroomen & Keetels, 2010; Zampini et al., 2005) of individuals with obesity and healthy weight participants. Individuals with obesity had a reduced temporal sensitivity to visuo-tactile asynchrony, meaning that they perceived synchronously the multisensory signals over a larger range of SOAs than healthy weight participants. This finding agrees with the previous experimental evidence in the audio-visual domain (Scarpina et al., 2016), suggesting that the reduced temporal sensitivity extends to different pairings of sensory modalities and, eventually, it might affect the *whole* mechanism of multisensory integration in obesity.

It has been proposed that the atypical temporal sensitivity to multisensory simultaneity might be related to an anomalous neural oscillatory activity (Babiloni et al., 2011; Del Percio et al., 2013; Dubbelink et al., 2008) and/or altered cerebral anatomy/metabolisms (Maayan et al., 2011; Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Volkow et al., 2009; Weise et al., 2013; Willette & Kapogiannis, 2015; Yokum et al., 2012) in obesity. In accordance with the previous findings in the audio-visual domain (Scarpina et al., 2016) and our results with visuo-tactile stimuli, the mentioned mechanisms would conceivably affect the temporal resolution beyond the specific sensory modalities considered. Nevertheless, an alternative interpretation of our findings might be given considering the cognitive difficulties reported in obesity (see Prickett, Brennan & Stolwyk 2015, for a review). Specifically, impairments in attention and executive functions (above all inhibition; Fagundo et al., 2012) might have affected patients' ability to cope with the task. This consideration is specifically true for the SJT that we adopted. However, multiple cognitive domains have been proven to be impaired in obesity (see Prickett, Brennan & Stolwyk 2015, for a review), such as memory (Gunstad et al., 2006; Nilsson & Nilsson, 2009). Therefore, several tasks might be affected and, accordingly, a preliminary general assessment of the cognitive profile should be recommended regardless the specific paradigm used.

Anyway, our result contrasts with the prediction made in Chapter 3 of a proper perception of visuo-tactile simultaneity. In addition, the larger temporal binding window reported in Chapter 4 would favour the integration of the perceptual conflicting information generating the RHI even at larger temporal discrepancy. Thus, individuals with obesity should have experienced the illusion also during the asynchronous stimulation. This was not the case. Nevertheless, the SOA used in the RHI (1000 ms) was far higher than the participants’ temporal binding window. Consequently, they might have properly segregated the inputs during the asynchronous stimulation. On the other hand, SOAs closer to patients’ temporal binding window might induce a different integration/segregation behaviour across groups, determining a dissimilar RHI susceptibility.

To probe this issue, in Chapter 5 the RHI was delivered by a slightly different paradigm, which enabled a precise timing of visuo-tactile stimulation (Costantini et al., 2016) with five different SOAs (0 ms, 100 ms, 150 ms, 200 ms, 1000 ms). Unfortunately, this procedure did not work properly in our sample. The typical experience of the RHI indeed was not replicated even in healthy weight participants; therefore, any comparison with the data collected in obesity has no experimental value. We found out later (since it was not reported in the published work) that the original procedure included a phase of training, where participants learn the causality between a small light and the touch. Indeed, this relationship is not commonly acquired during the lifespan, differently from the association between a brush and its touch on the skin (as in the traditional paradigm). The fact that we did not implement this preliminary learning phase might explain the failure of the paradigm. Participants might not have integrated the information because they judged that the stimuli were not conceivably related, despite being perceived as synchronous. Future studies should carry on this line of research since it might add strong evidence in favour of the relationship between the temporal resolution of visuo-tactile integration and the RHI susceptibility (Costantini et al., 2016). Furthermore, it would clarify whether the altered multisensory integration in obesity might actually affect the bodily experience.

What's next?

This seminal work aimed to fill the gap present in literature considering aspects of body representation that have never been investigated in obesity (such as the implicit representation of the body and bodily self-consciousness). Furthermore, for the first time, the possible relationship between multisensory integration and the bodily experience in obesity has been explored. Obviously, this investigation should not be considered exhaustive, yet it provides many interesting cues for future researches.

First, it seems that some aspects of body representation might not be altered in obesity while others might be more affected. Furthermore, some components of body representation might be less malleable in this clinical population than in healthy weight individuals. Therefore, a systematic investigation of different body representations in obesity is recommendable, beyond body dissatisfaction.

The adoption of a more recent theoretical framework, namely the implicit/explicit model (Longo, 2015) of body representations, might help to guide the new investigations. A direct comparison (i.e., among the same individuals) between implicit and explicit representations in obesity would be highly recommended. In this way, the dissociation speculated here between implicit and explicit body representations in obesity may be tested directly. A clear picture of which body representations are affected (and which one are not) might help to clarify the reasons of this dissociation and, eventually, the mechanisms that underpin the peculiar bodily experience in obesity.

It has been speculated that the high level of body concerns reported in obesity might affect the explicit representation of the body but not the implicit one. Futures studies may probe this hypothesis. For instance, a multidimensional evaluation of the attitudinal components of body representation (e.g., the Multidimensional Body-Self Relations Questionnaire – MBSRQ; Cash, 2015) might be correlated with the estimation errors found in the implicit and explicit representation. If our hypothesis is correct, one might expect that body concerns would correlate only with the misperceptions of the body delivered by the explicit representation. Importantly, this investigation should involve both several body parts and the body as a whole.

Furthermore, it has been pointed out that an atypical processing of multisensory information, and more specifically a reduced temporal sensitivity to stimuli simultaneity, might have a role in altering some components of body representation in obesity. Specifically, in the RHI we reported that position sense was not manipulated according to the current afferent signals. An altered multisensory integration might impede individuals with obesity to efficiently and rapidly update the *status quo* of the body relative to the external space. Indeed, position sense strictly depends on the rapid processing of the incoming sensory inputs (e.g., Dijkerman & de Haan, 2007; Longo et al., 2010). This topic needs further investigation.

Additionally, the investigation of multisensory perception in obesity should be extended to all the possible combinations of sensory modalities to clarify whether this impairment is generalized. For instance, visuo-proprioceptive integration has never been investigated in obesity. As previously reported, the *mirror illusion* (Holmes et al., 2004; Holmes & Spence, 2005; Snijders et al., 2007) might be a suitable paradigm to probe this issue. Specifically, one might expect the visual capture of hand position to be reduced in obesity similarly to what happened for the proprioceptive drift in the RHI. Interestingly, the visual capture of hand proprioception in the mirror illusion is higher when participants move the hands synchronously than when they keep them motionless. This evidence suggests that visuo-motor congruency enhances the integration of visuo-proprioceptive signals (Holmes & Spence, 2005; Liu & Medina, 2017). It can be speculated that when movements are asynchronous the mirror illusion does not work since the integration is impeded. Similarly, when participants see a virtual three-dimensional hand moving synchronously with their own, proprioception is modulated according to the position of the virtual hand (Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Slater, 2009). Conversely, the illusion does not occur when the virtual hand moves asynchronously (Sanchez-Vives et al., 2010; Slater, 2009). Later, an analogous finding was reported using a rubber hand (Kalckert & Ehrsson, 2012). To our purpose, it would be interesting to investigate what would happen in obesity in both the mirror illusion and these modified versions of the RHI. Furthermore, it might be worth introducing incremental offsets between the movement of the hand (i.e., the proprioceptive input) and the movement seen. The temporal offset might be easily manipulated in virtual reality; otherwise, a delayed recording of the hand movements might be displayed on a screen (Nobusako et al., 2018). In this way, it could be possible to measure the maximum gap that can occur so that the visuo-proprioceptive information is perceived simultaneously and then bounded. Thus, the temporal resolution of this process could be evaluated, similarly to the traditional investigation with other pairings of sensory modalities. Also, passive movements might be used; so that it might be possible to address more specifically the visuo-proprioceptive integration excluding the visuo-motor component (Nobusako et al., 2018).

Importantly, we considered only the temporal resolution of the multisensory mechanisms. However, whether and how the anomalous perception of simultaneity across sensory modalities might influence higher-level multisensory perceptions in obesity should be probed further. For instance, experimental paradigms in which the behaviour of participants is known to depend on the integration of multisensory stimuli might be adopted, such as the McGurk effect (Mcgurk & Macdonald, 1976) and the flash-beeps illusion (Shams, Kamitani, & Shimojo, 2002).

Finally, the reason why multisensory integration is impaired in obesity is a topic that deserves additional investigations. This research might help in clarifying the relationship between multisensory integration and body representation in obesity. Moreover, future studies should deepen the feasibility of multisensory bodily illusions to manipulate body representation (e.g., body dissatisfaction), improving the rehabilitative outcomes (Riva, 2011; Serino & Dakanalis, 2017).

As previously mentioned, the cognitive difficulties often reported in obesity might have affected our results, as well as many previous findings. Therefore, it is desirable that future studies assess participants' cognitive profile to probe whether the performance is affected by possible cognitive impairments or by a truly altered processing of multisensory stimuli or distorted body representation.

Similarly, also interindividual variability should be considered since obesity is a complex medical condition and individuals might have very different clinical profiles. Furthermore, future investigations might consider the role of gender since it is well-known that it can have significant influence on both body representation (e.g., Feingold & Mazzella, 1998) and multisensory integration (e.g,. Cadieux, Barnett-Cowan, & Shore, 2010). These aspects might mediate the relationship between obesity and body representation anomalies, therefore more research is needed on this topic.

In my opinion, if future studies will address these questions a significant advancement in the filed might be gained.

7 CONCLUSIONS

The vast majority of previous investigations in obesity focused on body dissatisfaction (Schwartz & Brownell, 2004; Weinberger et al., 2016). However, body representation is a multidimensional construct that involved many different components (e.g., de Vignemont, 2010). The findings discussed demonstrate that body representation difficulties in obesity go beyond the emotional domain. However, certain components of body representation might be spared. Indeed, obesity seems to act differently on dissimilar aspects of the bodily experience. This result might not be surprising since it is commonly known that body representation constituents might be, at least to a certain degree, independent (e.g., Dijkerman & de Haan, 2007; Longo, 2015; Schwoebel et al., 2005). On the other hand, by definition, all aspects of body representation also interact with each other (de Vignemont, 2010; Proske & Gandevia, 2012; Taylor-Clarke, Jacobsen, & Haggard, 2004), leading to the experience of the body as a whole.

Importantly, for the first time, the possible relationship between multisensory integration and the bodily experience in obesity has been explored. In fact, up to date very little is known about the cognitive mechanisms that might underpin body representation disorders in this population. Multisensory integration might have a crucial role, but further investigations are required.

A proper and comprehensive characterization of body representation in obesity might be very challenging: many issues remain undone. Globally, new lines of research should be opened, and more innovative theoretical frameworks and points of view adopted. In other words, more systematic and wide-ranging commitment is desirable on this topic. Only in this way, we could develop a comprehensive understanding of the bodily experience in obesity and of the cognitive and emotional mechanisms involved. Importantly, this will enable the development of efficacious treatments, improving people's quality of life.

The body is the instrument through which we experience the world, but it vehicles also the experience of our *self*. The representation of the body has a crucial role in describing *how* we are and *where* we are (physically), but it defines *who* we are too. The self and the body are intrinsically related. Hence, any misperceptions of our physical body can affect the conceptualization of ourselves as *human beings*.

Thus, a proper bodily experience is a fundamental constituent of the individual's well-being. Consequently, the possibility to improve these aspects in obesity, and indeed in all people, is remarkably worthy.

REFERENCES

Abdulkarim, Z., & Ehrsson, H. H. (2016). No causal link between changes in hand position sense and feeling of limb ownership in the rubber hand illusion. *Attention, Perception, and Psychophysics*, *78*(2), 707–720. https://doi.org/10.3758/s13414-015-1016-0

Alais, D., & Burr, D. (2004). The Ventriloquist Effect Results from Near-Optimal Bimodal Integration. *Current Biology*, *14*(3), 257–262. https://doi.org/10.1016/j.cub.2004.01.029

Alloway, K. D., Rosenthal, P., & Burton, H. (1989). Quantitative measurements of receptive field changes during antagonism of GABAergic transmission in primary somatosensory cortex of cats. *Experimental Brain Research*, *78*(3), 514–532. https://doi.org/10.1007/BF00230239

Altabe, M., & O’Garo, K. N. (2002). Hispanic body images. In *Body image: A handbook of theory, research, and clinical practice* (pp. 250–256). Guilford Press New York.

Azañón, E., Tamè, L., Maravita, A., Linkenauger, S. A., Ferrè, E. R., Tajadura-Jiménez, A., & Longo, M. R. (2016). Multimodal Contributions to Body Representation. *Multisensory Research*, *29*(6–7), 635–661. https://doi.org/https://doi.org/10.1163/22134808-00002531

Babiloni, C., Marzano, N., Lizio, R., Valenzano, A., Triggiani, A. I., Petito, A., … Del Percio, C. (2011). Resting state cortical electroencephalographic rhythms in subjects with normal and abnormal body weight. *NeuroImage*, *58*(2), 698–707. https://doi.org/10.1016/j.neuroimage.2011.05.080

Barofsky, I., Fontaine, K. R., & Cheskin, L. J. (1997). Pain in the obese: Impact on Health-Related Quality-of-Life. *Annals of Behavioral Medicine*, *19*(4), 408–410. https://doi.org/10.1007/BF02895160

Baune, B. T., Ponath, G., Golledge, J., Varga, G., Arolt, V., Rothermundt, M., & Berger, K. (2008). Association between IL-8 cytokine and cognitive performance in an elderly general population—

The MEMO-Study. *Neurobiology of Aging*, *29*(6), 937–944. https://doi.org/10.1016/j.neurobiolaging.2006.12.003

Beebe, D. W., Holmbeck, G. N., & Grzeskiewicz, C. (1999). Normative and Psychometric Data on the Body Image Assessment-Revised. *Journal of Personality Assessment*, *73*(3), 374–394. https://doi.org/10.1207/S15327752JPA7303_6

Bekrater-Bodmann, R., Foell, J., Diers, M., Kamping, S., Rance, M., Kirsch, P., … Flor, H. (2014). The Importance of Synchrony and Temporal Order of Visual and Tactile Input for Illusory Limb Ownership Experiences – An fMRI Study Applying Virtual Reality. *PLoS ONE*, *9*(1), e87013. https://doi.org/10.1371/journal.pone.0087013

Bell, C., Kirkpatrick, S. W., & Rinn, R. C. (1986). Body image of anorexic, obese, and normal females. *Journal of Clinical Psychology*, *42*(3), 431–439. https://doi.org/10.1002/1097-4679(198605)42:3<431::AID-JCLP2270420305>3.0.CO;2-I

Berlucchi, G., & Aglioti, S. M. (2010). The body in the brain revisited. *Experimental Brain Research*, *200*(1), 25–35. https://doi.org/10.1007/s00221-009-1970-7

Bermúdez, J. L. (1998). *The paradox of self-consciousness*. MIT Press Cambridge, MA.

Bertelson, P., & De Gelder, B. (2004). The psychology of multimodal perception. *Crossmodal Space and Crossmodal Attention*, 141–177.

Binder, M. (2015). Neural correlates of audiovisual temporal processing – Comparison of temporal order and simultaneity judgments. *Neuroscience*, *300*, 432–447. https://doi.org/10.1016/j.neuroscience.2015.05.011

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience*, *13*(8), 556–571. https://doi.org/10.1038/nrn3292

Blanke, O., Landis, T., Spinelli, L., & Seeck, M. (2004). Out-of-body experience and autoscopy of neurological origin. *Brain*, *127*(2), 243–258. https://doi.org/10.1093/brain/awh040

Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, Neural, and Computational Principles of Bodily Self-Consciousness. *Neuron*, *88*(1), 145–166. https://doi.org/10.1016/j.neuron.2015.09.029

Boeka, A., & Lokken, K. (2008). Neuropsychological performance of a clinical sample of extremely obese individuals. *Archives of Clinical Neuropsychology*, *23*(4), 467–474. https://doi.org/10.1016/j.acn.2008.03.003

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, *391*(6669), 756–756. https://doi.org/10.1038/35784

Boulinguez, P., & Rouhana, J. (2008). Flexibility and individual differences in visuo-proprioceptive integration: Evidence from the analysis of a morphokinetic control task. *Experimental Brain Research*, *185*(1), 137–149. https://doi.org/10.1007/s00221-007-1140-8

Bremner, A. J., Hill, E. L., Pratt, M., Rigato, S., & Spence, C. (2013). Bodily illusions in young children: Developmental change in visual and proprioceptive contributions to perceived hand position. *PLoS ONE*, *8*(1), e51887. https://doi.org/10.1371/journal.pone.0051887

Brown, P. B., Fuchs, J. L., & Tapper, D. N. (1975). Parametric studies of dorsal horn neurons responding to tactile stimulation. *Journal of Neurophysiology*, *38*(1), 19–25.

Burgess, P. R., Wei, J. Y., Clark, F. J., & Simon, J. (1982). Signaling of Kinesthetic Information by Peripheral Sensory Receptors. *Annual Review of Neuroscience*, *5*(1), 171–188. https://doi.org/10.1146/annurev.ne.05.030182.001131

Bushara, K. O., Grafman, J., & Hallett, M. (2001). Neural Correlates of Auditory–Visual Stimulus Onset Asynchrony Detection. *The Journal of Neuroscience*, *21*(1), 300–304.

https://doi.org/10.1523/JNEUROSCI.21-01-00300.2001

Bussolaro, R. A., Garcia, E. B., Zanella, M. T., & Ferreira, L. M. (2012). Impaired abdominal skin sensory function in morbid obesity and after bariatric surgery. *Obesity Surgery*, *22*(3), 353–359. https://doi.org/10.1007/s11695-011-0485-z

Buxbaum, L. J., & Coslett, H. B. (2001). Specialised structural descriptions for human body parts: evidence from autotopagnosia. *Cognitive Neuropsychology*, *18*(4), 289–306. https://doi.org/10.1080/02643290042000071

Cadieux, M. L., Barnett-Cowan, M., & Shore, D. I. (2010). Crossing the hands is more confusing for females than males. *Experimental Brain Research*, *204*(3), 431–446.

Calvert, G., Spence, C., & Stein, B. E. (2004). *The handbook of multisensory processes*. MIT press.

Cappon, D., & Banks, R. (1968). Distorted body perception in obesity. *The Journal of Nervous and Mental Disease*, *146*(6), 465–467.

Carpenter, K. M., Hasin, D. S., Allison, D. B., & Faith, M. S. (2000). Relationships between obesity and DSM-IV major depressive disorder, suicide ideation, and suicide attempts: results from a general population study. *American Journal of Public Health*, *90*(2), 251–257. https://doi.org/10.2105/AJPH.90.2.251

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L., & Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception. *Autism*, *16*(4), 406–419. https://doi.org/10.1177/1362361311430404

Cash, T.F. (2002). The management of body image problems. In *Eating disorders and obesity: A comprehensive handbook* (Vol. 2, pp. 599–603). Guilford Press New York.

Cash, T.F. (2015). Multidimensional Body–Self Relations Questionnaire (MBSRQ). In *Encyclopedia of Feeding and Eating Disorders* (pp. 1–4). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-287-087-2_3-1

Cash, T.F., & Strachan, M. D. (2002). Cognitive-behavioral approaches to changing body image. In *Body image: A handbook of theory, research, and clinical practice* (pp. 478–486). Guilford Press NY.

Cash, Thomas F., & Deagle, E. A. (1997). The nature and extent of body-image disturbances in anorexia nervosa and bulimia nervosa: A meta-analysis. *International Journal of Eating Disorders*, *22*(2), 107–126. https://doi.org/10.1002/(SICI)1098-108X(199709)22:2<107::AID-EAT1>3.0.CO;2-J

Cecere, R., Rees, G., & Romei, V. (2015). Individual Differences in Alpha Frequency Drive Crossmodal Illusory Perception. *Current Biology*, *25*(2), 231–235. https://doi.org/10.1016/j.cub.2014.11.034

Celio, A. A., Zabinski, M. F., & Wilfley, D. E. (2002). African American body images. In *Body image: A handbook of theory, research, and clinical practice* (pp. 234–242). Guilford Press New York, NY.

Chao, H.-L. (2015). Body Image Change in Obese and Overweight Persons Enrolled in Weight Loss Intervention Programs: A Systematic Review and Meta-Analysis. *PLOS ONE*, *10*(5), e0124036. https://doi.org/10.1371/journal.pone.0124036

Cleveland, S. E. (1962). Perception of Body Size in Schizophrenia. *Archives of General Psychiatry*, *7*(4), 277. https://doi.org/10.1001/archpsyc.1962.01720040043004

Cody, F. W. J., Garside, R. A. D., Lloyd, D., & Poliakoff, E. (2008). Tactile spatial acuity varies with site and axis in the human upper limb. *Neuroscience Letters*, *433*(2), 103–108. https://doi.org/10.1016/j.neulet.2007.12.054

Coelho, L. A., & Gonzalez, C. L. (2018). The visual and haptic contributions to hand perception. *Psychological Research*, *82*(5), 866–875. https://doi.org/10.1007/s00426-017-0870-x

Coello, Y., Milleville-Pennel, I., & Orliaguet, J. P. (2004). Position coding in a video-controlled pointing task with a rotated visual display: evidence for individual differences in visuo-proprioceptive interaction. *Neuroscience Letters*, *369*(3), 214–218. https://doi.org/10.1016/j.neulet.2004.07.066

Collins, J. K., Beumont, P. J. V, Touyz, S. W., Krass, J., Thompson, P., & Philips, T. (1987). Variability in body shape perception in anorexic, bulimic, obese, and control subjects. *International Journal of Eating Disorders*, *6*(5), 633–638. https://doi.org/10.1002/1098-108X(198709)6:5<633::AID-EAT2260060506>3.0.CO;2-U

Collins, J. K., McCabe, M. P., Jupp, J. J., & Sutton, J. E. (1983). Body percept change in obese females after weight reduction therapy. *Journal of Clinical Psychology*, *39*(4), 507–511. https://doi.org/10.1002/1097-4679(198307)39:4<507::AID-JCLP2270390408>3.0.CO;2-K

Cooke, J., Poch, C., Gillmeister, H., Costantini, M., & Romei, V. (2019). Oscillatory Properties of Functional Connections Between Sensory Areas Mediate Cross-Modal Illusory Perception. *The Journal of Neuroscience*, *39*(29), 5711–5718. https://doi.org/10.1523/JNEUROSCI.3184-18.2019

Cooper, Z., & Fairburn, C. G. (2001). A new cognitive behavioural approach to the treatment of obesity. *Behaviour Research and Therapy*, *39*(5), 499–511. https://doi.org/10.1016/S0005-7967(00)00065-6

Cornsweet, T. N. (1962). The Staircase-Method in Psychophysics. *The American Journal of Psychology*, *75*(3), 485. https://doi.org/10.2307/1419876

Costantini, M., Robinson, J., Migliorati, D., Donno, B., Ferri, F., & Northoff, G. (2016). Temporal limits on rubber hand illusion reflect individuals' temporal resolution in multisensory perception. *Cognition*, *157*, 39–48. https://doi.org/10.1016/j.cognition.2016.08.010

Cuzzolaro, M., Vetrone, G., Marano, G., & Garfinkel, P. E. (2006). The Body Uneasiness Test (BUT): Development and validation of a new body image assessment scale. *Eating and Weight Disorders -*

Studies on Anorexia, Bulimia and Obesity, *11*(1), 1–13. https://doi.org/10.1007/BF03327738

de Vignemont, F. (2010). Body schema and body image-Pros and cons. *Neuropsychologia*, *48*(3), 669–680. https://doi.org/10.1016/j.neuropsychologia.2009.09.022

Del Percio, C., Triggiani, A. I., Marzano, N., Valenzano, A., De Rosas, M., Petito, A., … Babiloni, C. (2013). Poor desynchronisation of resting-state eyes-open cortical alpha rhythms in obese subjects without eating disorders. *Clinical Neurophysiology*, *124*(6), 1095–1105. https://doi.org/10.1016/j.clinph.2013.01.001

Denes, G., & Pizzamiglio, L. (1999). *Handbook of clinical and experimental neuropsychology*. Psychology Press.

Dijkerman, H. C., & de Haan, E. H. F. (2007). Somatosensory processes subserving perception and action. *Behavioral and Brain Sciences*, *30*(2), 189–201. https://doi.org/10.1017/S0140525X07001392

Ding, C., Palmer, C. J., Hohwy, J., Youssef, G. J., Paton, B., Tsuchiya, N., … Thyagarajan, D. (2017). Parkinson's disease alters multisensory perception: Insights from the Rubber Hand Illusion. *Neuropsychologia*, *97*(January), 38–45. https://doi.org/10.1016/j.neuropsychologia.2017.01.031

Dixon, J. B. (2010). The effect of obesity on health outcomes. *Molecular and Cellular Endocrinology*, *316*(2), 104–108. https://doi.org/10.1016/j.mce.2009.07.008

Dixon, J. B., Dixon, M. E., & O'Brien, P. E. (2003). Depression in Association With Severe Obesity. *Archives of Internal Medicine*, *163*(17), 2058. https://doi.org/10.1001/archinte.163.17.2058

Docteur, A., Urdapilleta, I., Defrance, C., & Raison, J. (2010). Body perception and satisfaction in obese, severely obese, and normal weight female patients. *Obesity*, *18*(7), 1464–1465. https://doi.org/10.1038/oby.2009.418

Dubbelink, K. T. E. O., Felius, A., Verbunt, J. P. A., Van Dijk, B. W., Berendse, H. W., Stam, C. J., & Delemarre-Van De Waal, H. A. (2008). Increased resting-state functional connectivity in obese adolescents; a magnetoencephalographic pilot study. *PLoS ONE*, *3*(7). https://doi.org/10.1371/journal.pone.0002827

Ehrenstein, W. H., & Ehrenstein, A. (1999). Psychophysical Methods. In *Modern Techniques in Neuroscience Research* (pp. 1211–1241). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-58552-4_43

Ehrsson, H. H. (2005). Touching a Rubber Hand: Feeling of Body Ownership Is Associated with Activity in Multisensory Brain Areas. *Journal of Neuroscience*, *25*(45), 10564–10573. https://doi.org/10.1523/JNEUROSCI.0800-05.2005

Ehrsson, H. H. (2007). The Experimental Induction of Out-of-Body Experiences. *Science*, *317*(5841), 1048–1048. https://doi.org/10.1126/science.1142175

Ehrsson, H. H., Spence, C., & Passingham, R. (2004). That’s My Hand! Acriviy in Premotor Cortex Reflects Feelings of Ownership of a Limb. *Science*, *305*(6), 875–877. https://doi.org/10.1126/science.1097011

Ehrsson, H.H. (2012). The concept of body ownership and its relationship to multisensory integration. *The New Hand Book of Multisensory Processes*, 1–39. Retrieved from http://mitpress.mit.edu/catalog/item/default.asp?ttype=2&tid=12794

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*(6870), 429–433. https://doi.org/10.1038/415429a

Eshkevari, E., Rieger, E., Longo, M. R., Haggard, P., & Treasure, J. (2012). Increased plasticity of the bodily self in eating disorders. *Psychological Medicine*, *42*(4), 819–828.

https://doi.org/10.1017/S0033291711002091

Etou, H., Sakata, T., Fujimoto, K., Kurata, K., Terada, K., Fukagawa, K., … Miller, R. E. (1989). Characteristics of psychomotor performance and time cognition in moderately obese patients. *Physiology & Behavior*, *45*(5), 985–988. https://doi.org/10.1016/0031-9384(89)90225-4

Fabricatore, A. N., & Wadden, T. A. (2004). Psychological aspects of obesity. *Clinics in Dermatology*, *22*(4), 332–337. https://doi.org/10.1016/j.clindermatol.2004.01.006

Fagundo, A. B., de la Torre, R., Jiménez-Murcia, S., Agüera, Z., Granero, R., Tárrega, S., … Fernández-Aranda, F. (2012). Executive Functions Profile in Extreme Eating/Weight Conditions: From Anorexia Nervosa to Obesity. *PLoS ONE*, *7*(8), e43382. https://doi.org/10.1371/journal.pone.0043382

Falling, C., & Mani, R. (2016). Ageing and obesity indices influences the tactile acuity of the low back regions: A cross-sectional study. *Manual Therapy*, *23*, 25–31. https://doi.org/10.1016/j.math.2016.02.004

Farrell, C., Lee, M., & Shafran, R. (2005). Assessment of body size estimation: A review. *European Eating Disorders Review*, *13*(2), 75–88. https://doi.org/10.1002/erv.622

Feingold, A., & Mazzella, R. (1998). Gender Differences in Body Image Are Increasing. *Psychological Science*, *9*(3), 190–195. https://doi.org/10.1111/1467-9280.00036

Fergenbaum, J. H., Bruce, S., Lou, W., Hanley, A. J. G., Greenwood, C., & Young, T. K. (2009). Obesity and Lowered Cognitive Performance in a Canadian First Nations Population. *Obesity*, *17*(10), 1957–1963. https://doi.org/10.1038/oby.2009.161

Ferrer-García, M., & Gutiérrez-Maldonado, J. (2008). Body image assessment software: Psychometric data. *Behavior Research Methods*, *40*(2), 394–407. https://doi.org/10.3758/BRM.40.2.394

Ferri, F., Nikolova, Y. S., Perrucci, M. G., Costantini, M., Ferretti, A., Gatta, V., … Northoff, G. (2017). A Neural “Tuning Curve” for Multisensory Experience and Cognitive-Perceptual Schizotypy. *Schizophrenia Bulletin*, *43*(4), 801–813. https://doi.org/10.1093/schbul/sbw174

Ferri, F., Venskus, A., Fotia, F., Cooke, J., & Romei, V. (2018). Higher proneness to multisensory illusions is driven by reduced temporal sensitivity in people with high schizotypal traits. *Consciousness and Cognition*, *65*, 263–270. https://doi.org/10.1016/j.concog.2018.09.006

French, S. J. (1999). The effects of specific nutrients on the regulation of feeding behaviour in human subjects. *Proceedings of the Nutrition Society*, *58*(3), 533–540. https://doi.org/10.1017/S0029665199000701

Friedman, K. E. E., Reichmann, S. K. K., Costanzo, P. R. R., & Musante, G. J. J. (2002). Body image partially mediates the relationship between obesity and psychological distress. *Obes Res*, *10*(1), 33–41. https://doi.org/10.1038/oby.2002.5

Friedman, M. A., & Brownell, K. D. (1995). Psychological correlates of obesity: Moving to the next research generation. *Psychological Bulletin*, *117*(1), 3–20. https://doi.org/10.1037/0033-2909.117.1.3

Fries, P. (2015). Rhythms for Cognition: Communication through Coherence. *Neuron*, *88*(1), 220–235. https://doi.org/10.1016/j.neuron.2015.09.034

Gallagher, S. (2005). *How the body shapes the mind*. Clarendon Press.

Ganea, N., & Longo, M. R. (2017). Projecting the self outside the body: Body representations underlying proprioceptive imagery. *Cognition*, *162*, 41–47. https://doi.org/10.1016/j.cognition.2017.01.021

Gardner, R. M., Gallegos, V., Martinez, R., & Espinoza, T. (1989). Mirror feedback and judgments of body size. *Journal of Psychosomatic Research*, *33*(5), 603–607. https://doi.org/10.1016/0022-

3999(89)90067-6

Gardner, R. M., Martinez, R., & Sandoval, Y. (1987). Obesity and body image: an evaluation of sensory and non-sensory components. *Psychological Medicine*, *17*(4), 927–932. https://doi.org/10.1017/S0033291700000738

Garner, D. M., Garfinkel, P. E., Stancer, H. C., & Moldofsky, H. (1976). Body Image Disturbances in Anorexia Nervosa and Obesity. *Psychosomatic Medicine*, *38*(5), 327–336. https://doi.org/10.1097/00006842-197609000-00005

Gheorghiu, V. A., & Huebner, M. (1992). Die Sensorische Suggestibilitaetsskala (SSK) als Erhebungsverfahren fuer Taeuschbarkeit. The Scale of Sensory Suggestibility as assessment of deception. *Experimentelle Und Klinische Hypnose*, *8*(2), 117–129.

Glucksman, M. L., Hirsch, J., McCully, R. S., Barron, B. A., & Knittle, J. L. (1968). The response of obese patients to weight reduction. II. A quantitative evaluation of behavior. *Psychosomatic Medicine*, *30*(4), 359–373. https://doi.org/10.1097/00006842-196807000-00001

Guardia, D., Metral, M., Pigeyre, M., Bauwens, I., Cottencin, O., & Luyat, M. (2013). Body distortions after massive weight loss: Lack of updating of the body schema hypothesis. *Eating and Weight Disorders*, *18*(3), 333–336. https://doi.org/10.1007/s40519-013-0032-0

Gunstad, J., Lhotsky, A., Wendell, C. R., Ferrucci, L., & Zonderman, A. B. (2010). Longitudinal Examination of Obesity and Cognitive Function: Results from the Baltimore Longitudinal Study of Aging. *Neuroepidemiology*, *34*(4), 222–229. https://doi.org/10.1159/000297742

Gunstad, J., Paul, R. H., Cohen, R. A., Tate, D. F., & Gordon, E. (2006). Obesity is associated with memory deficits in young and middle-aged adults. *Eating and Weight Disorders - Studies on Anorexia, Bulimia and Obesity*, *11*(1), e15–e19. https://doi.org/10.1007/BF03327747

Hari, R., Levänen, S., & Raij, T. (2000). Timing of human cortical functions during cognition: role of MEG. *Trends in Cognitive Sciences*, *4*(12), 455–462. https://doi.org/10.1016/S1364-6613(00)01549-7

Haslam, D. W., & James, W. P. T. (2005). Obesity. *Lancet*, *366*(9492), 1197–1209. https://doi.org/10.1016/S0140-6736(05)67483-1

Head, H., & Holmes, G. (1911). Sensory disturbances from cerebral lesions. *Brain*, *34*(2–3), 102–254. https://doi.org/10.1093/brain/34.2-3.102

Heinberg, L. J., Thompson, J. K., & Matzon, J. L. (2001). Body image dissatisfaction as a motivator for healthy lifestyle change: Is some distress beneficial? In *Eating disorders: Innovative directions in research and practice.* (pp. 215–232). Washington: American Psychological Association. https://doi.org/10.1037/10403-011

Hill, A. J. (2005). Psychological aspects of obesity. *Psychiatry*, *4*(4), 26–30. https://doi.org/10.1383/psyt.4.4.26.63443

Holle, H., McLatchie, N., Maurer, S., & Ward, J. (2011). Proprioceptive drift without illusions of ownership for rotated hands in the “rubber hand illusion” paradigm. *Cognitive Neuroscience*, *2*(3–4), 171–178. https://doi.org/10.1080/17588928.2011.603828

Holmes, N. P., Crozier, G., & Spence, C. (2004). When mirrors lie: “Visual capture” of arm position impairs reaching performance. *Cognitive, Affective, & Behavioral Neuroscience*, *4*(2), 193–200. https://doi.org/10.3758/CABN.4.2.193

Holmes, N. P., Snjders, H. J., & Spence, C. (2006). Reaching with alien limbs: Visual exposure to prosthetic hands in a mirror biases proprioception without accompanying illusions of ownership. *Perception and Psychophysics*, *68*(4), 683–701. Retrieved from https://link.springer.com/content/pdf/10.3758%2FBF03208768.pdf

Holmes, N. P., & Spence, C. (2005). Visual bias of unseen hand position with a mirror: spatial and temporal factors. *Experimental Brain Research*, *166*(3–4), 489–497. https://doi.org/10.1007/s00221-005-2389-4

IJsselsteijn, W. A., de Kort, Y. A. W., & Haans, A. (2006). Is This My Hand I See Before Me? The Rubber Hand Illusion in Reality, Virtual Reality, and Mixed Reality. *Presence: Teleoperators and Virtual Environments*, *15*(4), 455–464. https://doi.org/10.1162/pres.15.4.455

Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., … Blanke, O. (2011). Multisensory Mechanisms in Temporo-Parietal Cortex Support Self-Location and First-Person Perspective. *Neuron*, *70*(2), 363–374. https://doi.org/10.1016/J.NEURON.2011.03.009

Istvan, J., Zavela, K., & Weidner, G. (1992). Body weight and psychological distress in NHANES I. *International Journal of Obesity and Related Metabolic Disorders : Journal of the International Association for the Study of Obesity*, *16*(12), 999–1003. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1335980

Jackson, T. D., Grilo, C. M., & Masheb, R. M. (2002). Teasing history and eating disorder features: An age- and body mass index[ndash]matched comparison of bulimia nervosa and binge-eating disorder. *Comprehensive Psychiatry*, *43*(2), 108–113. https://doi.org/10.1053/comp.2002.30793

Jeffreys, H. (1961). *Theory of probability, Clarendon*. Oxford University Press.

Kahn, B. B., & Flier, J. S. (2000). Obesity and insulin resistance. *Journal of Clinical Investigation*, *106*(4), 473–481. https://doi.org/10.1172/JCI10842

Kalckert, A., & Ehrsson, H. H. (2012). Moving a Rubber Hand that Feels Like Your Own: A Dissociation of Ownership and Agency. *Frontiers in Human Neuroscience*, *6*(MARCH 2012), 1–14.

https://doi.org/10.3389/fnhum.2012.00040

Kállai, J., Kincses, P., Lábadi, B., Dorn, K., Szolcsányi, T., Darnai, G., … Rpád Csathó, • A ´. (2017). Multisensory integration and age-dependent sensitivity to body representation modification induced by the rubber hand illusion. *Cognitive Processing*, *18*(4), 349–357. https://doi.org/10.1007/s10339-017-0827-4

Kammers, M. P. M., de Vignemont, F., Verhagen, L., & Dijkerman, H. C. (2009). The rubber hand illusion in action. *Neuropsychologia*, *47*(1), 204–211. https://doi.org/10.1016/j.neuropsychologia.2008.07.028

Kaplan, R. A., Enticott, P. G., Hohwy, J., Castle, D. J., & Rossell, S. L. (2014). Is Body Dysmorphic Disorder Associated with Abnormal Bodily Self-Awareness? A Study Using the Rubber Hand Illusion. *PLoS ONE*, *9*(6), e99981. https://doi.org/10.1371/journal.pone.0099981

Keil, J., & Senkowski, D. (2017). Individual Alpha Frequency Relates to the Sound-Induced Flash Illusion. *Multisensory Research*, *30*(6), 565–578. https://doi.org/10.1163/22134808-00002572

Keizer, A., Smeets, M. A. M., Dijkerman, H. C., Uzunbajakau, S. A., van Elburg, A., & Postma, A. (2013). Too fat to fit through the door: first evidence for disturbed body-scaled action in anorexia nervosa during locomotion. *PLoS ONE*, *8*(5), 1–7. https://doi.org/10.1371/journal.pone.0064602

Keizer, A., Smeets, M. A. M., Dijkerman, H. C., van den Hout, M., Klugkist, I., van Elburg, A., & Postma, A. (2011). Tactile body image disturbance in anorexia nervosa. *Psychiatry Research*, *190*(1), 115–120. https://doi.org/10.1016/j.psychres.2011.04.031

Keizer, A., Smeets, M. A. M., Postma, A., van Elburg, A., & Dijkerman, H. C. (2014). Does the experience of ownership over a rubber hand change body size perception in anorexia nervosa patients? *Neuropsychologia*, *62*(1), 26–37. https://doi.org/10.1016/j.neuropsychologia.2014.07.003

Kim, B., & Feldman, E. L. (2015). Insulin resistance as a key link for the increased risk of cognitive impairment in the metabolic syndrome. *Experimental & Molecular Medicine*, *47*(3), e149–e149. https://doi.org/10.1038/emm.2015.3

Kivipelto, M., Ngandu, T., Fratiglioni, L., Viitanen, M., Kåreholt, I., Tuomilehto, J., … Soininen, H. (2005). Obesity and Vascular Risk Factors at Midlife and the Risk of Dementia and Alzheimer Disease. *Archives of Neurology*, *62*(10). https://doi.org/10.1001/archneur.62.10.1556

Klein, S. A. (2001). Measuring, estimating, and understanding the psychometric function: A commentary. *Perception and Psychophysics*, *63*(8), 1421–1455. Retrieved from https://link.springer.com/content/pdf/10.3758/BF03194552.pdf

Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in Psychtoolbox-3. *Perception*, *36*(14), 1. Retrieved from https://pure.mpg.de/rest/items/item_1790332/component/file_3136265/content

Kösem, A., Gramfort, A., & van Wassenhove, V. (2014). Encoding of event timing in the phase of neural oscillations. *NeuroImage*, *92*, 274–284. https://doi.org/10.1016/j.neuroimage.2014.02.010

Kreitler, S., & Chemerinski, A. (1990). Body-image disturbance in obesity. *International Journal of Eating Disorders*, *9*(4), 409–418. https://doi.org/10.1002/1098-108X(199007)9:4<409::AID-EAT2260090407>3.0.CO;2-U

Kreitler, S., & Kreitler, H. (1988). *Body image: The dimension of size. Genetic, social, and general psychology monographs*. Heldref Publications. Retrieved from https://psycnet.apa.org/record/1988-22957-001

Kuling, I. A., Brenner, E., & Smeets, J. B. J. (2013). Proprioception Is Robust under External Forces. *PLoS ONE*, *8*(9), e74236. https://doi.org/10.1371/journal.pone.0074236

Lamarche, B., Lemieux, I., & Despres, J. P. (1999). The small, dense LDL phenotype and the risk of coronary heart disease: epidemiology, patho-physiology and therapeutic aspects. *Diabetes and Metabolism*, *25*, 199–212. Retrieved from https://www.semanticscholar.org/paper/The-small%2C-dense-LDL-phenotype-and-the-risk-of-and-Lamarche-Lemieux/84e42b8118731a45405f135e9afed28e2d0f4c43

Legrand, D. (2006). The Bodily Self: The Sensori-Motor Roots of Pre-Reflective Self-Consciousness. *Phenomenology and the Cognitive Sciences*, *5*(1), 89–118. https://doi.org/10.1007/s11097-005-9015-6

Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video Ergo Sum: Manipulating Bodily Self-Consciousness. *Science*, *317*(5841), 1096–1099. https://doi.org/10.1126/science.1143439

Linkenauger, S. A., Wong, H. Y., Geuss, M., Stefanucci, J. K., McCulloch, K. C., Bülthoff, H. H., … Proffitt, D. R. (2015). The perceptual homunculus: The perception of the relative proportions of the human body. *Journal of Experimental Psychology: General*, *144*(1), 103–113. https://doi.org/10.1037/xge0000028

Liu, Y., & Medina, J. (2017). Influence of the Body Schema on Multisensory Integration: Evidence from the Mirror Box Illusion. *Scientific Reports*, *7*(1), 5060. https://doi.org/10.1038/s41598-017-04797-0

Lokken, K. L., Boeka, A. G., Yellumahanthi, K., Wesley, M., & Clements, R. H. (2010). Cognitive performance of morbidly obese patients seeking bariatric surgery. *The American Surgeon*, *76*(1), 55–59. Retrieved from https://www.ingentaconnect.com/content/sesc/tas/2010/00000076/00000001/art00011

Longo, M. R. (2014). The effects of immediate vision on implicit hand maps. *Experimental Brain Research*, *232*(4), 1241–1247. https://doi.org/10.1007/s00221-014-3840-1

Longo, M. R. (2015a). Implicit and explicit body representations. *European Psychologist*, *20*(1), 6–15. https://doi.org/10.1027/1016-9040/a000198

Longo, M. R. (2015b). Three-dimensional coherence of the conscious body image. *The Quarterly Journal of Experimental Psychology*, *68*(6), 1116–1123. https://doi.org/10.1080/17470218.2014.975731

Longo, M. R. (2017). Distorted body representations in healthy cognition. *Quarterly Journal of Experimental Psychology*, *70*(3), 378–388. https://doi.org/10.1080/17470218.2016.1143956

Longo, M. R., Azañón, E., & Haggard, P. (2010). More than skin deep: body representation beyond primary somatosensory cortex. *Neuropsychologia*, *48*(3), 655–668. https://doi.org/10.1016/j.neuropsychologia.2009.08.022

Longo, M. R., & Haggard, P. (2010). An implicit body representation underlying human position sense. *Proceedings of the National Academy of Sciences*, *107*(26), 11727–11732. https://doi.org/10.1073/pnas.1003483107

Longo, M. R., & Haggard, P. (2011). Weber’s illusion and body shape: anisotropy of tactile size perception on the hand. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(3), 720–726. https://doi.org/10.1037/a0021921

Longo, M. R., & Haggard, P. (2012a). A 2.5-D representation of the human hand. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 9–13. https://doi.org/10.1037/a0025428

Longo, M. R., & Haggard, P. (2012b). Implicit body representations and the conscious body image. *Acta Psychologica*, *141*(2), 164–168. https://doi.org/10.1016/j.actpsy.2012.07.015

Longo, M. R., Long, C., & Haggard, P. (2012). Mapping the Invisible Hand: A Body Model of a Phantom Limb. *Psychological Science*, *23*(7), 740–742. https://doi.org/10.1177/0956797612441219

Longo, M. R., & Morcom, R. (2016). No Correlation between Distorted Body Representations Underlying Tactile Distance Perception and Position Sense. *Frontiers in Human Neuroscience*, *10*(December). https://doi.org/10.3389/fnhum.2016.00593

Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition*, *107*(3), 978–998. https://doi.org/10.1016/j.cognition.2007.12.004

Longo, Matthew R. (2015a). Intuitive anatomy: Distortions of conceptual knowledge of hand structure. *Cognition*, *142*, 230–235. https://doi.org/10.1016/j.cognition.2015.05.024

Longo, Matthew R. (2015b). Posture modulates implicit hand maps. *Consciousness and Cognition*, *36*(August), 96–102. https://doi.org/10.1016/j.concog.2015.06.009

Love, S. A., Petrini, K., Pernet, C. R., Latinus, M., & Pollick, F. E. (2018). Overlapping but Divergent Neural Correlates Underpinning Audiovisual Synchrony and Temporal Order Judgments. *Frontiers in Human Neuroscience*, *12*, 1–11. https://doi.org/10.3389/fnhum.2018.00274

Maayan, L., Hoogendoorn, C., Sweat, V., & Convit, A. (2011). Disinhibited eating in obese adolescents is associated with orbitofrontal volume reductions and executive dysfunction. *Obesity*, *19*(7), 1382–1387. https://doi.org/10.1038/oby.2011.15

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. *Behavioural Brain Research*, *191*(1), 1–10. https://doi.org/10.1016/j.bbr.2008.02.041

Mancini, F., Bauleo, A., Cole, J., Lui, F., Porro, C. A., Haggard, P., & Iannetti, G. D. (2014). Whole-body mapping of spatial acuity for pain and touch. *Annals of Neurology*, *75*(6), 917–924. https://doi.org/10.1002/ana.24179

Mancini, F., Longo, M. R., Iannetti, G. D., & Haggard, P. (2011). A supramodal representation of the body surface. *Neuropsychologia*, *49*(5), 1194–1201. https://doi.org/10.1016/j.neuropsychologia.2010.12.040

Marano, G., Cuzzolaro, M., Vetrone, G., Garfinkel, P. E., Temperilli, F., Spera, G., … Group, the Q. S. (2007). Validating the Body Uneasiness Test (BUT) in obese patients. *Eating and Weight Disorders - Studies on Anorexia, Bulimia and Obesity*, *12*(2), 70–82. https://doi.org/10.1007/BF03327581

Maravita, A., Spence, C., & Driver, J. (2003). Multisensory integration and the body schema: Close to hand and within reach. *Current Biology*, *13*, 531–539. https://doi.org/10.1016/S0960-9822(03)00449-4

Marotta, A., Tinazzi, M., Cavedini, C., Zampini, M., & Fiorio, M. (2016). Individual differences in the rubber hand illusion are related to sensory suggestibility. *PLoS ONE*, *11*(12), 1–12. https://doi.org/10.1371/journal.pone.0168489

Marotta, A., Zampini, M., Tinazzi, M., & Fiorio, M. (2018). Age-related changes in the sense of body ownership: New insights from the rubber hand illusion. *PLOS ONE*, *13*(11), e0207528. https://doi.org/10.1371/journal.pone.0207528

Marqués-Iturria, I., Pueyo, R., Garolera, M., Segura, B., Junqué, C., García-García, I., … Jurado, M. Á. (2013). Frontal cortical thinning and subcortical volume reductions in early adulthood obesity. *Psychiatry Research: Neuroimaging*, *214*(2), 109–115. https://doi.org/10.1016/j.pscychresns.2013.06.004

Massie, B. M. (2002). Obesity and Heart Failure — Risk Factor or Mechanism? *New England Journal of Medicine*, *347*(5), 358–359. https://doi.org/10.1056/NEJMe020065

Mattioni, S., & Longo, M. R. (2014). The effects of verbal cueing on implicit hand maps. *Acta*

Psychologica, *153*(October), 60–65. https://doi.org/10.1016/j.actpsy.2014.09.009

McCabe, M. P., Ricciardelli, L. A., Sitaram, G., & Mikhail, K. (2006). Accuracy of body size estimation: Role of biopsychosocial variables. *Body Image*, *3*(2), 163–171. https://doi.org/10.1016/j.bodyim.2006.01.004

MCGURK, H., & MACDONALD, J. (1976). Hearing lips and seeing voices. *Nature*, *264*(5588), 746–748. https://doi.org/10.1038/264746a0

Mechelli, A., Price, C. J., Friston, K. J., & Ishai, A. (2004). Where bottom-up meets top-down: neuronal interactions during perception and imagery. *Cerebral Cortex November*, *14*(11), 1256–1265. https://doi.org/10.1093/cercor/bhh087

Mercier, M. R., Molholm, S., Fiebelkorn, I. C., Butler, J. S., Schwartz, T. H., & Foxe, J. J. (2015). Neuro-Oscillatory Phase Alignment Drives Speeded Multisensory Response Times: An Electro-Corticographic Investigation. *The Journal of Neuroscience*, *35*(22), 8546–8557. https://doi.org/10.1523/JNEUROSCI.4527-14.2015

Meyer, J. E., & Tuchelt-Gallwitz, A. (1968). A study on social image, body image and the problem of psychogenetic factors in obesity. In *Comprehensive Psychiatry* (Vol. 9, pp. 148–154). Elsevier Science.

Milkewicz, N., & Cash, T. F. (2000). Dismantling the heterogeneity of obesity: Determinants of body images and psychological functioning. In *Poster Present at the Convention of the Association for Advancement of Behavior Therapy; Association for Advancement of Behavior Therapy: New Orleans, LA, USA*.

Miller, A. A., & Spencer, S. J. (2014). Obesity and neuroinflammation: A pathway to cognitive impairment. *Brain, Behavior, and Immunity*, *42*, 10–21. https://doi.org/10.1016/j.bbi.2014.04.001

Miscio, G., Guastamacchia, G., Brunani, A., Priano, L., Baudo, S., & Mauro, A. (2005). Obesity and peripheral neuropathy risk: a dangerous liaison. *Journal of the Peripheral Nervous System*, *10*(4), 354–358. https://doi.org/10.1111/j.1085-9489.2005.00047.x

Mölbert, S. C., Thaler, A., Mohler, B. J., Streuber, S., Romero, J., Black, M. J., … Giel, K. E. (2018). Assessing body image in anorexia nervosa using biometric self-avatars in virtual reality: Attitudinal components rather than visual body size estimation are distorted. *Psychological Medicine*, *48*(4), 642–653. https://doi.org/10.1017/S0033291717002008

Mölbert, Simone Claire, Klein, L., Thaler, A., Mohler, B. J., Brozzo, C., Martus, P., … Giel, K. E. (2017). Depictive and metric body size estimation in anorexia nervosa and bulimia nervosa: A systematic review and meta-analysis. *Clinical Psychology Review*, *57*(December 2016), 21–31. https://doi.org/10.1016/j.cpr.2017.08.005

Moravveji, H., Ghanbari, A., & Kamali, F. (2017). Proprioception of Knee Joint in Athletes and Non-Athletes Obese. *Global Journal of Health Science*, *9*(2). https://doi.org/10.5539/gjhs.v9n2p286

Moseley, G. L., Olthof, N., Venema, A., Don, S., Wijers, M., Gallace, A., & Spence, C. (2008). Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. *Proceedings of the National Academy of Sciences*, *105*(35), 13169–13173. https://doi.org/10.1073/pnas.0803768105

Moussally, Joanna M., Rochat, L., Posada, A., & Van Der Linden, M. (2017). A database of body-only computer-generated pictures of women for body-image studies: development and preliminary validation. *Behavior Research Methods*, *49*(1), 172–183. https://doi.org/10.3758/s13428-016-0703-7

Moussally, Joanna Myriam, Grynberg, D., Goffinet, S., Simon, Y., & Van der Linden, M. (2017). Novel assessment of own and ideal body perception among women: validation of the computer-generated figure rating scale. *Cognitive Therapy and Research*, *41*(4), 632–644.

https://doi.org/10.1007/s10608-016-9827-4

Muth, J. L., & Cash, T. F. (1997). Body-Image Attitudes: What Difference Does Gender Make?1. *Journal of Applied Social Psychology*, *27*(16), 1438–1452. https://doi.org/10.1111/j.1559-1816.1997.tb01607.x

Nava, E., Mattioli, F., Gamberini, C., Stampatori, C., Bellomi, F., Turati, C., … Bolognini, N. (2018). Altered bodily self-consciousness in multiple sclerosis. *Journal of Neuropsychology*, *12*(3), 463–470. https://doi.org/10.1111/jnp.12134

Nava, E., Steiger, T., & Roder, B. (2014). Both developmental and adult vision shape body representations. *Scientific Reports*, *4*. https://doi.org/10.1038/srep06622

Nilsson, L.-G., & Nilsson, E. (2009). Overweight and cognition. *Scandinavian Journal of Psychology*, *50*(6), 660–667. https://doi.org/10.1111/j.1467-9450.2009.00777.x

Nobusako, S., Ishibashi, R., Takamura, Y., Oda, E., Tanigashira, Y., Kouno, M., … Morioka, S. (2018). Distortion of Visuo-Motor Temporal Integration in Apraxia: Evidence From Delayed Visual Feedback Detection Tasks and Voxel-Based Lesion-Symptom Mapping. *Frontiers in Neurology*, *9*(August), 1–23. https://doi.org/10.3389/fneur.2018.00709

Ochner, C. N., Green, D., Jason Van Steenburgh, J., Kounios, J., & Lowe, M. R. (2009). Asymmetric prefrontal cortex activation in relation to markers of overeating in obese humans. *Appetite*, *53*(1), 44–49. https://doi.org/10.1016/j.appet.2009.04.220

OECD/EU. (2017). *Obesity Update 2017*. *Diabetologe* (Vol. 13). https://doi.org/10.1007/s11428-017-0241-7

Olivé, I., & Berthoz, A. (2012). Combined Induction of Rubber-Hand Illusion and Out-of-Body Experiences. *Frontiers in Psychology*, *3*(May), 1–8. https://doi.org/10.3389/fpsyg.2012.00128

Paillard, J. (1999). Body Schema and body image-a double dissociation. *Motor Control, Today and Tomorrow*, *48*(3), 197–214. https://doi.org/10.1016/j.neuropsychologia.2009.09.022

Palmeira, A. L., Branco, T. L., Martins, S. C., Minderico, C. S., Silva, M. N., Vieira, P. N., … Teixeira, P. J. (2010). Change in body image and psychological well-being during behavioral obesity treatment: Associations with weight loss and maintenance. *Body Image*, *7*(3), 187–193. https://doi.org/10.1016/j.bodyim.2010.03.002

Palomo, P., Borrego, A., Cebolla, A., Llorens, R., Demarzo, M., & Baños, R. M. (2018). Subjective, behavioral, and physiological responses to the rubber hand illusion do not vary with age in the adult phase. *Consciousness and Cognition*, *58*, 90–96. https://doi.org/10.1016/j.concog.2017.10.014

Pannacciulli, N., Del Parigi, A., Chen, K., Le, D. S. N. T., Reiman, E. M., & Tataranni, P. A. (2006). Brain abnormalities in human obesity: A voxel-based morphometric study. *NeuroImage*, *31*(4), 1419–1425. https://doi.org/10.1016/j.neuroimage.2006.01.047

Papadopoulos, S., & Brennan, L. (2015). Correlates of weight stigma in adults with overweight and obesity: A systematic literature review. *Obesity*, *23*(9), 1743–1760. https://doi.org/10.1002/oby.21187

Pasqualotto, A., Dumitru, M. L., & Myachykov, A. (2016). Multisnesory Integration: Brain, Body, and World. *Frontiers in Psychology*, *6*, 246. https://doi.org/10.1038/44139

Paton, B., Hohwy, J., & Enticott, P. G. (2012). The Rubber Hand Illusion Reveals Proprioceptive and Sensorimotor Differences in Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders*, *42*(9), 1870–1883. https://doi.org/10.1007/s10803-011-1430-7

Pavani, F., & Zampini, M. (2007). The role of hand size in the fake-hand illusion paradigm. *Perception*, *36*(10), 1547–1554. https://doi.org/10.1068/p5853

Pearlson, G. D., Flournoy, L. H., Simonson, M., & Slavney, P. R. (1981). Body image in obese adults. *Psychological Medicine*, *11*(1), 147–154.

Penfield, W., & Boldrey, E. (1937). Somatic Motor and Sensory Representation in the Cerebral Cortex of Man as Studied by Electrical Stimulation. *Brain, 60*(4), 389-443. Retrieved from http://brain.oxfordjournals.org/

Perpiñá, C., Segura, M., & Sánchez-Reales, S. (2017). Cognitive flexibility and decision-making in eating disorders and obesity. *Eating and Weight Disorders - Studies on Anorexia, Bulimia and Obesity*, *22*(3), 435–444. https://doi.org/10.1007/s40519-016-0331-3

Petkova, V. I., & Ehrsson, H. H. (2008). If I Were You: Perceptual Illusion of Body Swapping. *PLoS ONE*, *3*(12), e3832. https://doi.org/10.1371/journal.pone.0003832

Petkova, V. I., Zetterberg, H., & Ehrsson, H. H. (2012). Rubber hands feel touch, but not in blind individuals. *PLoS ONE*, *7*(4), 1–10. https://doi.org/10.1371/journal.pone.0035912

Peviani, V., & Bottini, G. (2018). The distorted hand metric representation serves both perception and action. *Journal of Cognitive Psychology*, *30*(8), 880–893. https://doi.org/10.1080/20445911.2018.1538154

Pöppel, E., Schill, K., & von Steinbüchel, N. (1990). Sensory integration within temporally neutral systems states: A hypothesis. *Naturwissenschaften*, *77*(2), 89–91. https://doi.org/10.1007/BF01131783

Prickett, C., Brennan, L., & Stolwyk, R. (2015). Examining the relationship between obesity and cognitive function: A systematic literature review. *Obesity Research and Clinical Practice, 9*(2), 93–113. https://doi.org/10.1016/j.orcp.2014.05.001

Proske, U., & Gandevia, S. C. (2012). The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. *Physiological Reviews*, *92*(4), 1651–1697. https://doi.org/10.1152/physrev.00048.2011

Puhl, R., & Brownell, K. D. (2001). Bias, discrimination, and obesity. *Obesity Research*, *9*(12), 788–805. https://doi.org/10.1038/oby.2001.108

Puhl, R. M., & Heuer, and C. A. (2009). The Stigma of Obesity: A Review and Update. *Obesity*, *17*(5), 941–964. https://doi.org/10.1038/oby.2008.636

Raji, C. A., Ho, A. J., Parikshak, N. N., Becker, J. T., Lopez, O. L., Kuller, L. H., … Thompson, P. M. (2010). Brain structure and obesity. *Human Brain Mapping*, *31*(3), 353–364. https://doi.org/10.1002/hbm.20870

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, *114*(3), 510.

Reitman, E. E., & Cleveland, S. E. (1964). Changes in body image following sensory deprivation in schizophrenic and control groups. *Journal of Abnormal and Social Psychology*, *68*(2), 168–176. https://doi.org/10.1037/h0046252

Riva, G. (2011). The key to unlocking the virtual body:virtual reality in the treatment of obesity and eating disorders. *Journal of Diabetes Science and Technology*, *5*(2), 283–292. https://doi.org/10.1177/193229681100500213

Riva, G. (2012). Neuroscience and eating disorders: The allocentric lock hypothesis. *Medical Hypotheses*, *78*(2), 254–257. https://doi.org/10.1016/j.mehy.2011.10.039

Riva, G., Gutiérrez-Maldonado, J., & Wiederhold, B. K. (2016). Virtual Worlds versus Real Body: Virtual Reality Meets Eating and Weight Disorders. *Cyberpsychology, Behavior, and Social Networking*, *19*(2), 63–66. https://doi.org/10.1089/cyber.2016.29025.gri

Riva, G., Wiederhold, B. K., & Mantovani, F. (2019). Neuroscience of Virtual Reality: From Virtual Exposure to Embodied Medicine. *Cyberpsychology, Behavior, and Social Networking*, *22*(1), 82–96. https://doi.org/10.1089/cyber.2017.29099.gri

Roberts, M. E., Demetriou, L., Treasure, J. L., & Tchanturia, K. (2007). Neuropsychological profile in the overweight population: An exploratory study of set-shifting and detail focused processing styles. *Therapy*, *4*(6), 821–824. https://doi.org/10.2217/14750708.4.6.821

Rodin, J., Silberstein, L., & Striegel-Moore, R. (1984). Women and weight: A normative discontent. In *Nebraska symposium on motivation*. University of Nebraska Press.

Rohde, M., Luca, M., & Ernst, M. O. (2011). The rubber hand illusion: Feeling of ownership and proprioceptive drift Do not go hand in hand. *PLoS ONE*, *6*(6). https://doi.org/10.1371/journal.pone.0021659

Rucker, C. E., & Cash, T. F. (1992). Body images, body-size perceptions, and eating behaviors among African-American and white college women. *International Journal of Eating Disorders*, *12*(3), 291–299. https://doi.org/10.1002/1098-108X(199211)12:3<291::AID-EAT2260120309>3.0.CO;2-A

Saleh, M. S. ., & El-Nabie, W. A. E.-H. A. (2017). Influence of obesity on proprioception of knee and ankle joints in obese prepubertal children. *Bulletin of Faculty of Physical Therapy*, *23*, 9–14.

Sanchez-Vives, M. V., Spanlang, B., Frisoli, A., Bergamasco, M., & Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. *PLoS ONE*, *5*(4), 1–6. https://doi.org/10.1371/journal.pone.0010381

Sargénius, H. L., Lydersen, S., & Hestad, K. (2017). Neuropsychological function in individuals with morbid obesity: a cross-sectional study. *BMC Obesity*, *4*(1), 6. https://doi.org/10.1186/s40608-017-0143-7

Sarwer, D. B., Thompson, J. K., & Cash, T. F. (2005). Body image and obesity in adulthood. *Psychiatric Clinics of North America*, *28*(1), 69–87. https://doi.org/10.1016/j.psc.2004.09.002

Sarwer, D. B., Wadden, T. A., & Foster, G. D. (1998). Assessment of body image dissatisfaction in obese women: Specificity, severity, and clinical significance. *Journal of Consulting and Clinical Psychology*, *66*(4), 651–654. https://doi.org/10.1037/0022-006X.66.4.651

Satizabal, C. L., Zhu, Y. C., Mazoyer, B., Dufouil, C., & Tzourio, C. (2012). Circulating IL-6 and CRP are associated with MRI findings in the elderly. *Neurology*, *78*(10), 720 LP – 727. https://doi.org/10.1212/WNL.0b013e318248e50f

Scarpina, F., Castelnuovo, G., & Molinari, E. (2014). Tactile mental body parts representation in obesity. *Psychiatry Research*, *220*(3), 960–969. https://doi.org/10.1016/j.psychres.2014.08.020

Scarpina, F., Cau, N., Cimolin, V., Galli, M., Castelnuovo, G., Priano, L., … Capodaglio, P. (2017). Body-scaled action in obesity during locomotion: Insights on the nature and extent of body representation disturbances. *Journal of Psychosomatic Research*, *102*(June), 34–40. https://doi.org/10.1016/j.jpsychores.2017.09.004

Scarpina, F., Migliorati, D., Marzullo, P., Mauro, A., Scacchi, M., & Costantini, M. (2016). Altered multisensory temporal integration in obesity. *Scientific Reports*, *6*, 28382. https://doi.org/10.1038/srep28382

Scarpina, F., Van der Stigchel, S., Nijboer, T. C. W., & Dijkerman, H. C. (2013). Prism adaptation changes the subjective proprioceptive localization of the hands. *Journal of Neuropsychology*, *9*(1), 21–32. https://doi.org/10.1111/jnp.12032

Schwartz, M. B., & Brownell, K. D. (2004). Obesity and body image. *Body Image*, *1*(1), 43–56. https://doi.org/10.1016/S1740-1445(03)00007-X

Schwartz, M. B., Chambliss, H. O., Brownell, K. D., Blair, S. N., & Billington, C. (2003). Weight Bias among Health Professionals Specializing in Obesity. *Obesity Research*, *11*(9), 1033–1039. https://doi.org/10.1038/oby.2003.142

Schwoebel, J., Branch Coslett, H., & Coslett, H. B. (2005). Evidence for multiple, distinct representations of the human body. *Journal of Cognitive Neuroscience*, *17*(4), 543–553. Retrieved from https://www.mitpressjournals.org/doi/pdfplus/10.1162/0898929053467587

Sedda, A., & Scarpina, F. (2012). Dorsal and ventral streams across sensory modalities. *Neuroscience Bulletin*, *28*(3), 291–300. https://doi.org/10.1007/s12264-012-1223-9

Senkowski, D., Gomez-Ramirez, M., Lakatos, P., Wylie, G. R., Molholm, S., Schroeder, C. E., & Foxe, J. J. (2007). Multisensory processing and oscillatory activity: Analyzing non-linear electrophysiological measures in humans and simians. *Experimental Brain Research*, *177*(2), 184–195. https://doi.org/10.1007/s00221-006-0664-7

Serino, A., Alsmith, A., Costantini, M., Mandrigin, A., Tajadura-jimenez, A., & Lopez, C. (2013). Bodily ownership and self-location : Components of bodily. *Consciousness and Cognition*, *22*(4), 1239–1252. https://doi.org/10.1016/j.concog.2013.08.013

Serino, A., & Haggard, P. (2010). Touch and the body. *Neuroscience and Biobehavioral Reviews*, *34*(2), 224–236. https://doi.org/10.1016/j.neubiorev.2009.04.004

Serino, S., & Dakanalis, A. (2017). Bodily illusions and weight-related disorders: Clinical insights from experimental research. *Annals of Physical and Rehabilitation Medicine*, *60*(3), 217–219. https://doi.org/10.1016/j.rehab.2016.10.002

Serino, S., Scarpina, F., Keizer, A., Pedroli, E., Dakanalis, A., Castelnuovo, G., … Riva, G. (2016). A Novel Technique for Improving Bodily Experience in a Non-operable Super–Super Obesity Case.

Frontiers in Psychology, *7*, 1–6. https://doi.org/10.3389/fpsyg.2016.00837

Shams, L., Kamitani, Y., & Shimojo, S. (2002). Visual illusion induced by sound. *Cognitive Brain Research*, *14*(1), 147–152. https://doi.org/10.1016/S0926-6410(02)00069-1

Shimada, S., Suzuki, T., Yoda, N., & Hayashi, T. (2014). Relationship between sensitivity to visuotactile temporal discrepancy and the rubber hand illusion. *Neuroscience Research*, *85*, 33–38. https://doi.org/10.1016/j.neures.2014.04.009

Slade, P. D., & Russell, G. F. M. (1973). Experimental Investigations of Bodily Perception in Anorexia Nervosa and Obesity. *Psychotherapy and Psychosomatics*, *22*(2–6), 359–363. https://doi.org/10.1159/000286543

Slater, M. (2009). Inducing illusory ownership of a virtual body. *Frontiers in Neuroscience*, *3*(2), 214–220. https://doi.org/10.3389/neuro.01.029.2009

Smeets, M. A. M., Ingleby, J. D., Hoek, H. W., & Panhuysen, G. E. M. (1999). Body size perception in anorexia nervosa: A signal detection approach. *Journal of Psychosomatic Research*, *46*(5), 465–477. https://doi.org/10.1016/S0022-3999(99)00005-7

Smith, E., Hay, P., Campbell, L., & Trollor, J. N. (2011). A review of the association between obesity and cognitive function across the lifespan: Implications for novel approaches to prevention and treatment. *Obesity Reviews*, *12*(9), 740–755. https://doi.org/10.1111/j.1467-789X.2011.00920.x

Snijders, H. J., Holmes, N. P., & Spence, C. (2007). Direction-dependent integration of vision and proprioception in reaching under the influence of the mirror illusion. *Neuropsychologia*, *45*(3), 496–505. https://doi.org/10.1016/j.neuropsychologia.2006.01.003

Sørensen, T. I. A., & Sonne-Holm, S. (1985). Intelligence test performance in obesity in relation to educational attainment and parental Social Class. *Journal of Biosocial Science*, *17*(4), 379–387.

https://doi.org/10.1017/S002193200001590X

Spence, C. (2007). Audiovisual multisensory integration. *Acoustical Science and Technology*, *28*(2), 61–70. https://doi.org/10.1250/ast.28.61

Spence, C. (2015). Multisensory Flavor Perception. *Cell*, *161*(1), 24–35. https://doi.org/10.1016/j.cell.2015.03.007

Spitoni, G. F., Galati, G., Antonucci, G., Haggard, P., & Pizzamiglio, L. (2010). Two forms of touch perception in the human brain. *Experimental Brain Research*, *207*(3–4), 185–195. https://doi.org/10.1007/s00221-010-2446-5

Spyridaki, E. C., Avgoustinaki, P. D., & Margioris, A. N. (2016). Obesity, inflammation and cognition. *Current Opinion in Behavioral Sciences*, *9*, 169–175. https://doi.org/10.1016/j.cobeha.2016.05.004

Spyridaki, E. C., Simos, P., Avgoustinaki, P. D., Dermitzaki, E., Venihaki, M., Bardos, A. N., & Margioris, A. N. (2014). The association between obesity and fluid intelligence impairment is mediated by chronic low-grade inflammation. *British Journal of Nutrition*, *112*(10), 1724–1734. https://doi.org/10.1017/S0007114514002207

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses.* The MIT Press.

Stevenson, R. A., & Wallace, M. T. (2013). Multisensory temporal integration: task and stimulus dependencies. *Experimental Brain Research*, *227*(2), 249–261. https://doi.org/10.1007/s00221-013-3507-3

Taylor-Clarke, M., Jacobsen, P., & Haggard, P. (2004). Keeping the world a constant size: Object constancy in human touch. *Nature Neuroscience*, *7*(3), 219–220. https://doi.org/10.1038/nn1199

Tchernof, A., Lamarche, B., Prud’homme, D., Nadeau, A., Moorjani, S., Labrie, F., … Despres, J.-P.

(1996). The Dense LDL Phenotype: Association with plasma lipoprotein levels, visceral obesity, and hyperinsulinemia in men. *Diabetes Care*, *19*(6), 629–637. https://doi.org/10.2337/diacare.19.6.629

Teachman, B. A., Gapinski, K. D., Brownell, K. D., Rawlins, M., & Jeyaram, S. (2003). Demonstrations of implicit anti-fat bias: The impact of providing causal information and evoking empathy. *Health Psychology*, *22*(1), 68–78. https://doi.org/10.1037/0278-6133.22.1.68

Thakkar, K. N., Nichols, H. S., McIntosh, L. G., & Park, S. (2011). Disturbances in Body Ownership in Schizophrenia: Evidence from the Rubber Hand Illusion and Case Study of a Spontaneous Out-of-Body Experience. *PLoS ONE*, *6*(10), e27089. https://doi.org/10.1371/journal.pone.0027089

Thaler, A., Geuss, M. N., Mölbert, S. C., Giel, K. E., Streuber, S., Romero, J., … Mohler, B. J. (2018). Body size estimation of self and others in females varying in BMI. *PLoS ONE*, *13*(2), 1–24. https://doi.org/10.1371/journal.pone.0192152

Trollor, J. N., Smith, E., Baune, B. T., Kochan, N. A., Campbell, L., Samaras, K., … Sachdev, P. (2010). Systemic inflammation is associated with MCI and its subtypes: the Sydney Memory and Aging Study. *Dementia and Geriatric Cognitive Disorders*, *30*(6), 569–578.

Tsakiris, M. (2017). The multisensory basis of the self: From body to identity to others. *Quarterly Journal of Experimental Psychology*, *70*(4), 597–609. https://doi.org/10.1080/17470218.2016.1181768

Tsakiris, M., & Haggard, P. (2005). The Rubber Hand Illusion Revisited: Visuotactile Integration and Self-Attribution. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(1), 80–91. https://doi.org/10.1037/0096-1523.31.1.80

Tsakiris, M., Prabhu, G., & Haggard, P. (2006). Having a body versus moving your body: How agency structures body-ownership. *Consciousness and Cognition*, *15*(2), 423–432. https://doi.org/10.1016/j.concog.2005.09.004

Vallar, G., & Ronchi, R. (2009). Somatoparaphrenia: a body delusion. A review of the neuropsychological literature. *Experimental Brain Research*, *192*(3), 533–551. https://doi.org/10.1007/s00221-008-1562-y

Valtolina, G. G. (1998). Body size estimation by obese subjects. *Perceptual and Motor Skills*, *86*(3), 1363–1374. https://doi.org/10.2466/pms.1983.57.3.1005

van Beers, R. J., Wolpert, D. M., & Haggard, P. (2002). When Feeling Is More Important Than Seeing in Sensorimotor Adaptation. *Current Biology*, *12*(10), 834–837. https://doi.org/10.1016/S0960-9822(02)00836-9

Volkow, N. D., Wang, G. J., Telang, F., Fowler, J. S., Goldstein, R. Z., Alia-Klein, N., … Pradhan, K. (2009). Inverse association between BMI and prefrontal metabolic activity in healthy adults. *Obesity*, *17*(1), 60–65. https://doi.org/10.1038/oby.2008.469

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, & Psychophysics*, *72*(4), 871–884. https://doi.org/10.3758/APP.72.4.871

Wadden, T. A., Butryn, M. L., Sarwer, D. B., Fabricatore, A. N., Crerand, C. E., Lipschutz, P. E., … Williams, N. N. (2006). Comparison of Psychosocial Status in Treatment-Seeking Women with Class III vs. Class I–II Obesity. *Obesity*, *14*(3S), 90S-98S. https://doi.org/10.1038/oby.2006.288

Wallace, M. T., Roberson, G. E., Hairston, W. D., Stein, B. E., Vaughan, J. W., & Schirillo, J. A. (2004). Unifying multisensory signals across time and space. *Experimental Brain Research*, *158*(2), 252–258. https://doi.org/10.1007/s00221-004-1899-9

Walther, K., Birdsill, A. C., Glisky, E. L., & Ryan, L. (2010). Structural brain differences and cognitive functioning related to body mass index in older females. *Human Brain Mapping*, *31*(7), 1052–1064. https://doi.org/10.1002/hbm.20916

Wan, X., Spence, C., Mu, B., Zhou, X., & Ho, C. (2014). Assessing the benefits of multisensory audiotactile stimulation for overweight individuals. *Experimental Brain Research*, *232*(4), 1085–1093. https://doi.org/10.1007/s00221-013-3792-x

Wang, C., Chan, J. S. Y., Ren, L., & Yan, J. H. (2016). Obesity Reduces Cognitive and Motor Functions across the Lifespan. *Neural Plasticity*, *2016*, 1–13. https://doi.org/10.1155/2016/2473081

Wang, L., Li, J. X., Xu, D. Q., & Hong, Y. L. (2008). Proprioception of ankle and knee joints in obese boys and nonobese boys. *Medical Science Monitor*, *14*(3), 129–135. https://doi.org/10.13140/2.1.3317.8249

Weber, E. H. (1996). *EH Weber on the tactile senses*. Psychology Press.

Weinberger, N. A., Kersting, A., Riedel-Heller, S. G., & Luck-Sikorski, C. (2016). Body Dissatisfaction in Individuals with Obesity Compared to Normal-Weight Individuals: A Systematic Review and Meta-Analysis. *Public Health*, *9*(6), 424–441. https://doi.org/10.1159/000454837

Weise, C. M., Thiyyagura, P., Reiman, E. M., Chen, K., & Krakoff, J. (2013). Fat-free body mass but not fat mass is associated with reduced gray matter volume of cortical brain regions implicated in autonomic and homeostatic regulation. *NeuroImage*, *64*, 712–721. https://doi.org/10.1016/j.neuroimage.2012.09.005

Welch, R. B., Widawski, M. H., Harrington, J., & Warren, D. H. (1979). An examination of the relationship between visual capture and prism adaptation. *Perception & Psychophysics*, *25*(2), 126–132. https://doi.org/10.3758/BF03198798

Whitmer, R. A., Gunderson, E. P., Barrett-Connor, E., Quesenberry, C. P., & Yaffe, K. (2005). Obesity in middle age and future risk of dementia: a 27 year longitudinal population based study. *BMJ*, *330*(7504), 1360. https://doi.org/10.1136/bmj.38446.466238.E0

Willette, A. A., & Kapogiannis, D. (2015). Does the brain shrink as the waist expands? *Ageing Research Reviews*, *20*, 86–97. https://doi.org/10.1016/j.arr.2014.03.007

Wilson, C. J., Finch, C. E., & Cohen, H. J. (2002). Cytokines and cognition--the case for a head-to-toe inflammatory paradigm. *Journal of the American Geriatrics Society*, *50*(12), 2041–2056. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12473019

Wolf, P. A., Beiser, A., Elias, M. F., Au, R., Vasan, R. S., & Seshadri, S. (2007). Relation of obesity to cognitive function: importance of central obesity and synergistic influence of concomitant hypertension. The Framingham Heart Study. *Current Alzheimer Research*, *4*(2), 111–116.

World Health Organization. (1995). *Physical status: The use of and interpretation of anthropometry, Report of a WHO Expert Committee*. Geneva: World Health Organization. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/37003/WHO_TRS_854.pdf

Yokum, S., Ng, J., & Stice, E. (2012). Relation of Regional Grey and White Matter Volumes to Current BMI and Future Increases in BMI: A Prospective MRI Study. *International Journal of Obesity*, *36*(5), 656–664. https://doi.org/10.1038/ijo.2011.175

Yuan, X., Li, H., Liu, P., Yuan, H., & Huang, X. (2016). Pre-stimulus beta and gamma oscillatory power predicts perceived audiovisual simultaneity. *International Journal of Psychophysiology*. https://doi.org/10.1016/j.ijpsycho.2016.06.017

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005). Audio-visual simultaneity judgments. *Perception & Psychophysics*, *67*(3), 531–544. https://doi.org/10.3758/BF03193329

Zampini, M., Shore, D. I., & Spence, C. (2003). Audiovisual temporal order judgments. *Experimental*

Brain Research, *152*(2), 198–210. https://doi.org/10.1007/s00221-003-1536-z

Zandstra, E. H., De Graaf, C., Mela, D. J., & Van Staveren, W. A. (2000). Short- and long-term effects of changes in pleasantness on food intake. *Appetite*, *34*(3), 253–260. https://doi.org/10.1006/appe.1999.0304

Zimmet, P., Alberti, K. G. M. M., & Shaw, J. (2001). Global and societal implications of the diabetes epidemic. *Nature*, *414*(6865), 782–787. https://doi.org/10.1038/414782a