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METE Project: Multisensory Embodied Transformative Experiences

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

" I want a perfect body, I want a perfect soul"

Radiohead

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Introduction

The human body presents a fundamental paradox in studying embodied cognition and phenomenological experience. It serves as the primary interface through which we perceive and interact with the environment and constitutes the physical substrate of personal identity. Despite its key functions, conscious body awareness often remains limited under normal circumstances and in everyday life. We tend to give our body as a guarantee until it becomes the vehicle of signals that something is going wrong, forcing us to become aware of its (inner and outer) characteristics. There is, however, another way in which we become aware of our bodies that goes beyond illness and injuries: we can become aware of our body through "the eyes of the Other", namely when our body becomes an object to be observed and/or when we are observed by Others. Indeed, one of the core features of our body is that it can be both a subject and an object at the same time. This special "dual role" of the body is at the heart of a reflection that cuts across both psychology and neuroscience.

Blanke (2012) defined the body as "the most multisensory object" as it emerges from the probabilistic combination of information from different sensory modalities and spatial frames, which has been defined as "Multisensory Integration Processing" (MSI). If we try to understand MSI according to the Predictive Coding framework (Friston, 2010), MSI involves inferential mechanisms in which the brain compares incoming (online) information with what it expects based on our prior (offline) experiences. In other words, the brain integrates a stream of incoming information from inside and outside the body into a coherent representation and compares it with what it already knows and expects about the body itself. This probabilistic process generates a model of the body: the Body Matrix (Riva, 2018). This implies that the way we represent our body is based both on actual bodily information (e.g., somatosensory, visual, tactile) but also from stored prior information that can be conceptual (the meaning attributed to the body), perceptual (the size and shape of the body), and episodic (the autobiographical events related to the experience of the body). Then, body experience is not strictly a matter of how the body physically looks (Blanke, 2012).

This constitutes the starting point of my PhD project: the way we represent our body is the result of an inferential process in which different pieces of online and offline information from inside and outside the body are coherently put together. But what happens when this predictive mechanism becomes disrupted? I hypothesized that distorted body representation, such as the ones observed in patients affected by Anorexia Nervosa and Bulimia Nervosa, may fundamentally stem from multisensory predictive process impairments. Reformulating, my idea is that the discrepancy between the objective physical body and its subjective perception is linked to an altered inferential and probabilistic process of online and offline bodily information.

Then, this PhD project aims to contribute to research on the complex nature of subjective bodily experience, intended as the result of a probabilistic multisensory integration process. In particular, the experimental research presented throughout the following pages will try to understand how we can use multisensory experiences to manipulate the Body Matrix with the final goal of finding new possibilities to help individuals struggling with their body's representation.

In the following pages, I will outline my doctoral thesis journey. The first chapter will explain the multisensory nature and the ontogenetic model of body representation. The second chapter will focus on the role of the body in patients affected by Anorexia Nervosa and Bulimia Nervosa, pathologies that were taken as examples of conditions in which objective and subjective body experience do not correspond. Here, I will explain my proposal to look at distorted body experience in these conditions, focusing on MSI and predictive mechanisms, based on systematic literature review findings. Subsequently, I will present a machine learning study supporting the key role of the body in Anorexia Nervosa maintenance and relapse, and, consequently, the importance of developing body-focused interventions. The third chapter will present Virtual Reality (VR) technology as a suitable means to study and manipulate bodily experience using immersive multisensory experiences as Full Body Illusions (FBI). The core VR features will be presented to clarify the unique opportunities this technology offers in the study of the body. At this point, I will explain the object of the research, the theoretical background, and the methodology. The chapter will continue by presenting experimental studies investigating how we can use this framework and tools to manipulate the Body Matrix. In a first study, I developed a gender-specific VR FBI experience to investigate whether males and females respond differently to the FBI. As this research highlighted significant differences, suggesting the need for gender-specific bodily approaches, the project will only focus on females starting from this point. This is because most patients affected by Anorexia Nervosa are women. Then, I will present an improved version of the FBI that I developed specifically for the female population. The second experiment in the chapter will instead investigate the role of spatial perspective in the effectiveness of the body illusion in inducing changes in the Body Matrix. The study revealed a different role of first and third-person perspectives on body representation development and update. The last chapter will go more into detail on the use of VR technology in the Eating Disorder field. A scoping review will then be presented to systematize the existing procedures using VR to assess, understand, and treat these conditions. After this broad overview, I will present a single-subject case study in which I will test the acceptance, feasibility, and preliminary efficacy of an innovative VR intervention to improve the subjective body experience in a patient affected by Anorexia Nervosa. This study was possible thanks to the collaboration of the IRCCS Istituto Auxologico Italiano.

All the studies in this thesis have already been published in peer-reviewed international journals, while others were presented at international conferences.

The empirical findings of this PhD thesis present promising avenues for both theoretical advancement and clinical application. While demonstrating significant potential and opportunities, further research is necessary to strengthen their reliability and generalizability. Nonetheless, this thesis makes a substantive contribution to our understanding of subjective body experience and its underlying mechanisms. This work thus tried to bridge the gap between research and clinical practice, offering new perspectives for addressing the complex challenges faced by individuals struggling with body-related disturbances.

Acknowledgments

A thank to my first supporter, from Earth and beyond - Elisa Z.

1. The Multisensory Body

This thesis project focuses on how we experience our bodies, a subject that has fascinated me due to the body's unique dual nature: it serves both as a perceiving subject and as a perceptual object. We experience our bodies in two primary ways: directly, through an internal sense of our body (coenaesthesis), and indirectly, by observing it from the outside. The dynamic integration of these modalities, referred to as the optical-coenaesthetic proportion, is fundamental to maintaining a coherent and satisfying body experience (Stanghellini et al., 2019).

Beyond this duality, other aspects make the body a multifaceted and intriguing subject of study. Its significance extends far beyond physicality, influencing cognitive processes, shaping our sense of self, and mediating our interactions with the world. This chapter delves deeper into these dimensions, exploring the body's role in cognition, its ontological foundations, and its inherently multisensory nature.

1.1 The body at the basis of cognitive processes

The body is not merely a container that carries us through the world. It is the foundation of our experience, shaping our thoughts, emotions, and interactions. It serves as the primary interface through which we engage with our surroundings and ourselves. It is a dynamic and adaptable entity, influencing everything from our identity to social connections. In this intricate dance of existence, the body is more than a physical form, and its importance transcends its physical properties: it plays a critical role in our psychological well-being, self-awareness, and the way we interpret the world inside and around us.

This premise forms the basis of a recent approach defined as Embodied Cognition (EC). EC emphasizes the key role of the body in shaping the mind. It suggests that our thoughts, perceptions, and emotions are deeply influenced by physical experiences and world interactions (Shapiro, 2019). That is, cognition is not just a product of brain activity but emerges from the dynamic interplay between the brain, the body, and the environment. This mind-body connection is well exemplified by the concept of the "body schema", namely *the recurring dynamic patterns of our perceptual interactions and motor programs that provide structure and coherence to our experience* (p. 14; Johnson, 1987). The idea is that, from birth, our understanding of the world begins with our physical and sensory experiences. These early interactions—such as grasping objects, moving through space, or feeling sensations—are not just raw data but are structured into image schemas. Such schemas should be intended as recurring patterns that emerge from our bodily interactions with the world, which are extended and abstracted to shape more complex, non-physical concepts (Mandler, 2012).

Indeed, we develop increasingly complex concepts by combining image schemas with perceptual representations. In doing so, we merge two systems of spatial representation— egocentric and allocentric - which together shape the conceptual system (Riva, 2014). Egocentric representations position the body at the center, offering a first-person perspective (1PP), whereas allocentric representations position the body as an object in space, providing a third-person perspective (3PP). Notably, 1PP refers to those aspects of body awareness that are uniquely accessible to the individual (the self), while 3PP refers to those aspects of body awareness that could potentially be observed by others (Zwicker, Moore, & Povinelli, 2012). Egocentric and allocentric body representations might differ, as exemplified by phantom limb experiences. It follows that our egocentric and allocentric body representation deeply influences our experience.

Body representation plays a critical role not only in mapping the external environment but also in generating meaning, structuring our experiences, and forming our identity. Damasio (1998) was among the first authors to systematize the relation between the body and the self. He tried to understand how the brain integrates information to create a unified sensory experience and how we perceive these experiences as belonging to ourselves (Parvizi & Damasio, 2001). Damasio proposed a three-layer model of consciousness: the *proto-self*, *core consciousness*, and *extended consciousness* (Damasio, 1998). The *proto-self* is the most fundamental level, comprising neural patterns that track the body's internal state in real-time. This level operates outside of conscious awareness, forming a foundational "landscape of the body" that underlies our sense of Self. Various brain structures, including the brainstem, insular cortex, and hypothalamus, sustain this *proto-self* (Craig, 2002; 2004; 2010). *Core consciousness* represents the second level, arising from the integration of *proto-self* information. It creates a real-time, body-centered awareness of the present, though it lacks memory or language. Damasio described this level as akin to a "minimal self," providing a first sense of Self without the need for autobiographical narratives. Finally, *extended consciousness* integrates memory, language, and the autobiographical Self, allowing for a more complex and time-encompassing sense of identity. This third layer constructs a narrative that spans past, present, and future, solving the problem of how consciousness extends beyond the immediate moment. Then, according to Damasio, the Self is fundamentally embodied: it originates in the physical body and its continuous monitoring. His concept of consciousness is intimately tied to bodily experiences, evolving from primal, biological states into higher levels of awareness. This view highlights the essential role the body plays in forming the Self and consciousness, capturing EC principles.

1.2 Ontology of Body Representation

Riva (2018) proposed an ontogenetic model of body representation, integrating Damasio' perspective on the embodied cognition framework and recent neuroscientific evidence. Riva's model (2018) provides a comprehensive framework for understanding the development of body representation through six distinct stages: the sentient body, spatial body, active body, personal body, objectified body, and social body. These stages reflect the evolving relationship between "body representation" and "body experience" throughout a person's life, beginning at birth. Together, they form a unified, supra-modal representation known as the Body Matrix, which integrates multiple sensory inputs and shapes our perception of self within space and time.

The first stage, known as the "sentient body," forms at birth and is closely related to Damasio's *proto-self*. It refers to the egocentric perception of the body, grounded in somatotopic maps. These maps, which represent sensory information such as interoception and proprioception, allow the newborn to begin developing a fundamental awareness of being in a body. These early maps, although transient, provide a non-conscious, moment-to-moment representation of the body, which is essential for managing physical changes and maintaining homeostasis. This stage reflects the most basic level of bodily experience, where infants feel and respond to sensations like pleasure, pain, and tension, yet have no concept of time or self beyond the immediate experience.

As infants grow, their body representation evolves into the "spatial body." Between birth and six months of age, the integration of sensory inputs such as vision, hearing, proprioception, and touch allows the infant to develop a spatial sense of self. This egocentric framework is vital for perceiving the body in space and interacting with the surrounding environment. The spatial body represents the first step toward developing a more complex understanding of the world, as infants begin to experience their physical presence about external objects and people.

By the second half of the first year, the "active body" emerges. At this stage, infants start to integrate motor actions with sensory information, enabling them to interact with the world more dynamically. Coordinating visual and proprioceptive information allows infants to perceive their actions as intentional, leading to the development of agency—the sense that they control their bodily movements. The active body thus represents a critical stage in the development of the core self, where bodily actions are experienced as purposeful and coordinated.

Despite these advances in bodily awareness, infants do not yet have a unified sense of owning their entire body. This integration begins between 18 and 36 months of age with the emergence of the "personal body." Through observing their own and others' actions, children gradually construct a complete body schema that includes all parts of the body, resulting in a cohesive representation of the self in space. This stage is also associated with the development of body size and shape awareness. By observing how their body fits into their environment, infants learn to navigate and understand their body's limits, enhancing their ability to interact with the world around them.

With the personal body established, the development of the autobiographical self becomes possible. This advanced stage of selfhood is closely linked with episodic memory, allowing individuals to recall past bodily experiences and anticipate future ones. Memory serves as a crucial bridge, connecting the body's experiences over time and enabling the individual to maintain a continuous sense of self. According to Riva (2018), this connection between body and memory suggests that the body is not just a series of sensory maps but a complex, evolving system that incorporates past experiences into a broader, temporal understanding of self.

The development of the "objectified body" marks a turning point in self-perception. As children grow, they begin to recognize their bodies not just from their own egocentric perspective but from the viewpoint of others. This shift in perspective is pivotal because it allows children to see themselves as others do, realizing that their bodies can be judged and evaluated. This new awareness is often distressing because it exposes the child to external scrutiny, leading to the formation of body image. The objectified body is thus not just an internal representation, but a socially constructed concept shaped by societal expectations and norms.

In this context, the integration of the objectified body with societal ideals gives rise to body image, a construct that governs how individuals perceive, evaluate, and feel about their bodies. As children grow older, their body image becomes more complex and influenced by cultural standards. Social comparison, media influence, and peer interactions all play a role in shaping body image, which in turn affects self-esteem and body satisfaction. This dynamic is particularly evident in the modern world, where social norms and media often emphasize idealized body types, leading some individuals to alter their appearance, for example, through plastic surgery, to align with societal expectations.

The final stage in this developmental process is the formation of the "social body," which encapsulates the individual's body in relation to others. This stage highlights the interpersonal nature of body representation, where individuals not only develop their body image but also internalize how others view and react to their bodies. The social body is intertwined with the concept of identity, as individuals learn to navigate their place in society through their body image and how others perceive their appearance (*Figure 1*).

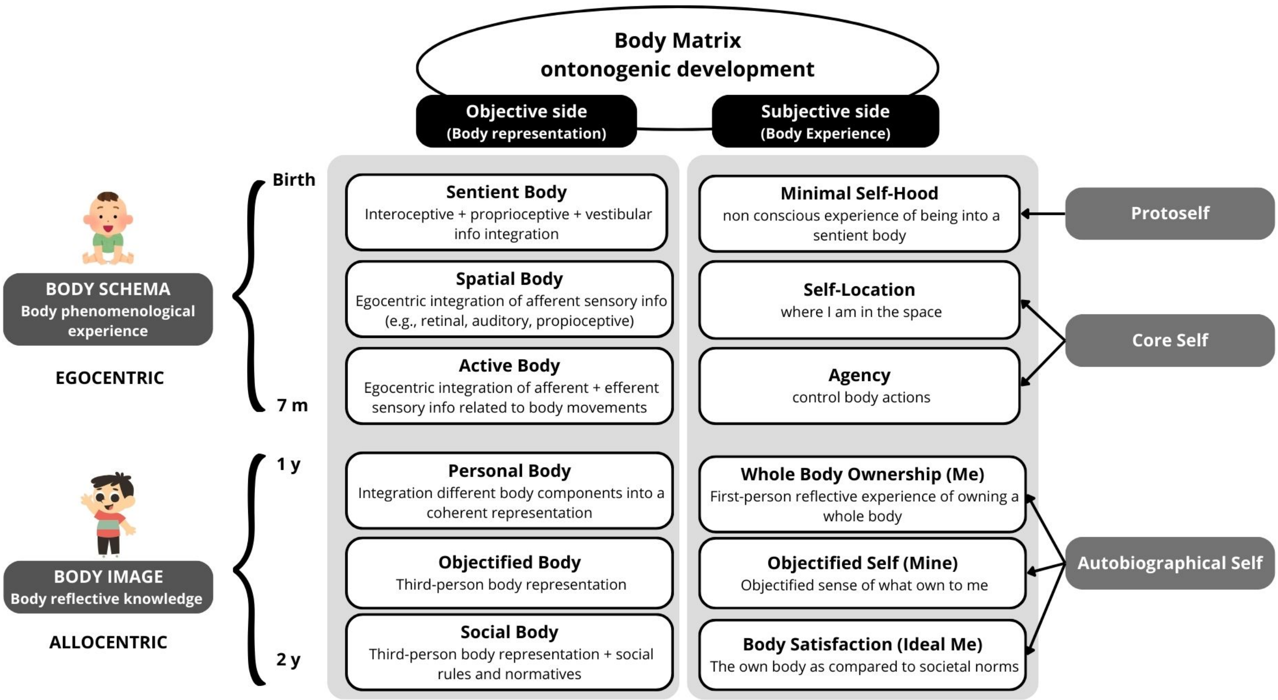

Figure 1. Ontogenetic body representation development. Adaptation from Riva (2018).

All these body representations - sentient, spatial, active, personal, objectified, and social - are not isolated but are integrated into a cohesive whole called the "Body Matrix." This is described as a "supramodal multisensory representation" (Riva, 2018) and serves to unify the various sensory inputs related to the body, enabling individuals to maintain a coherent sense of self in space and time. By defining the body's boundaries and the space around it, the Body Matrix also delineates where the self is situated, underscoring the interconnectedness between bodily perception and the sense of self.

Notably, the body matrix is not a static construct but an emergent property of complex multisensory integration, reflecting the continuous interaction between the body, brain, and environment. This integrated system helps individuals achieve a functional balance within their bodily experiences, ensuring a coherent sense of self that is grounded in the body's physical boundaries and sensory inputs.

1.3 The body: the most multisensory object of perception

In the previous section, we discussed how our bodily experience is shaped by integrating information from different sensory domains, spatial frames, and cultural information, through a process defined as Multisensory Integration (MSI; Brizzi et al., 2023). This is why the body is also referred to as "the most multisensory object of perception" (Blanke, 2012).

The unique specificity of the body is that it requires the combination of sensory modalities from both inside (e.g., visceral and proprioceptive information) and outside the body (e.g., visual, tactile information) as well as from egocentric and allocentric spatial frames (Brizzi et al., 2023). Neuroimaging research showed that such integration relies on different cortical areas, including the premotor, temporoparietal, posterior parietal, and extrastriate brain areas (Byrne et al., 2007).

The optimal integration of all these pieces of the puzzle indeed allows obtaining what we defined as a supra-modal and coherent representation of the body and space around it (i.e., perispersonal space) called "Body Matrix".

Recent computational models propose an effective way to explain such a complex procedure. Specifically, they suggest that the Body Matrix stems from a maximum-likelihood estimation process - also called prediction error minimization or free energy principle – in which (dis)agreement between expected sensory information and the actual sensory inputs based on various somatic and cognitive body representations (Talsma, 2015).

According to the Predictive Coding theory (PP; Clark, 2024; 2015), the Body Matrix maintains a mental model of the body and its surrounding space by generating sensory predictions and working to reduce unexpected discrepancies between the actual input and the expected one (i.e., prediction error). This dynamic process implies that the Body Matrix adapts to new sensory information (perceptual inference and learning), while actions are taken to confirm the predictions generated by the matrix based on one's intentions (Friston, 2010). What is interesting about this framework is that top-down predictive signals indeed shape the Body Matrix's contents and are constantly updated by bottom-up prediction errors (Brizzi et al., 2023).

Even if we will go into more detail about this process in the next chapters, let's try to understand how this multisensory predictive process works with an example. Let's consider the Rubber Hand Illusion (RHI; Botvinick & Cohen, 1998). During the RHI, the perception that a rubber hand belongs to one's body (sense of ownership) is created by synchronously stroking the visible rubber hand and the participant's real hidden hand. That is, there is a mismatch – prediction error - between the predicted information (real hand) and the actual sensory information (rubber hand), and we try to solve such error by altering the Body Matrix content by integrating the rubber hand into our body representation (Clark, 2018). Notably, the same process also applies to higher-level body representations, such as when illusions of owning a body of a different race led to changes in low-level body representations, which subsequently influence higher-level processes like attitudes and beliefs about one's own body (Peck, Seinfeld, Aglioti, & Slater, 2013).

Within this probabilistic framework, our experience of the body might diverge from its true physical characteristics: rather than directly reflecting the physical form, we perceive a version of the body shaped by likelihood—what the brain deems "the most probable" based on sensory inputs and prior expectations. That is, body perception is not a direct representation of physical reality, but rather the brain's "best guess" at what is most probable given the available information. If follows that the experience of our bodies is a subjective body that may only loosely resemble the actual physical properties.

This can lead to fascinating discrepancies between our subjective experience and objective reality. For instance, phantom limb sensations in amputees illustrate how the brain's expectations can override physical absence. Similarly, body dysmorphic disorders demonstrate how distorted prior beliefs can dramatically alter one's bodily self-image, despite contradictory sensory evidence.

Understanding the body as a probabilistic construct also has important implications for fields like medicine and psychology: it suggests that interventions targeting the brain's predictive models might be as effective in altering body perception as those focused on physical changes.

In conclusion, our subjective experience of embodiment is not a direct reflection of our physical form, but a complex, malleable construct shaped by the brain's ongoing attempts to predict and make sense of sensory inputs. This "most probable body" that we experience may only loosely resemble our actual physical characteristics, highlighting the profound influence of cognitive processes on our fundamental sense of self.

1.4 Conclusions

This chapter explains what we mean when we talk about the body as both subject and object of perception, highlighting its unique position in human experience. Through the lens of embodied cognition and the ontogenetic model of body representation, the discussion has traced how our bodily awareness develops from basic sensory experiences to complex social constructs. Then, the concept of Body Matrix was introduced as the most likely body prediction that integrates top-down and bottom-up information. Understanding body perception as a probabilistic process, rather than a direct reflection of physical reality, provides a theoretical foundation for investigating how this system might be disrupted in conditions characterized by altered body-self experience, like Eating Disorders.

2. Eating Disorders

Imagine yourself standing in front of one of those distorting mirrors at the amusement park, where the reflection you see does not correspond to your real image. For many people, this feeling goes beyond the fun of a moment: it becomes a constant in their daily lives. I will consider Eating Disorders as a prototypical example of conditions in which the subjective experience of the body is in some way altered. Indeed, Eating Disorders are more than food-related behaviors: they are complex conditions that profoundly alter bodily experience and self-perception, negatively impacting both the body and the mind (Riva & Gaudio, 2018).

In this project, I will focus on Anorexia and Bulimia Nervosa, as a large amount of research consistently showed that patients affected by these conditions are generally unable to correctly perceive their bodies (for instance, they are unable to estimate their real body size and the space occupied by their bodies, with a tendency to overestimate their dimensions; Riva & Gaudio, 2012). Notably, this incongruity between the experienced and objective body seems to contribute to the symptomatology onset and maintenance, reinforcing dangerous eating behaviors and weight control practices. That is, how patients experience their bodies plays a key role in shaping the course. Understanding how Eating Disorders turn the subjective body experience into a mental prison is essential to decipher the mechanisms that fuel these pathologies and to begin a healing process that leads to reconciliation with one's bodily self (Riva & Gaudio, 2018).

In this chapter, I will present the link between Eating Disorders and body experience. I will present what Anorexia and Bulimia Nervosa are, their features, and the role of the body in these conditions. Following this, I will present a systematic review of the literature investigating whether MSI processes underlying body experience are disrupted in these disorders. Finally, I will propose a Machine Learning approach to identify the key factors contributing to the discourse surrounding these pathologies.

2.1 What are Eating Disorders

Eating Disorders (ED) represent significant mental health challenges. They are a group of psychiatric conditions characterized by abnormal eating behaviours and a distorted relationship with food and body image (American Psychiatric Association, 2013). They include conditions such as Anorexia Nervosa, Bulimia Nervosa, and Binge-Eating Disorder, each presenting distinct clinical features.

The aetiology of EDs is multifactorial, involving genetic, psychological, social, and environmental factors. Research has shown that genetic predispositions may interact with environmental triggers, such as cultural pressures to maintain thinness, leading to the onset of these disorders (Dakanalis et al., 2016). Psychological factors, including perfectionism, low self-esteem, and difficulties with emotional regulation, are also significant contributors (Dakanalis et al., 2016). Additionally, neurobiological studies suggest that altered brain circuits, particularly those involving reward and emotion processing, may play a crucial role in the development and maintenance of EDs (Dakanalis et al., 2016). This multifactorial nature is the reason that makes these conditions extremely complex to fully understand.

Among the most common eating disorders are Anorexia Nervosa and Bulimia Nervosa, both of which involve an overwhelming fear of weight gain and an excessive preoccupation with the own body, though they manifest through distinct behaviours (Yamamotova et al., 2017).

Anorexia Nervosa

Anorexia Nervosa (AN) is a severe psychiatric disorder characterized by extreme food restriction, an intense fear of weight gain, and a distorted body image. Individuals with AN exhibit a persistent desire to maintain a body weight significantly below what is considered healthy for their age and height, often engaging in excessive exercise, restrictive eating, and other weight control behaviours (American Psychiatric Association, 2013; 2022).

One of the defining features of AN is a distorted perception of the body across multiple levels. Indeed, a large body of research showed that patients tend to see themselves as overweight, even when they are dangerously underweight (perceptual level), report high levels of body dissatisfaction (emotional and affective level) as well as dysfunctional cognitions related to the body (e.g., impossible thin ideals – cognitive level; Brizzi et al., 2023). Notably, this altered "body experience" is central to the disorder, as it influences symptomatology onset, maintenance, and relapse (Brizzi et al., 2023). The body indeed becomes a focal point of self-worth and identity, with individuals often equating thinness with success, control, and attractiveness.

Bulimia Nervosa

Bulimia Nervosa (BN) is characterized by recurrent episodes of binge eating, followed by compensatory behaviors such as self-induced vomiting, misuse of laxatives, or excessive exercise; individuals with BN experience a sense of loss of control during binge episodes, consuming large quantities of food in a short period of time, often followed by feelings of guilt and shame (American Psychiatric Association, 2013; 2022). Unlike AN, individuals with BN are typically within or above the normal weight range, but their relationship with their bodies remains deeply problematic (Yamamotova et al., 2017).

The role of the body in BN is centered around body dissatisfaction and the drive to avoid weight gain, which motivates the cycle of bingeing and purging (Brizzi et al., 2023). People with BN often have a distorted or exaggerated concern with body shape and weight, like those with AN, but with different behavioral manifestations. The binge-purge cycle reflects a struggle with body image, where binge eating serves to cope with emotional distress and purging acts as an attempt to mitigate the feared consequences of weight gain.

Like AN, individuals with BN also exhibit disturbances in body perception and experience. Research has shown that those with BN tend to overestimate their body size and feel disconnected from their physical appearance. This dysregulation in body perception, combined with emotional dysregulation, plays a significant role in the disorder, perpetuating the unhealthy relationship with food and body weight (*Figure 2*).

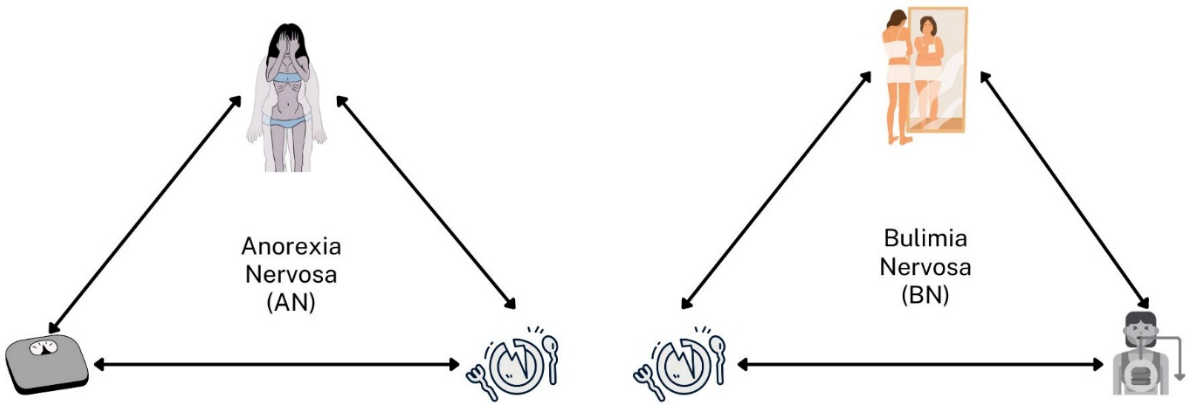

Figure 2. Anorexia and Bulimia Nervosa core features.

2.2 The Body in Eating Disorders

When we look in the mirror, we expect to see a reflection of ourselves—a snapshot of who we are in that moment. For most people, that reflection is at least somewhat accurate, though we might wish for better lighting or a magic filter. But for individuals with Eating Disorders, that mirror becomes more like a funhouse distortion, and not the amusing kind. The body they see doesn't always match the reality, leading to a complex and often painful relationship with their physical form (Riva, 2018).

Body experience—the way we perceive, interpret, and interact with our bodies—is at the heart of this struggle. While most of us occasionally question whether our pants shrank in the wash, people affected by Eating Disorders experience something far more profound: a disconnect between how their body feels and how it's perceived (Brizzi et al., 2023). It's as if their brain is sending mixed signals, and the body becomes an unsolvable puzzle. Imagine putting together a jigsaw puzzle where the pieces constantly change shape—that's what living with body image distortion can feel like.

Understanding this mismatch is key to understanding eating disorders themselves. It's not just about food; it's about the mind's stubborn refusal to acknowledge the body's true form. And while society's impossible beauty standards don't help (looking at you, Instagram filters), the issue runs deeper, rooted in the brain's multisensory integration—how we blend what we see, feel, and sense internally to create our overall body image.

2.2.1 The multisensory mind: a systematic review of multisensory integration processing in Anorexia and Bulimia Nervosa [1]

Introduction

Eating disorders (EDs) are mental illnesses characterized by abnormal eating behaviors and distorted thoughts about food, weight, and body shape. The National Institute of Mental Health in 2021 estimates that approximately 9% of the population experiences EDs, highlighting these pathologies may deserve special attention. In particular, the number of diagnoses of Anorexia Nervosa and Bulimia Nervosa has increased dramatically in recent years (Linardon et al., 2022), taking on the characteristics of a mental health emergency. Indeed, these conditions are associated with serious consequences for the well-being of the individual (van Hoeken D et al., 2020), and high mortality rates (van Eeden AE et al., 2021).

According to the Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-5; American Psychiatric Association, 2013), Anorexia Nervosa (AN) is characterized by a significant reduction in food intake, resulting in extremely low body weight and an overwhelming fear of becoming fat. Specifically, individuals affected by AN experience distorted perceptions of their body image and weight, which is closely associated with the adoption and maintenance of pathological behaviors such as severe food restriction and/or bingeing in an attempt to control body weight. Similarly, individuals affected by Bulimia Nervosa (BN) manifest body representation disturbances, in addition to altered eating behaviors characterized by recurrent binge eating episodes followed by compensatory strategies (e.g., laxative abuse, self-induced vomiting, or fasting) to regulate body weight (Anitha et al., 2019). Then, despite substantial differences, Anorexia Nervosa and Bulimia Nervosa symptomatology present similarities in the way patients experience their bodies (Yamamotova et al., 2017).

[1] This article has been published - Brizzi, G., Sansoni, M., Di Lernia, D., Frisone, F., Tuena, C., & Riva, G. (2023). The multisensory mind: a systematic review of multisensory integration processing in Anorexia and Bulimia Nervosa. Journal of Eating Disorders, 11(1), 204.

Our team's findings from two 4-years longitudinal studies, one with 2713 female college students (Dakanalis et al., 2017) and the other with 2507 male college students (Dakanalis et al., 2016) support the critical role of the body in the development of Eating Disorder symptomatology. In both groups, the onset and persistence of DSM-5 EDs at the 4-years follow-up were predicted by self-objectification, body dissatisfaction, internalization of the appearance ideal, dieting, and negative affectivity at baseline, as well as changes in these factors. Although all of these vulnerability factors are known to play a key role in the development and maintenance of EDs (see, for example, Calogero et al., 2010; Culbert et al., 2015), these studies revealed that different factors have distinct predictive values. First, body dissatisfaction and internalization of appearance ideals explain almost twice as much variance in the onset of symptoms as dieting and negative emotions. In addition, self-objectification, which is the tendency to adopt a third-person perspective on the self—i.e., to see one's body from the perspective of an outsider as an object to be viewed and evaluated based on its appearance (Rollero & De Piccoli, 2017)—explained almost four times more variance of EDs symptoms than dieting and over four times more than negative affects.

Particularly, when individuals objectify themselves, they tend to internalize an objectified self-image by using an allocentric frame of reference (observer mode) to recall events in which they judge themselves mainly based on how they look (Riva, Gaudio, & Dakanalis, 2015). Many studies supported the critical role of self-objectification in weight and eating disorders, stressing how it directly links the experience of the body to an individual's identity and values.

Thus, data from clinical practice and research agree that the body plays an important role in the development of Eating Disorders. As a result, a deeper understanding of body experience is necessary to fully understand how to appropriately support patients with EDs.

The Body in Eating Disorders

Body experience is a multidimensional construct that includes feelings, cognitions, and perceptions about one's body (Gaudio & Quattrocchi, 2012; Riva, 2018). The attitudinal component refers to experienced feelings about one's body appearance, the cognitive component consists of beliefs and attitudes about one's body, while the perceptual component refers to subjective expectations about one's body (e.g., recognizing, estimating, and identifying the own body size and shape; Gaudio et al., 2014). Research has consistently shown that patients with AN and BN are characterized by body alterations at all of these levels (Gaudio et al., 2014; Cash & Brown, 1987).

Several reviews and meta-analyses have highlighted abnormalities in the way individuals affected by AN and BN experience their bodies from both a behavioral and neural perspective, emphasizing changes in affective and cognitive components (e.g., high levels of body dissatisfaction and body concerns; (Cash & Deagle, 1997; Sepúveda, Botella & Leon, 2002). The presence of perceptual deficits instead remains still an open debate. A large body of research has shown that people with AN and BN tend to misperceive their body size (e.g., they overestimate their body dimensions (Brown, Shott & Frank, 2021; Mohr et al., 2016). Several studies investigated possible mechanisms involved in determining this phenomenon. Most studies have examined visual impairments (e.g., abnormal visual adaptation or visual scanning) as a possible explanation for the misperception, but they yielded inconsistent results (Mohr et al., 2016). These discrepancies may be related to the impossibility of reducing a complex phenomenon such as bodily experience to the purely visual domain (Malighetti et al., 2022). Indeed, the body is considered one of the most complex perceptual objects (Salomon et al., 2017; Stein et al., 2009). To fully understand this statement, it is necessary to understand where bodily perception comes from and what its underlying mechanisms are.

The Body and Multisensory Integration

The body is a special perceptual object compared to others because it requires the processing and merging of information coming from both outside and inside the body itself, namely exteroceptive (e.g., visual, somatosensory, auditory signals relayed from the outside world by sense organs), interoceptive (e.g., visceral and vestibular signals originating from sensory nerve endings), and proprioceptive (e.g., the sense of body position originating from muscles and joints) signals respectively (Riva, 2018).

In this view, our experience of the body results from the combination of a continuous stream of different information from the body to the brain, in a process defined as Multisensory Integration (MSI; (Salomon et al., 2017)). Going into detail, MSI refers to a sophisticated mechanism by which inputs from two or more senses (e.g., visual, tactile, auditory) are combined to enhance each other, resulting in a final product that cannot be directly disassembled to recover the components from which it was formed (Stein, Stanford, Rowland, 2009; Stein, Stanford, Rowland, 2014). To successfully merge signals, the brain must identify which of them contains related information—i.e., solve the correspondence problem—integrate this information, and dynamically resolve spatial or temporal conflicts that may arise between sensory modalities (Parise & Ernst, 2014).

In particular, for this combination to occur, the signals must be mapped to a common spatial frame. However, unimodal sensory areas have the disadvantage of encoding spatial positions differently in each modality, which poses a challenge when considering how multisensory representations are generated (Avillac et al., 2004). The term "spatial frames" refers to the reference frame from which a sensory signal is derived: specifically, it is possible to distinguish between egocentric (i.e., first-person perspective) and allocentric (i.e., third-person perspective) frames (Ehrsson, 2012). Avillac et al. (2004) suggested that unimodal reference frames are not remapped into a common reference frame, but rather adapt to the dominant modality: that is, signals from different sensory domains are aligned to the reference frame of the leading sense modality.

Putting all of these steps together, how we experience our bodies results from the integration of sensory information from both different modalities and from the allocentric and egocentric spatial frames into a single and coherent percept (*Figure 3*). The result of this process is a supramodal body representation called "Body Matrix" (Riva, 2018). In other words, we can conceptualize bodily experience as a jigsaw puzzle, where different elements are put together through a computational process so that the final perceptions appear seamless.

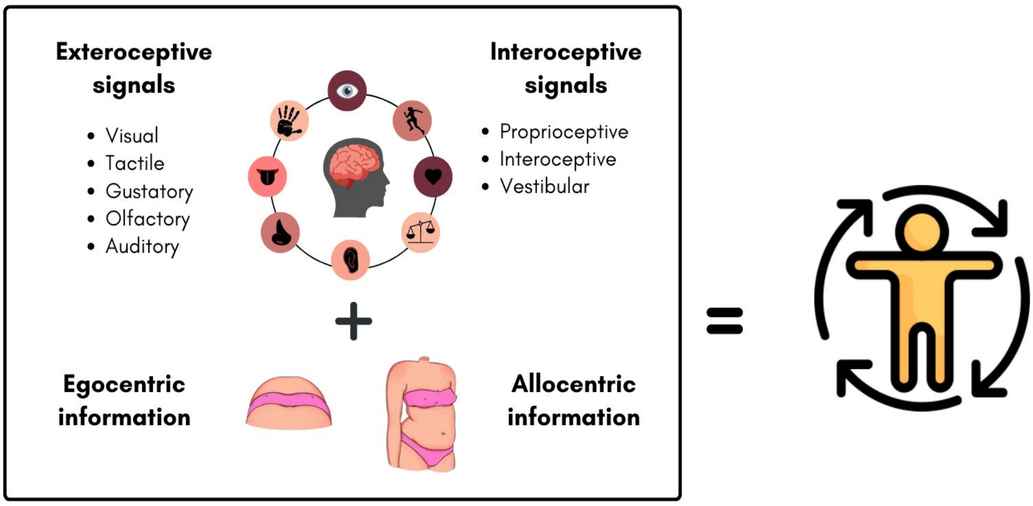

Figure 3. Multisensory Integration Processing in its two main components. The upper panel on the left shows different sensory modalities, including exteroceptive information and inner body signals (i.e., proprioceptive, vestibular, and interoceptive); the bottom panel on the left shows an example of information from egocentric and allocentric spatial frames; in the example, we refer to visual information from first and third-person perspectives. Panel on the right shows the output of the coherent integration of all this information, namely the Body Matrix.

Neurological and neuropsychological studies have revealed the crossmodal and fragmentary nature of bodily experience not only in neurological conditions (e.g., spatial neglect, phantom limb) but also in healthy individuals thanks to experimental manipulations exploiting multisensory conflicts (Blanke et al., 2022). A classic example is the Rubber Hand Illusion (RHI; Botvinick & Cohen, 1998), in which the spatially and temporally synchronous occurrence of multimodal visual-tactile stimulation applied over rubber and the real hands of participants leads individuals to experience a fake hand as their real hand, thus altering their bodily experience. Following the same principles, advanced multisensory technologies—such as Virtual Reality (VR)—have been used to create cross-modal conflicts (e.g., visual and tactile conflicts) that induce individuals to embody a full virtual body (Full Body Illusion - FBI; Petkova & Ehrsson, 2008). Paradigms such as the RHI and FBI are examples of the critical role of MSI in shaping and determining how we make experience of our bodies.

The Body, Multisensory Integration, and Eating Disorders

How people experience their bodies plays a key role in the development and maintenance of Anorexia Nervosa and Bulimia Nervosa, and research revealed that body experience is the result of a multisensory integration process. Therefore, a possible relationship between EDs and multisensory integration abilities was hypothesized. Specifically, it has been proposed that impairments in multimodal integration abilities may contribute to altered body experience (e.g., Gaudio, Brooks & Riva, 2014; Keizer et al., 2014). A growing body of research from the fields of cognitive science, neuroscience, and neuropsychology appears to support this hypothesis. Preliminary studies have shown that patients with AN and BN show abnormalities in the integration of stimuli from different sensory modalities (e.g., audio-visual integration deficits during the Sound-Induced Flash Illusion; Chirico et al., 2019), and revealed cortical abnormalities in brain regions hypothesized to be involved in cross-modal integration (e.g., frontal and parietal regions; Gaudio et al., 2016).

Rephrasing altered body experience in these terms, symptoms related to body misperception might reflect a deeper deficit of multisensory integration abilities rather than a malfunction of a single sensory modality (i.e., the overestimation of one's weight would not result from a mere visual deficit, but from the inability to combine crossmodal information necessary for the construction of one's body representation; Riva & Dakanalis, 2018; Riva & Gaudio, 2018).

Reading Eating Disorders through crossmodal integration concept could provide an important building block for achieving a better understanding of these conditions. This is crucial in light of the increasing number of AN and BN diagnoses and the limited effectiveness of current interventions (e.g., cognitive behavioral therapy, and family-based treatment; Berg et al., 2019). Such approaches mostly focus on the cognitive, behavioral, and interpersonal functioning of patients, leaving the bodily experience in the background. They are motivated by the idea that working on higher-level (top-down) processes may have indirect benefits on the way patients experience their bodies. However, this approach may be necessary but not sufficient: given the key role of the body, it may also be useful to understand and work from a perceptual (bottom-up) perspective.

Thus, the study of the multisensory integration process could provide important insights into the development of intervention protocols that can work from both a rational (top-down) and intuitive (bottom-up) perspective and address different aspects of patient functioning. This follows Bruch's (1962) suggestion, according to which relevant improvements in Eating Disorder pathologies are likely to be temporary remissions without addressing how patients experience their bodies.

Despite evidence suggesting that multisensory integration may play a critical role in AN and BN (Malighetti et al., 2022), to our knowledge no study has reviewed the empirical evidence on this topic. Therefore, the present systematic review aimed to investigate MSI in individuals with AN and BN to see whether these conditions are characterized by alterations in this process. Thus, we reviewed studies that assessed the behavioral dimension of MSI or its neurobiological underpinnings to obtain a complete picture of the phenomenon. We argue that this review process could support the analysis of possible gaps within this literature as well as suggest possible areas of investigation for further research to deepen understanding of EDs.

Methods

Protocol and registration

A systematic review of scientific literature was performed to identify studies assessing MSI in individuals with AN and BN. The present review was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Page et al., 2021) and it was pre-registered in the PROSPERO register (CRD42022383008).

Search strategy

Data sources were collected on December 12, 2022, through a computerized search of three prominent databases: PubMed, PsycINFO, and Web Of Science. Each was searched independently using a specific search string consisting of terms with different variations and truncations indicating the population and outcome of interest. The string below was used to filter the titles, abstracts, and keywords of the articles:

anorexia OR *bulimia* OR "*eating disorder**" AND

multisensory OR "*sensory integration*" OR *multimodal* OR *allocentric* OR *egocentric* OR "*frame of reference*" OR “*touch*” OR “*proprioception*” OR “*visuo-tactile*” OR “*auditory*”

Multisensory and frame-of-reference-related terms were used with the OR operator according to Avillac's conceptualization of multisensory integration (Avillact et al., 2004), while sensory modality terms were selected according to Stein et al. (2009) definition of MSI. We also used terms referring to single sensory modalities to broaden the search, although we included “visuo-tactile” instead of “visual” because much research outside the area of interest has been conducted to assess unimodal visual abilities in EDs. We did not a priori define a specific starting year of publication for the articles to be included. Details of each search result are provided in *Table 1* to allow for future replication of the study. The complete list from each database was imported into Rayyan (Ouzzani et al., 2016) to detect duplicates.

Anorexia AND	*PubMed*	*WebOfScience*	*PsycINFO*
multisensory	21	20	19
"sensory integration"	2	2	14
multimodal	135	141	118
allocentric	9	9	12
egocentric	9	10	12
"frame of reference"	4	4	8
touch	34	81	61
proprioception	9	18	9
visuo-tactile	4	9	2
auditory	54	69	63

Bulimia AND			
multisensory	5	4	4
"sensory integration"	1	1	3
multimodal	25	36	72
allocentric	3	3	2
egocentric	4	4	4
"frame of reference"	1	1	3
touch	7	40	21
proprioception	2	4	3
visuo-tactile	0	2	0
auditory	8	20	22
Eating Disorder AND*			
multisensory	30	25	37
"sensory integration"	4	6	31
multimodal	110	108	206
allocentric	14	14	21
egocentric	17	17	23
"frame of reference"	4	4	25
touch	28	30	105
proprioception	4	7	17
visuo-tactile	1	5	4
auditory	36	33	115
Sub Total	585	727	1036
Total			**2348**
Duplicates removal			1437
Identified studies for screening			**911**
Included studies			**13**

Table 1. Description of search strategy; the number of studies for each string in the included database, the total number of studies before and after duplicate removal, and the final studies included in the review are reported.

Eligibility criteria

We screened titles, abstracts, and full texts of the 911 individualized studies for inclusion criteria after eliminating duplicates. Specifically, we included studies that:

- Were available in English;
- Included were samples of adolescents and/or adults with a diagnosis of AN or BN based on the DSM—specifically the Fourth (DSM IV and DSM-IV-TR) and Fifth (DSM-5) editions—or the International Statistical Classification of Diseases and Related Health Problems, Tenth

Edition (ICD-10), as these are the most recent and widely used diagnostic tools. Thus, studies using other diagnostic manuals or earlier editions of the DSM or ICD were excluded; we also excluded studies that included AN and BN patients in the same group (patients with AN and BN were grouped, referred to as the "ED group") or that did not separate the two conditions in the data analysis. We did not consider the presence of possible confounding factors (i.e., comorbidities) as an exclusion criterion because of the limited number of studies in this area. In addition, studies that focused on non-clinical or subclinical populations (e.g., individuals with disordered eating), as well as other clinical conditions outside of those of interest (e.g., obesity, binge eating disorder) were excluded; studies involving animals were also not included. Notably, we chose to focus on AN and BN because of their similarities in terms of how patients experience their bodies, and in light of evidence reporting diagnostic crossover between these two conditions (Tozzi et al., 2005);

- Included a control group of healthy participants (HCs), a group of individuals without a diagnosis of EDs or any other pathological condition; when studies included participants with Anorexia Nervosa, we included only those studies in which the average body mass index (BMI) in the healthy control group was higher than that of the clinical group;
- Assessed MSI by using behavioral tasks (e.g., Rubber Hand Illusion) or neuroimaging techniques (e.g., functional magnetic resonance imaging);
- Conceptualized MSI according to the definitions of Stein et al. (2009) and Avillac et al. (2004; 2005). As a consequence, we included behavioral studies that: used MSI paradigms in which at least two different sensory modalities were stimulated at the same time (e.g., aperture task, size-weight illusion, sound-induced flash illusion), used multisensory technologies (e.g., Virtual Reality) to stimulate multiple sensory modalities at a time, or/and manipulated the spatial frame of reference (i.e., allocentric and egocentric; e.g., Guardia et al., 2012) in which the task is proposed. Regarding neuroscience studies, we included studies that analyze MSI

brain correlates in the populations of interest during multisensory tasks. Accordingly, studies investigating one sensory modality at a time and studies using resting-state neuroimaging techniques were not included. Additionally, studies investigating only bodiless imagery tasks (e.g., motor imagery task; Purcell et al., 2018) were not included;

- Were research studies evaluating MSI skills in individuals with AN and/or BN. Thus, other types of publications—such as editorials, book chapters, conference proceedings, reviews, and meta-analyses—were excluded; only peer-reviewed original articles were included;
- Were either quantitative behavioral studies or neuroscience research. Then, qualitative studies were not included.

Results

Of 2348 studies retrieved from PubMed, Web Of Science, and PsycINFO databases, 911 were unique articles. We screened the titles, abstracts, and full texts of these studies, ultimately including 13 articles in this review. The remaining studies were excluded because they did not meet the inclusion criteria. The most common reasons for rejection were: (a) studies did not include the population of interest (e.g., obese patients, non-clinical conditions, diagnosis not based on the specified diagnostic manuals), (b) they used multisensory paradigms and tasks to modify eating disorder symptoms or as a treatment, (c) they did not include a control condition (Tajadura-Jiménez et al., 2022), (d) they were other types of publications (e.g., editorials, reviews, meta-analyses, book chapters, and (e) they did not assess multisensory integration abilities as conceptualized here (e.g., they used neuroimaging techniques without multisensory tasks; e.g., Mohr et al., 2011). Further details of the study selection process are provided in the PRISMA flowchart (*Figure 4*).

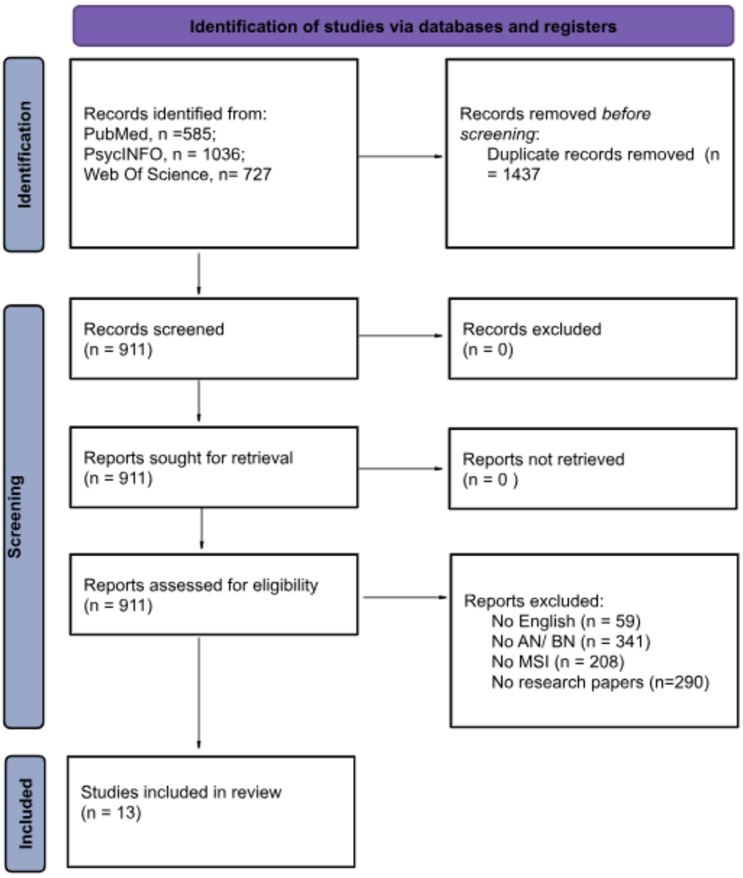

Figure 4. PRISMA flowchart. Flowchart presenting the extraction and selection process to reach the final number of included studies.

Quality assessment

Two reviewers (G.B., M.S.) separately assessed the risk of bias according to the checklist for assessing methodological quality proposed by Downs and Black (1998). This tool allows the evaluation of the methodological quality of both randomized and nonrandomized comparative studies across relevant parameters: specifically, reporting strategy, external and internal validity as well as power. Examples of items are "Are the characteristics of the patients included in the study clearly described?", "Were the subjects asked to participate in the study representative of the entire population from which they were recruited?", and "Was an attempt made to blind those measuring the main outcomes of the intervention?" (Downs & Black, 1998). Disagreements and/or ambiguities were resolved by consensus. The results of the risk of bias assessment are presented in *Table 2*. All included studies were considered to be fair or good in terms of bias according to the scoring criteria.

Item from the Downs and Black checklist	*Beckmann et al., 2021*	*Case et al., 2012*	*Chirico et al., 2019*	*Eshkevari et al., 2012*	*Keizer et al., 2016*	*Keizer et al., 2019*	*Guardia et al., 2010*	*Guardia et al., 2012*	*Guardia et al., 2013*	*Metral et al., 2014*	*Provenzano et al., 2019*	*Risso et al., 2020*	*Zopf et al., 2016*
Item 1	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 2	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 3	1	0	0	1	1	1	1	1	1	1	0	1	1
Item 4	1	0	1	1	1	1	1	1	1	1	1	0	1
Item 5	1	0	0	1	1	1	1	1	1	1	0	1	0
Item 6	1	0	1	1	1	1	1	1	1	1	1	0	1
Item 7	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 8	0	1	0	0	0	1	0	0	1	0	0	0	0
Item 9	0	1	1	1	0	1	1	1	1	0	0	0	0
Item 10	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 11	1	1	1	1	1	0	1	1	1	1	1	1	1
Item 12	1	1	1	1	1	0	1	1	1	1	1	1	1
Item 13	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 14	0	0	0	0	0	1	0	0	0	0	0	0	0
Item 15	0	0	0	0	0	0	0	0	0	0	0	0	0
Item 16	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 17	0	0	0	0	0	1	0	0	0	0	0	0	0
Item 18	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 19	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 20	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 21	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 22	1	1	1	1	1	1	1	1	1	1	1	1	1
Item 23	0	0	0	0	0	1	0	0	0	0	0	0	0
Item 24	0	0	0	0	0	1	0	0	0	0	0	0	0
Item 25	1	0	0	0	1	1	1	1	1	1	0	0	1
Item 26	0	1	1	1	1	1	1	1	1	1	1	1	1
Item 27	1	0	0	0	0	1	0	0	0	0	0	0	0
TOTAL SCORE	**19**	**16**	**17**	**19**	**19**	**24**	**20**	**20**	**21**	**19**	**16**	**16**	**18**

Table 2. Risk of bias assessment was performed following Downs and Black (48) assessment tool for items. Please confront the original tool for items explanation; note: 0 = No/Unable to determine, 1 = Yes. Only question 5 could be answered 0 = No, 1 = Partially, 2 = Yes, Cut-off total score: 24–28 points (excellent), 19–23 points (good; green color), 14–18 points (fair; orange color), 14 points or less (poor; yellow color).

Classification criteria

As introduced earlier, how we perceive our body results from the integration of information from different sensory modalities and spatial reference frames (i.e., multisensory integration).

Among the different sensory domains, we can distinguish between exteroceptive modalities—which include visual and tactile information- and interoceptive modalities—which include interoceptive, proprioceptive, and vestibular information. Some modalities -such as haptic information- are hybrid since they require co-participation of information from both the external environment and within the body.

Based on this distinction, we classified the studies according to the sensory modalities stimulated by the tasks used (Berlucchi & Aglioti, 2010). Based on previous research (Gaudio, Brooks & Riva, 2014) tactile input was considered present when the task involved a stimulus that touched the participants' skin. We distinguished it from haptic input, which instead refers to conditions where the task requires active haptic exploration of things (e.g., touching/grasping an object; Case & Wilson, 2012). We considered proprioceptive input to be present when the task required judgments about body parts and/or overall body posture, and vestibular ones where tasks required moving and/or maintaining specific body orientation (Warren & Whang, 1987). Interoceptive input was considered to be present when the task tested sensitivity to visceral activity (Gaudio, Brooks & Riva, 2014). Finally, visual input was considered to be present if the task required viewing the body-related stimuli (i.e., the whole body and/or specific body parts, virtual bodies) or if the task involved visual stimuli to which participants had to respond. The frame of reference was classified according to the spatial perspective in which the tasks were presented (i.e., first- and/or third-person perspective).

Regarding the different spatial frames, we reported studies that went on to manipulate the spatial perspective in which the specific task was presented. In particular, this criterion fits well with tasks such as body illusions, as they can be presented from an egocentric (first-person) or/and allocentric (third-person) perspective.

Data extraction

In the following sections, study characteristics and main results are presented to address the research question, namely the investigation of MSI abilities in individuals with AN and BN. As we did not find any neuroimaging studies that met our inclusion criteria, only behavioral studies will be presented. Detailed study characteristics, including relevant sample characteristics—such as age, body mass index (BMI), disease duration, gender, and diagnosis—sensory modalities involved, paradigms, techniques used to assess MSI, and main results for each study are summarized in *Table 3*. The spatial frame of reference was specified in the paradigms section where applicable. In addition, the interpretation of the main results according to the authors of the studies is also presented.

Study	Sensory modalities involved	Paradigms and measures	Main Outcomes	Main outcomes interpretation	Sample features (diagnosis, subtype, size, mean age, mean BMI, mean illness duration, and relative SD/ SE)	Gender
Provenzano et al. (2021)	Visual-Tactile-Proprioceptive	Full Body Illusion in Virtual Reality from egocentric (1st person) perspective) Embodiment measures: Embodiment questionnaire (see (54)), skin temperature Emotional Valence: Visual Analogue Scale. Avatar Selection Task in Virtual Reality from allocentric (3rd person) perspective	*Full Body Illusion in Virtual reality Embodiment measures* No significant differences between groups in embodiment measures. *Emotional Valence* Patients with AN experienced more negative emotions after being exposed to the avatar with a greater BMI as compared to the avatar with a lower BMI. The opposite pattern was instead found in the control group. *Avatar Selection Task in Virtual Reality* Individuals with AN and HCs differed in body dissatisfaction, with patients reporting overall higher levels of body dissatisfaction and a desire to have a thinner body. No differences were observed between groups in the real body estimation task; however, participants	Individuals with Anorexia might present alterations in the affective and emotional components of body experience, rather than in the perceptual one.	AN (Subtype restrictive) = 20; age (years) = 23.30 ±7.61 years; BMI (kg/m^2) = 15.87 ± 1.12; illness duration NR; diagnostic criteria DSM-5 HCs = 20; age (years) 23.85 ± 3.23; BMI (kg/m^2) = 18.98 ± 1.01	F

			in both groups tended to overestimate their body dimensions.			
Case et al. (2012)	Visual-Haptic-Proprioceptive Integration	Size Weight Illusion (Shams, Kamitani, Shimojo, 2000)	Patients with AN experienced the illusion (and the reversed size weight illusion) significantly less than controls. This is despite normal weight discrimination ability.	Individuals with AN seem to present abnormal visual-haptic-proprioceptive sensory integration abilities which might explain the reason why the visual perception of the body in a mirror does not correct the patient's distorted body representation image.	AN (Subtype NR)= 10; age (years) = 29.1±11.0 years; BMI (kg/m^2) = 17.1± 0.9; illness duration (months) = 36 (SD NR); diagnostic criteria DSM-IV-TR HCs = 10; mean age 25.8 ± 9.0 years; mean BMI 21.7±1.6 kg/m^2	F
Zopf et al. (2016)	Visual – Tactile – Proprioceptive	Rubber Hand Illusion from egocentric (1st person) perspective (Keizer et al., 2014) Embodiment measures: Embodiment questionnaire (Keizer et al., 2014; Gaudio et al., 2016) Body perception measures: Reaching task (Beckmann et al., 2021)	*Rubber Hand Illusion and Embodiment Questionnaire* Patients with AN reported significantly higher embodiment scores than controls in synchronous conditions. *Body perception measures* Differences in reaching trajectories were found between the groups; specifically, individuals with AN made more reach-to-grasp endpoint errors toward external visual information compared to controls.	Patients with AN show deficit in processing visual-proprioceptive signals compared to controls. Thus, the results seem to provide that multisensory perception of body position is abnormal in subjects with AN.	AN (Subtype NR) = 23; age (years) = 21.87, SD= 2.79; BMI (kg/m^2) = 15.82, SD = 1.27; illness duration (years) = 5.26, SD = 3.60; diagnostic criteria DSM-IV HCs = 23; age (years) = 21.48, SD = 2.35; BMI (kg/m^2) = 21.16, SD = 2.10	F

Guardia et al. (2013)	Visual-Haptic-Proprioceptive-Vestibular	Spatial orientation constancy and body orientation perception: Subjective Vertical Task and body Z– axis perception (Eshkevari et al., 2012)	Subjective Vertical Task Patients with AN showed a higher A-effect – meaning a deviation of the tactile and visual subjective verticality towards the body under tilted conditions *Body Z-axis* No differences emerged between groups concerning tactile and visual body Z-axis judgments in the upright position; differences instead emerged when tilting the body, where individuals with AN judged the body as more tilted compared to controls.	Participants with AN seem to present multisensory deficits in spatial orientation which can relate to a decrease in somatosensory information processing; such difference could be explained in terms of	AN (Subtype restrictive) = 25; age (years) = 22.24, SD = 8.59 years; BMI (kg/m^2) = 14.89, SD = 1.10; illness duration (years) = 4.57, SD = 6.52; diagnostic criteria DSM- IV-TR HCs = 25; age (years) = 22.88, SD = 3.63; BMI (kg/m^2) = 21.65, SD = 1.72	F

Risso et al. (2020)	Visual-Tactile	Multisensory Processing Assessment task (Guardia et al., 2010)	Patients with AN tended to overestimate the width of the ellipse more than HCs in the tactile modality, whereas no differences were observed in the visual condition. Participants with AN showed a higher visual and tactile discrimination threshold compared to controls. Individuals with AN accurately integrated tactile and visual information as HCs; however, differences emerged in terms of discrimination thresholds: the clinical group showed a lower bimodal threshold as compared to unimodal conditions whereas HCs showed similar thresholds across conditions.	Patients with AN might have difficulties in visual and tactile sensory processing instead of deficits in multisensory integration.	AN (Subtype restrictive) = 19; age (years) = 26.12, SD = 9.34; BMI (kg/m^2)= 15.15, SD = 2.64; illness duration NR; diagnostic criteria DSM-5 BCHC = 9; age (years) = 25.67, SD = 2.18; BMI (kg/m^2)= 20.49, SD = 1.43 HCs = 19; age (years) = 24.47, SD = 1.26; BMI (kg/m^2)= 19.86, SD = 1.94	F
Beckmann et al. (2020)	Visual-Proprioceptive-Vestibular	Aperture task from egocentric (1st person) perspective (Luyat et al., 2012)	Patients with AN reported a higher critical aperture/ shoulder ratio than HCs, meaning that patients rotate their shoulders for relatively larger door widths compared to controls.	Individuals with AN tend to rely on an incoherent body schema to plan and perform actions; specifically, they tend to unconsciously estimate their body size to be larger than in reality.	AN (Subtype restrictive) = 18; AN (Subtype binge/purge) = 5; age (years) = 24.67, SD = 5.61; BMI (kg/m^2)= 14.60, SD = 1.88; illness duration (years)= 5.81 SD = 4.83; diagnostic criteria ICD-10	F

					HCs = 21; age (years) = 24.19 , SD = 3.12; BMI (kg/m^2)= 21.95, SD = 1.30	
Chirico et al. (2019)	Auditory-visual	Sound-Induced Flash Illusion (Guardia et al., 2018)	Patients with AN were less accurate compared to HCs for each SOA and sensory modality. No significant differences were observed between groups in the visual condition for SOA from70ms to110ms; however, individuals with AN showed difficulties in visual trials with longer SOAs (i.e.,150ms, 230ms). Participants with AN were never able to detect the double sound in the auditory condition. In the visual condition, the clinical group reported a higher number of correct responses compared to the other two modalities; difficulties emerged for longer visual SOA, as well as for the bimodal condition across all SOA.	AN showed an impaired ability to integrate auditory and visual stimuli.	AN (Sybtype NR) = 9; age (years) = 30, SD = 10.46; BMI (kg/m^2) = 15.59, SD = 1.96; illness duration NR; diagnostic criteria DSM-5 HCs = 9; age (years)= 24.56, SD =1.67; BMI (kg/m^2) = 22.69, SD = 2.14	F

Eshkevcari et al. (2012)	Visual – Tactile – Proprioceptive	Rubber Hand Illusion from egocentric (1st person) perspective Embodiment measures: Embodiment Questionnaire, Proprioceptive drift. Finger localization task	*Embodiment Questionnaire* Clinical groups composed by patients with AN and BN reported higher levels of embodiment than HCs However, these differences were not significant when controlling for mood. *Proprioceptive drift* Patients with AN showed higher proprioceptive drift compared to HCs, whereas participants with BN did not differ from controls. *Finger localization task* Individuals with AN showed more biased finger location estimation compared to controls, whereas patients with BN did not differ from HCs	People with eating disorders show a plastic bodily self compared to healthy controls. This malleability may stem from alterations and deficits in processing body-related information.	AN (Sybtype restrictive) = 24; AN (Subtype binge/purge) = 12; age (years) = 23, SD = 18; BMI (kg/m^2) = 16.1, SD = 2.71; illness duration (years) = 6, SD = 11; diagnostic criteria DSM-IV-TR BN = 22; age (years) = 22.5, SD = 10; BMI (kg/m^2) = 20.9, SD = 4.28; illness duration (years) = 7, SD = 4; diagnostic criteria DSM-IV-TR ENDOS = 20; age (years) = 27.5, SD = 16; BMI (kg/m^2) = 19.7, SD = 5.54; illness duration (years) = 11.5, SD = 12; diagnostic criteria DSM-IV-TR HCs = 61; age (years) = 24.7, SD = 7; BMI (kg/m^2) = 21.5, SD = 2.80	F

Keizer et al., 2016	Visual-Tactile-Proprioceptive	Full Body Illusion in Virtual Reality from egocentric (1st person) perspective Embodiment measures: Embodiment Questionnaire Body Size Estimation Task	*Embodiment Questionnaire* No significant differences were observed between groups concerning illusion strength as reflected by Embodiment Questionnaire. *Body Size Estimation Task* Patients with AN tended to misestimate their body width and circumferences more than controls.	Participants tended to base their body size on the most recent visual information available to them. Additionally, the tendency of people with AN to overestimate their body size is not the result of a general bias to perceive their own body as larger than reality, but it is specifically limited to perceiving the body as wider and rounder.	AN (Subtype NR) = 30; age (years) = 22.03, SD = 3.67; BMI (kg/m^2) = 18.11, SD = 1.68; illness duration (months) = 110.61, SD = 11.62; diagnostic criteria DSM-IV HCs = 29; age (years) = 21.07, SD = 2.34; BMI (kg/m^2) = 20.77, SD = 1.48	F
Keizer et al., 2019	Visual-Proprioceptive-Vestibular	Hoop Task from egocentric (1st person) perspective	At the baseline, participants affected by AN tended to misestimate the smallest hoop that would allow them to fit through compared to controls.	Patients with AN seem to present a suboptimal ability to derive body size estimates from multisensory information processing of bodily information	AN (subtype NR) = 12; age (years) = 23.17, SD = 5.67; BMI (kg/m^2) = 20.11, SD = 1.17; illness duration (months) = 12.29, SD = 10.32; diagnostic criteria DSM-5 AN (subtype NR) = 14; age (years) = 22.87, SD = 2.90; BMI (kg/m^2) = 19.53, SD = 1.04; illness duration (months) = 7, SD = 3.93; diagnostic criteria DSM-5 HCs = 20 age (years) = 21.21, SD =1.44;	F

					BMI (kg/m2) = 20.80, SD = 1.61	
Metral et al., 2014	Visual-Proprioceptive-Vestibular	Aperture Task from egocentric (1st person) perspective asking both to image and pass through doorway-like apertures	Individuals with AN showed a higher passability ratio (i.e. the ratio between the critical aperture size and shoulder width) relative to HCs, both in motor imagery and real action aperture tasks.	Patients with AN show body schema alterations that influence action planning. Moreover, such alteration seems to resist correction by the sensorimotor feedback generated when performing motor tasks. These results suggest that the central nervous system in subjects affected by this condition might be locked to a false representation of the body that cannot be updated.	AN (2 subtype binge/purge, 12 rescriting) = 14 age (years) = 24.14, SD = 0.65; BMI (kg/m^2) = 14.70, SD = 1.50; illness duration (years) = 5.71, SD = 9.67; diagnostic criteria DSM-IV-R HCs = 14; age (years) = 25.21, SD = 7.77; BMI (kg/m^2) = 21.62, SD = 1.82	F
Guardia et al., 2010	Visual-Proprioceptive-Vestibular	Aperture Task from egocentric (1st person) perspective	The group composed of individuals with AN showed an abnormally higher critical aperture size to shoulder width ratio compared to controls. Additionally, this misestimation correlated with the duration of illness and the degree of body concerns.	Body size overestimation consistently observed in individuals with AN might not merely due to psychological and affective factors; specifically also perceptual processing of the body at a neural level might be impaired (i.e., alterations at the level of the parietal network)	AN (subtype NR) = 25; age (years) = 24.32, SD= 6.54 BMI (kg/m2) =15.14, SD = 1.55; illness duration (years) = 5.3, SD = 4.8; diagnostic crtieria DSM IV HCs = 25; age (years) = 23.04, SD= 5.98; BMI (kg/m2) = 21, SD = 1.99	F

Guardia et al., 2012	Visual-Proprioceptive-Vestibular	Aperture Task from both egocentric (1st person) and allocentric (3rd person) perspectives	Individuals with AN showed a higher passability ratio compared to HCs when the task was proposed from egocentric but not from allocentric spatial reference frame.	The body overestimation and the alteration in body schema reliably observed in individuals with AN might reflect a deeper deficit in the crossmodal integration ability of bodily information.	AN (12 subtype restricting, 13 binge/purge subtype= 25; age (years) = 28.84, SD = 7.75; BMI (kg/m^2) = 15.65, SD = 1.24; illness duration NR; diagnostic criteria DSM-IV-R HCs = 25; age (years) = 24.48, SD = 6.7; BMI (kg/m^2) = 22.06, SD = 2.37	F

Table 3. The table presents studies' characteristics based on extraction parameters, sample features, and main findings. Abbreviations: SD = standard deviation; NR = no reported; AN = anorexic patients; BN = patients with Bulimia Nervosa; HCs = healthy controls; BMI = Body Mass Index; SOA= stimulus onset asynchrony; F = female; BCHC = body shape concerns healthy controls; ENDOS = eating disorder not otherwise specified.

Study characteristics

Table3 shows study characteristics according to the extraction parameters.

Thirteen studies assessed multisensory integration abilities in patients with Anorexia Nervosa from a behavioral perspective (Chirico et al., 2019; Guardia et al., 2012; Case & Wilson, 2012; Zopf et al., 2016; Beckmann et al., 2021; Eshkevari et al., 2012; Guardia et al., 2010; Guardia et al., 2013; Keizer et al., 2014; Keizer et al., 2016; Mentral et al., 2014; Provenzano et al., 2019; Risso et al., 2020). Only one study included participants with Bulimia (Eshkevari et al., 2012). In addition, one study also included healthy individuals with high body concerns (BCHC; Risso et al., 2020) and one study included patients with eating disorders not otherwise specified (ENDOS; Eshkevari et al., 2012). Only two studies manipulated the frame of reference (Guardia et al., 2012; Provenzano et al., 2019) proposing tasks from allocentric and egocentric spatial frames.

Included studies used MSI tasks to compare performance between patients with a current diagnosis of AN and/or BN to HCs. Diagnoses for EDs were achieved according to the DSM-5 (Chirico et al., 2019; Keizer et al., 2014; Keizer et al., 2016; Provenzano et al., 2019; Risso et al., 2020), DSM-IV-TR (Guardia et al., 2012; Case & Wilson, 2012; Eshkevari et al., 2012; Guardia et al., 2013; Metral et al., 2014), or DSM-IV (Zopf et al., 2016; Guardia et al., 2010; 61] diagnostic criteria. One study used the ICD-10 (Beckmann et al., 2021).

Sample features were similar in terms of BMI and mean age across studies, whereas illness duration and subtype information were not always reported (Chirico et al., 2019; Guardia et al., 2012; Case & Wilson, 2012; Zopf et al., 2016; Keizer et al., 2019). Notably, all studies focused on female participants.

We did not find any studies investigating the functional neurobiological basis of crossmodal integration processing under the conditions of interest. In particular, most studies used resting-state and neuroimaging techniques to investigate brain changes in AN and/or BN that might be related to MSI processing, without combining neuroimaging techniques with multisensory tasks.

Among the included studies, four studies investigated Visual–Tactile–Proprioceptive integration (Zopf et al., 2016; Eshkevari et al., 2012; Keizer et al., 2016; Provenzano et al., 2019), one investigated Visual–Haptic–Proprioceptive–Vestibular integration (Guardia et all, 2013), one study focused on Visual–Tactile integration (Risso et al., 2020), one on Visual–Haptic–Proprioceptive Integration (Case & Wilson, 2012), and one Auditory–Visual integration (Chirico et al., 2019). The remaining five studies instead investigated Visual–Proprioceptive–Vestibular integration (Guardia et al., 2012; Beckmann et al., 2021; Guardia et al., 2010; Keizer et al., 2019; Metral et al., 2014).

In the following sections, the main results of the included studies are reported and discussed according to the sensory modalities involved in the experimental tasks.

Visual–proprioceptive–vestibular–integration

Five studies included in this systematic review investigated Visual–Proprioceptive–Vestibular–Integration (Guardia et al., 2012; Beckmann et al., 2021; Guardia et al., 2010; Keizer et al., 2019; Metral et al., 2014). All of them examined individuals with Anorexia Nervosa and healthy controls when performing body-scaled action tasks. Specifically, four studies used the Aperture Task (Guardia et al., 201; Beckmann et al., 2021; Guardia et al., 2013; Metral et al., 2014) and one study used the Hoop Task (Keizer et al., 2019).

The Aperture Task (Warren & Wang, 1987) is a behavioral task in which participants must determine whether they can fit through various door-like openings without turning their hips or shoulders. It is considered an implicit measure of body experience; specifically, it assesses body schema, namely the unconscious body representation dedicated to movement and action performance (de Vignemont, 2011). The underlying idea is that the person needs to recall their body size and compare environmental and bodily measures to evaluate whether it is possible to pass through an aperture (Beckmann et al., 2021). For this process to be effective, the integration of different bodily sensory modalities (i.e., visual, proprioceptive, vestibular) is required. Thus, deficits in passability judgments and appropriately interacting with the environment reveal MSI deficits and altered body experience (Beckmann et al., 2021). In this task, the outcome of interest is the ratio of participants' shoulder width to the minimum aperture width at which participants began to rotate their body, a measure called the critical aperture-to-shoulder ratio (cA/S).

All studies in this review that used this procedure found that patients with AN reported a higher passability ratio compared to HCs, meaning that they rotated their shoulders for relatively larger door widths compared to controls. Notably, cA/S was not found to correlate significantly with relevant clinical parameters such as BMI and disease duration (Beckmann et al., 2021). The study by Guardia et al. (2012) proposed the same task from an egocentric and allocentric perspective: in the first condition, participants had to judge their own passability through the different apertures, whereas, in the second condition, they had to estimate the passability of another person. They found that participants with AN were able to accurately judge the passability of others (i.e., allocentric perspective), similar to controls so that differences emerged only in the egocentric condition.

Only one study used the Hoop Task (Keizer et al., 2019). Here participants had to judge the smallest hula hoop they could step through. Similar to findings from the Aperture Task, individuals with AN tended to overestimate the smallest opening they could pass through.

None of the included studies investigated visual, proprioceptive, and vestibular integration in patients affected by Bulimia Nervosa.

Visual–tactile–proprioceptive integration

Four studies in this review (Zopf et al., 2016; Eshkevari et al., 2012; Keizer et al., 2016; Provenzano et al., 2019) examined the integration of visual, tactile, and proprioceptive bodily signals in patients with Anorexia Nervosa. This process has been examined employing body illusions: precisely, the RHI (Botvinick & Cohen, 1998) and the Full Body Illusion (FBI; Serino, Polli & Riva, 2019).

The Rubber Hand Illusion (Botvinick & Cohen, 1998) is a perceptual illusion in which individuals perceive a fake hand as their hand after synchronous visual-tactile stimulation of the rubber and real hands; the rubber hand is placed in the biological position of the real hand, which is instead outside the subject's visual field; then both the rubber hand and the subject's real hand are stimulated at the same time and in the same position (visual-tactile synchrony), causing the subject to experience the fake hand as the real one (Botvinick & Cohen, 1998). The underlying idea is that the embodiment of the rubber hand results from the resolution of a Visual–Tactile–Proprioceptive conflict (Zopf et al., 2016). Notably, the illusion is reduced when the multisensory visual-tactile over the real and fake bodies are not spatially and temporally synchronized (visual-tactile asynchrony; Zopf et al., 2016). The strength of the illusion is measured by self-report measures such as the Embodiment Questionnaire (Lenggenhager et al., 2007), behavioral measures such as changes in perceived hand localization (e.g., proprioceptive drift and endpoint errors, meaning reaching responses towards visual targets), and physiological measures such as skin temperature (Provenzano et al., 2019).

When administering the Rubber Hand Illusion to a sample of patients with Anorexia Nervosa, Zopf et al. (2016) and Eshkevari et al. (2012) found patients experiencing higher embodiment levels over the fake hand compared to controls. Both the research groups found that individuals with AN experienced higher levels of body ownership over the fake hand as measured by the Embodiment Questionnaire. The same pattern was observed when endpoint errors and proprioceptive drift were considered behavioral measures of illusion strength: patients exhibited more endpoint errors and proprioceptive drift after synchronous stimulation compared to healthy controls. Notably, the same pattern was observed regardless of the condition (i.e., whether the visuo-tactile stimulation was synchronous or asynchronous). Additionally, Eshkevari et al. (2012) found no between-group differences in embodiment levels as measured by the questionnaire when controlling for mood, while differences in proprioceptive drift remained. Notably, the same group reported that patients also tended to misperceive the location of their hand (i.e., closer to the midline) during the baseline hand localization tasks compared to controls.

The study by Eshkevari et al. (2012) is the only study in this review including participants with Bulimia Nervosa. The authors found that individuals with Bulimia tended to report greater embodiment levels compared to controls, even when controlling for mood for embodiment levels as measured by questionnaires. No differences instead were detected when considering proprioceptive drift.

The Full Body Illusion (Serino, Polli & Riva, 2019) can be seen as an advanced version of the Rubber Hand Illusion. The FBI is a perceptual illusion that, after synchronous visuo-tactile stimulation of the virtual and real bodies, induces individuals to experience a virtual body as their own, similar to the RHI. The main difference between these two procedures is that the first induces embodiment over the whole body, whereas the second induces embodiment over a specific part of the body. Consequently, the site of multisensory stimulation to promote body ownership is different in the two procedures: the FBI requires stimulation of the abdominal area, whereas the RHI requires stimulation of the back of the hand. In addition, the FBI has largely been presented in virtual reality, as it allows the individual to be fully immersed in a virtual environment. The strength of the full-body illusion is measured by self-report measures such as the Embodiment Questionnaire (Lenggenhager et al., 2007) and physiological measures such as skin temperature (e.g., a drop in temperature indicates a stronger illusory experience; Provenzano et al., 2019). Additionally, Visual Analog Scales (VAS) can be used to assess the emotional activation induced by the experience (Provenzano et al., 2019).

Two studies in this review (Keizer et al., 2016; Provenzano et al., 2019) employed Full Body Illusion in Virtual Reality to study body experience in patients with AN. In contrast to previous results with the rubber hand illusion, both studies found that people with AN did not experience the illusion differently than controls, as assessed by skin temperature (Provenzano et al., 2019), questionnaires, and VAS (Keizer et al., 2016; Provenzano et al., 2019).

Provenzano et al. (2019) presented participants with an additional task: the avatar selection task. Here, participants had to select their ideal and real body shapes from several possible bodies in order to assess body satisfaction, i.e., the differences between the two selected bodies, and perceptual accuracy, i.e., the ability to identify the body most similar to their own among the possible options. While the embodiment procedure was presented from an egocentric frame, i.e., participants looked directly at their stomach to see the virtual body, the avatar selection task was presented from a third-person perspective, i.e., they saw the possible options from an allocentric perspective as objects in front of them. Results showed no significant differences in embodiment levels and no differences in perceptual accuracy, meaning that individuals with Anorexia Nervosa and controls did not differ on all embodiment measures and in the ability to recognize their bodies. Differences emerged instead concerning body satisfaction, where participants with Anorexia Nervosa showed greater levels of dissatisfaction than controls. Related to these findings, they also observed that patients experienced more positive emotions when exposed to thinner bodies compared to higher BMI bodies, in an opposite trend compared to controls.

Visual–haptic–proprioceptive integration

One study included in this review (Case & Wilson, 2012) examined visual, haptic, and proprioceptive integration abilities in individuals with Anorexia Nervosa compared to healthy controls. Case et al. (2012) proposed participants with the Size-Weight Illusion (SWI - Plaisier & Smeets, 2016 - which is an experimental paradigm where two objects equal in shape and mass but different in size have to be compared to determine which one is heavier. The SWI occurs because of multisensory conflicts, under the implicit assumptions that large objects are heavier than small ones and that two objects of equal measure have the same weight (Guardia et al., 2013). When proposing this procedure to patients with AN, Case, et al. (2012) observed a significantly reduced SWI (and reduced "reverse" SWI) in participants with Anorexia Nervosa as compared to controls, despite a baseline normal weight discrimination ability.

The visual, haptic, and proprioceptive integration process in individuals with Bulimia Nervosa was not examined in the included studies.

Visual–haptic–proprioceptive–vestibular integration

In the study by Guardia et al. (2013), the integration of visual, haptic, proprioceptive, and vestibular information was examined in individuals with AN using the Subjective Vertical (SV) task. The SV task (Luyat et al., 2012) is a measure of spatial orientation constancy that requires manual adjustment of a rod to a perceived vertical position. Spatial orientation constancy is not maintained in healthy individuals under certain circumstances: specific conditions such as darkness or head and/or body tilt lead to systematic deviations in SV (Luyat et al., 2012). These deviations are referred to as the A and E effects. The A effect is characterized by SV deviations toward the head axis and is typically associated with vision and large tilts, whereas the E effect is characterized by SV deviations away from the head axis and is typically associated with tactile adaptation (Guardia et al., 2013).

In their study, Guardia et al. (2013) asked participants with Anorexia Nervosa and healthy controls to make visual and tactile spatial orientation judgments by adjusting a rod toward the vertical in an upright position and with lateral whole-body tilt (90° clockwise or counterclockwise from the vertical line). Results showed that the tactile and visual SV measured in the upright position was very close to the gravitational vertical axis in both groups, whereas differences emerged in the tilted body conditions, where patients showed deviations of the tactile and visual SV with a greater A-effect (i.e., the bar was moved toward the head axis) regardless of the specific side. Notably, no baseline unimodal tactile or visual discrimination ability abnormalities were observed between groups. Similarly, tactile and visual body Z-axis judgments were similar between the groups in the upright body position, and differences emerged in the tilted body conditions, where individuals with AN judged the body as more tilted than it was compared to controls.

The integration of visual, tactile, proprioceptive, and vestibular information in patients with Bulimia Nervosa has not been investigated among the included studies.

Auditory-visual integration

The study by Chirico et al. (2019) investigated whether multimodal integration of auditory and visual information is impaired in patients with Anorexia Nervosa. Specifically, they used the Sound-Induced Flash Illusion (SIFI) to investigate whether individuals with AN presented an impaired temporal discrimination processing of visual-auditory stimuli compared to healthy controls. The SIFI (Shams, Kamitani & Shimojo, 2000) presents respondents with auditory and visual stimuli at different stimulus onset asynchronies (SOA; 70 ms, 110 ms, 150 ms, 230 ms) and requires participants to determine the number of either visual or auditory stimuli presented in different conditions (only visual, only auditory, and bimodal auditory-visual stimulation). Overall, they found that individuals with AN showed lower accuracy compared to HCs for each SOA and presentation modality. Moreover, patients tended to report more incorrect responses compared to healthy controls. The only exception was found for a shorter interval between the onset of two visual stimuli (from 70 to 110 ms), where there were no significant differences between the groups. However, impaired performance at longer SOA was reported by the former in the visual condition (150 ms, 230 ms). Notably, individuals with AN were never able to detect the double tone in the auditory condition. Instead, they reported a higher number of correct responses in the visual condition compared to the other two modalities. Abnormalities in patients with Anorexia Nervosa compared to controls were observed for longer visual SOA, as well as for the bimodal condition across all stimulus onset asynchronies, with a shorter temporal binding window (i.e., the time interval in which stimuli are perceived as occurring simultaneously).

None of the included studies investigated multimodal integration of visual, tactile, and proprioceptive information in individuals with Bulimia Nervosa.

Visuo-tactile integration

The study by Risso et al. (2020) assessed multisensory deficits in AN focusing on how participants integrate crossmodal sensory information. For this purpose, the Multisensory Processing Assessment Task (MPA; Helbig & Ernst, 2007) was used. The MPA allows the assessment of sensory and multisensory processing, taking into account the reliability of both visual and tactile unisensory modalities as well as their integration. The task requires participants to discriminate the shape of small ellipses using only visual, tactile, or both visual and tactile information. The experimenter places a stimulus plate with a raised ellipse on it in the structure and positions it behind a hole in the plate. In the visual condition, participants see the raised ellipse through a hole in the plate, whereas in the tactile condition, they have to move their arms behind the plate and feel the raised ellipse without being able to see it. In contrast, in the bimodal conditions, participants simultaneously see and touch a double-sided printed ellipse, seeing the ellipse on the front of the stimulus panel while simultaneously touching the ellipse on the back. Concerning the shape distortion of the ellipses, Risso et al. (2020) found that participants with Anorexia Nervosa tended to overestimate the ellipses more than healthy controls in the tactile modality, whereas no differences emerged in the visual domain, where the level of accuracy was relatively high in both groups. Discrimination thresholds showed that patients had higher visual and tactile thresholds than controls. Analysis of multimodal integration in the bimodal conditions revealed that patients with AN integrated tactile and visual information as well as controls in terms of accuracy, but differences emerged in terms of discrimination thresholds, with patients showing a lower bimodal threshold than unimodal, whereas healthy controls reported no significantly different thresholds across conditions.

The integration of visual and tactile information in individuals with Bulimia Nervosa was not explored in any of the included studies.

Discussion

This systematic review of the literature identified thirteen studies investigating multisensory integration abilities in patients affected by Anorexia Nervosa, of which only one study included individuals with Bulimia Nervosa (Eshkevari et al., 2012). No studies were found that examined brain function during multisensory integration tasks in these conditions.

Overall, behavioural studies provide evidence for alterations in Visual–Haptic–Proprioceptive–Vestibular (Guardia et al., 2013), Visual–Haptic–Proprioceptive (Case & Wilson, 2012), Auditory–Visual (Chirico et al., 2019), and Visual–Proprioceptive–Vestibular integration (Guardia et al., 2012; Beckmann et al., 2021; Guardia et al., 2013; Keizer et al.

2019; Metral et al., 2014) in individuals with Anorexia Nervosa. Concerns arise when considering visuo–tactile integration (Risso et al., 2020) and visual-proprioceptive-vestibular integration, where different paradigms have yielded inconsistent results. Specifically, in this regard, patients with AN showed an abnormal illusory experience during the Rubber Hand Illusion (Zopf et al., 2016; Eshkevari et al., 2012), but contrasted results were found when using the Full Body Illusion (Keizer et al., 2016; Provenzano et al., 2020). The small number of studies included in this review suggests that multimodal integration processing has received little attention in Anorexia Nervosa, despite available evidence suggesting possible abnormalities in this process (Cash, 1987). In contrast, there has been minimal research on Bulimia Nervosa. Therefore, future studies are needed to clarify possible differences and similarities between the two conditions to understand how patients affected by these pathologies experience their bodies.

In the following sections, we will discuss the results of the studies according to the sensory modalities involved, attempting to integrate the behavioral results of this review with neuropsychological and neuroscientific evidence.

Visual–proprioceptive–vestibular integration

Findings from this review (Guardia et al., 2017; Beckmann et al. 2021; Guardia et al., 2010; Keizer et al., 2019; Metral et al., 2014) suggest the presence of alterations in the integration of visual-proprioceptive-vestibular information integration in patients with Anorexia Nervosa. Indeed, all included studies found that individuals with AN tended to report an abnormally higher critical aperture-to-shoulder ratio compared to healthy controls in body-scaled action tasks (Downs & Black, 1998).

One possible explanation for this difference may rely on distorted body information stored in memory: if the body representation stored in memory is inaccurate, it may mislead both perceptual and action-related body representations. That is, patients may process and program motor responses accurately but based on altered body size information retrieved from memory (Keizer et al., 2013). In addition, negative emotional top-down processes may also be involved: individuals with AN indeed show high levels of negative affect (e.g., body dissatisfaction), and such emotional aspects have been found to influence both motor decisions and size estimations (Keizer et al., 2013). Although these aspects were not investigated in the studies included in this review, they may partially account for their findings. Another possible explanation for the motor task findings may be related to locomotor variables, such as walking speed (Wilmut & Barnett, 2005). For example, it may be that patients tend to have a faster walking speed during the task, which in turn may lead to less accuracy and attention during the action, resulting in less accurate judgments.

Neuroscientific studies may also partially explain the differences observed between patients with Anorexia Nervosa and healthy individuals. Alterations in body schema were found to be associated with lesions in the parietal and dorsolateral frontal cortices (Schwoebel & Coslett, 2005), and abnormalities in the frontoparietal-cingulate network and the frontal gyrus seemed to be associated with distorted body experience and disturbances in self-identity (Mishima et al., 2021). Resting-state neurofunctional and neurostructural studies revealed alterations in frontal regions in patients with AN. For example, decreased gray matter volume was observed in the superior frontal gyrus and right middle frontal gyrus (Mishima et al., 2021) as well as at the level of the dorsal and rostral anterior and cingulate cortices (Joos et al., 2010). Since body-scale action tasks require movement, another possible explanation for these findings could involve the cerebellum. Indeed, this structure is involved in the integration of information from sensory cortices to ensure sensorimotor coordination (Ishikawa, Shimuta & Häusser, 2015; Zhu & Yung, 2006) and optimal information processing (Siciliano, Olivito & Leggio, 2022). Some research showed that cerebellar changes are associated with body-scale motor tasks (Siciliano, Olivito & Leggio, 2022), and some neuroimaging studies have highlighted possible structural changes in this region in individuals with AN (Mishima et al., 2021).

The reasons for such cortical differences are still in doubt, but they seem to be related to prolonged food deprivation (Mühlau et al., 2007), which might cause deficits in perceptual organization (e.g., the ability to group visual elements to process a visual stimulus as a whole; McCormick et al., 2008). If this is true, there should be a relationship between cortical alterations and disease severity (e.g., greater disease severity, greater cortical changes, and MSI deficits). However, data are still limited and results are only partially consistent: additional neuroimaging studies while participants perform multisensory tasks are needed to test this hypothesis. Therefore, we can only conclude that differences in cortical functioning in fronto-parietal regions and the cerebellum may underlie differences between patients with Anorexia Nervosa and healthy individuals in multisensory integration performance as reflected by motor tasks.

Visual–tactile–proprioceptive integration

In terms of Visual–Tactile–Proprioceptive integration, the studies in this review that used the Rubber Hand Illusion in a sample of individuals with AN (Zopf et al., 2016; Eshkevari, Rieger & Longo, 2012) found that patients reported significantly greater embodiment over the rubber hand than healthy controls, suggesting an abnormal cross-modal integration process. These findings are consistent with other research showing that individuals affected by Eating Disorders tended to report higher embodiment during the Rubber Hand Illusion than controls, both behaviorally (i.e., proprioceptive drift) and cognitively (Ehrsson, 2014; Preston & Ehrsson, 2014). Such findings have been interpreted as evidence that patients with AN have a highly malleable bodily self (Eshkevari, Rieger & Longo, 2012). The authors interpreted their findings as suggesting that patients with Eating Disorders might have a flexible and malleable body experience (Zopf et al., 2016; Eshkevari, Rieger & Longo, 2012).

One of the reasons for these results may be a tendency of patients to rely on visual inputs in constructing the representation of their own body compared to other sources of information (e.g., proprioceptive, tactile). This was supported by the significant differences in the body illusion regardless of the condition (synchronous or asynchronous). In addition, another possible reason for these findings could be the strong reliance on visual information and the associated difficulty in detecting internal body information (e.g., interoceptive, vestibular, and proprioceptive signals; Malighetti et al., 2022).

The use of body illusion paradigms as a treatment for distorted body representation in individuals with Eating Disorders is also consistent with this hypothesis: some authors (Zopf et al., 2016; Eshkevari, Rieger & Longo, 2012) have suggested that the effectiveness of paradigms such as the FBI in modifying body representations may be related precisely to patients' tendency to base their representations on the most recent visual input (Beckmann et al., 2021). This implies that the suggestion of a body other than one's own (i.e., the avatar) would provide visual information capable of modifying body perception, at least temporarily.

The research group led by Eshkevari (2014) examined also a sample of patients discharged from the Eating Disorders, including patients who recovered from AN. They found that participants who recovered from Anorexia Nervosa showed significantly higher embodiment scores compared to healthy individuals, but no significant differences emerged concerning proprioceptive drift. Thus, they found a pattern similar to that observed between controls and participants with Bulimia Nervosa (Eshkevari, Rieger & Longo, 2012).

Thus, flexibility in bodily experience seems to persist even after recovery from pathology at the explicit but not implicit level. Several studies have shown the persistence of interoceptive deficits even after recovery from Anorexia Nervosa (Martin et al., 2019), which could then explain the outcome in terms of a persistent tendency to base one's bodily experience on visual information. However, this tendency may be reduced after recovery, resulting in an inconsistency between explicit and implicit embodiment measures. Interestingly, the similarity between individuals recovered from Anorexia Nervosa and patients with Bulimia Nervosa is consistent with the diagnostic crossover that often leads to an oscillation between these two disorders (Eddy et al., 2008).

A second explanation for why patients with AN embody the rubber hand more than controls may be related to a self-objectification process (Calogero, Tantleff-Dunn & Thompson, 2010; Calogero, Davis & Thompson, 2005). Patients who tend to view their bodies as objects may choose to use a visual imagery strategy that emphasizes a third-person perspective, as opposed to a motor strategy that emphasizes a first-person perspective. Indeed, as discussed in the Introduction, self-objectification was the largest contributor to both the onset and maintenance of EDs in two 4-year longitudinal studies (Dakanalis et al., 2016; Dakanlis et al., 2017). In addition, previous research has found a positive association between embodiment in the RHI illusion and levels of self-objectification (Eshkevari, Rieger & Longo, 2012). Furthermore, self-objectification may also explain the tendency to prioritize visual information over other bodily signals, as well as negatively affect cognitive functions (e.g., critical thinking, and problem-solving; Winn & Cornelius, 2020) necessary to process incoming information.

Neuroscientific studies have found cortical alterations in patients with AN that may account for the behavioral results observed during the RHI. Functional Magnetic Resonance (fMRI) studies showed that the RHI experience is associated with increased activation in the premotor cortices, intraparietal cortices, and cerebellum, suggesting that these regions may be actively involved in resolving multisensory conflicts during body illusions (Ehrsson, 2005). Furthermore, the precuneus and parietal regions are thought to be particularly involved in the cross-modal integration required for body experience and body illusions (Gaudio & Quattrocchi, 2012), and they appear to be involved in the egocentric and allocentric coding of spatial information too (Gaudio & Quattrocchi, 2012). In support of this, previous studies have found alterations in these regions in patients affected by body awareness disorders (Mühlau et al., 2007). Patients with AN generally show lower baseline functional connectivity in all of these areas (Mishima et al., 2021; Favaro et al., 2012) and research appears to be highly consistent regarding the presence of neurostructural and neurofunctional alterations in the precuneus and parietal areas in patients with AN (Castro-Fornieles et al., 2009; Pietrini et al., 2011). Thus, cortical abnormalities at the level of the precuneus and parietal networks may, in part, account for abnormal embodiment and body-ownership experiences during RHI.

Notably, while research has shown alterations in parietal regions and the precuneus in AN, no structural or functional abnormalities have been found in patients with BN (Joos et al., 2010). Previous research on BN found a lower degree of cortical alterations in this pathology compared to AN (Amianto et al., 2013): thus, cortical differences may support the differences in RHI observed between individuals with AN and BN in the study by Eshkevari et al. (2012).

Despite this evidence, it is important to note that neuroscientific data regarding cortical impairments in patients with Anorexia Nervosa—as well as Eating Disorders in general—are still contradictory and limited, so it is not possible to find a direct and precise link between brain function and body illusion experience. Indeed, general and broader impairments within brain networks due to both genetic and disordered eating symptomatology (e.g., starvation) may account for behavioral outcomes.

However, the results of this review regarding the integration between visual, tactile, and proprioceptive stimuli are controversial. When assessing cross-modal integration of the same sensory modalities, Provenzano et al. (2019) and Keizer et al. (2016) observed opposite results: they found that individuals with AN did not report differences in embodiment compared to healthy controls, either at the explicit or implicit level. Instead, they reported significant differences in body satisfaction. These findings seem to support the idea that individuals with AN are characterized by abnormalities in cognitive-emotional rather than perceptual body components.

Through this systematic review, we identified differences between the Rubber Hand and Full Body Illusions, specifically concerning the body site being stimulated to promote the illusion (palm and abdomen, respectively). These two areas differ significantly in emotional valence for patients (the abdomen being more emotionally engaging compared to the hand palm). Thus, affective factors may influence body ownership, as demonstrated by studies in which differences in embodiment levels between groups decreased when controlling for mood (Eshkevari, Rieger, & Longo, 2012).

Another potential mechanism involved in such differences concerns cardiovascular and thermoregulatory abnormalities. Previous studies have shown that varying hand temperature and arm blood flow increase the amount of proprioceptive drift during synchronous visuo-tactile stimulation (Teaford et al., 2021): as Anorexia Nervosa is associated with cardiovascular and thermoregulatory abnormalities, individual differences in these processes may also affect body illusion results reflected by skin temperature (Brown & Mehler, 2015).

The results by Provenzano et al. (2019) highlight the potential effect of the spatial frame of reference in which the tasks were presented. Indeed, the stimulus to induce embodiment over the fake body was presented from a first-person perspective, whereas the ideal and real body choice task was presented from a third-person perspective. Thus, as suggested by the authors, the discrepancies between these two tasks could be interpreted as evidence that patients with AN could be characterized by an impairment in multisensory integration, defined as the ability to combine egocentric and allocentric bodily information (Riva & Dakanalis, 2018; Riva & Gaudio, 2012).

These data are consistent with the proposal offered by the Allocentri Lock Theory (ALT; Riva & Gaudio, 2012) regarding the aetiology of Eating Disorders. The ALT suggests that patients affected by EDs may have deficits in the ability to integrate allocentric (somatic information stored in memory) and egocentric (incoming sensory information) information through a multisensory integration process (Nico et al., 2010). Several studies support the ALT hypothesis, suggesting the use of body illusions to modify the allocentric body of patients affected by Eating Disorders (for more, see Petkova & Ehrsson, 2008; Serino, Polli & Riva, 2019; Serino et al., 2016). In addition, the ALT found its strength in evidence from neuroscientific studies, specifically focusing on parietal and temporal structures. We have discussed the role of the parietal lobe in shaping body experience in previous sections. The temporal lobe, on the other hand, is involved in visual and auditory processing, while the hippocampus and surrounding temporal structures are involved in long-term spatial memory and the generation of allocentric representations, including bodily ones (Riva, 2010). Since body experience results from the integration of egocentric and allocentric bodily information (Riva & Gaudio, 2018; Riva, 2014), alterations in parietal and temporal areas observed in individuals with ED may lead to deficits in the ability to correctly store body-related information from a third-person perspective in memory, resulting in an altered experience of one's own body (Riva, 2010).

Visual–haptic–proprioceptive integration

Case et al. (2012) used Size Weight Illusion to investigate visual-haptic-proprioceptive integration in patients with AN compared to healthy controls, providing evidence for cross-modal sensory integration deficits in individuals with AN. In particular, the reduced sensitivity to the size-weight illusion in patients with AN showed some similarities to the performance of patients with left temporal parietal lesions (Li et al., 2007). As previously discussed, patients with Anorexia Nervosa show widespread cortical alterations, including within temporal and parietal networks (Favaro et al., 2012). Thus, possible abnormalities in temporal areas may partially support the altered illusory experience in AN.

However, the study by Case et al. (2012) has some methodological problems. Indeed, it is not clear which specific modalities are involved (e.g., whether impairments involve visual-proprioceptive or tactile-proprioceptive integration). Other authors identified this limitation, criticizing the inability of Case's paradigm to distinguish between the contribution of visual and haptic information and to assess the integration of this information with proprioceptive input (Engel et al., 2020). Therefore, recent research has proposed an extended version of the Size Weight Illusion by including visual and haptic conditions (Engel et al., 2020). Using this version of the task, no differences were found between participants with AN and healthy controls, suggesting no impairment of visual-haptic integration. Thus, multisensory integration difficulties may arise when proprioceptive information needs to be combined with visual and tactile inputs. This hypothesis could be supported by specific nerve fibers involved in the transmission of somatosensory information: indeed, patients with AN show atrophy of type II nerve fibers, which could reduce somatosensory information and lead to an abnormal response to this type of stimuli (Teaford et al., 2021).

Visual–haptic–proprioceptive–vestibular integration

Visual–Haptic–Proprioceptive–Vestibular integration was investigated by Guardia et al. (2013) using the Subjective Vertical task (SV). Authors found alterations in participants with AN compared to controls, with patients reporting deviations of tactile and visual SV toward the body in tilted conditions. Thus, people with AN showed impairments in the constancy of spatial orientation and thus in the ability to integrate multisensory inputs to make correct spatial judgments. Individuals with Anorexia Nervosa seem to show widespread cortical alterations, including within temporal and parietal networks, which play a critical role in spatial judgments and cross-modal sensory integration (Nico et al., 2010; Grunwald, 2002). Thus, SV task performance may be associated with changes in brain function.

Furthermore, the increased A-effect in patients with AN might be framed according to the Allocentric Lock Hypothesis (Riva & Gaudio, 2012). In these terms, patients may be more likely to rely on an allocentric frame of reference due to difficulties in combining egocentric and allocentric information (Riva & Gaudio, 2018). Also in this context, behavioral data could be related to the atrophy of type II nerve fibers, which could reduce somatosensory information flow and processing (Guardia et al., 2013; Teaford et al., 2021).

Auditory–visual integration

Auditory–visual integration in individuals with AN is a relatively unexplored area of research. Indeed, only one study in this review investigated this integration process in patients with Anorexia Nervosa, using the Sound-Induced Flash Illusion task (Chirico et al., 2019). The results of this study indicated that individuals with AN tended to make fewer correct responses than controls, particularly for longer SOA. Although no previous research has been conducted on a sample of patients with AN, and it was not possible to make comparisons across studies, this finding seems to provide additional evidence for an impaired cross-modal integration ability in this pathology.

Similar results were found in individuals with Autism Spectrum Disorders. Similar audiovisual tasks have been proposed for individuals with autism as opposed to healthy individuals, revealing difficulties in multisensory processing in the clinical group (Stevenson et al., 2014; Kawakami & Otsuka, 2021). This abnormality has been proposed to be related to pathology-specific factors, including cortical alterations in specific brain areas for multisensory integration (e.g., parietal lobe), social deficits (e.g., audiovisual integration is required for face-voice association), and sensory overload (e.g., hypersensitivity to sensory stimuli; Stevenson et al., 2014; Kawakami & Otsuka, 2021). Notably, these aspects seem to be common to both Autism Spectrum Disorders and Anorexia Nervosa, and studies have shown that autistic traits are likely to be present in individuals who are affected by AN (Sauro, Laasonen & Raevuori, 2021). Thus, the results from this review may be related in some way to specific features that Autism Spectrum Disorders and Anorexia Nervosa have in common.

Visuo-tactile integration

The visuo-tactile integration process was assessed by only one study included in the review (Risso et al., 2020). Here, individuals with AN were presented with the Multisensory Processing Assessment Task (MPA), which assessed both individual visual and tactile sensory modalities as well as the visuo-tactile MSI process. Results showed that patients with AN tended to overestimate stimulus width more than controls, which is consistent with previous research showing that patients with AN overestimate the distance between two points (Keize et al., 2011). Since a similar pattern was not found in individuals with high body concern (BCHC), data suggest that this alteration is not related to body concern or other bodily cognitive-affective factors. This supports the idea that patients with AN may show perceptual alterations that are something different compared to body concerns and body dissatisfaction. However, it is not clear whether the higher threshold was due to the precision of the comparison or estimation processes. Based on the results of Risso et al. (2020), patients seem to be characterized by unimodal low-level processing deficits in tactile and visual modalities, but not in the integration of such information (Keizer et al., 2011; Sterzer et al., 2018).

However, the interpretation of these results might be misleading because of methodological issues. Indeed, results may be influenced by the way the discrimination threshold was measured, given the small number of trials, as well as by sample characteristics (e.g., disease duration which may affect the severity of multisensory abilities) that were not extensively collected and/or reported. Given these concerns, the results should be interpreted with caution.

Neuroscience studies seem to suggest that the presence of visuo-tactile integration alterations in patients with eating disorders may be related to the activity of the somatosensory network (Favaro et al., 2012; Teaford et al., 2021). Indeed, the somatosensory system is involved in visuo-tactile integration, among other functions (Kwon, Jang & Lee, 2017), and it contributes to the processing of body-related information across sensory modalities (Yau & DeAngelis, 2015) suggesting its role in multisensory integration (Kwon, Jang & Lee, 2017; Di Zy & Fuster, 2000). Alterations in this circuit could then lead to deficits in integrating visual-tactile stimuli, as supported by the affective-touch literature (Ebish et al., 2011). However, the data in this review do not support this hypothesis. A possible reason for this discrepancy may be related to emotional factors: while visuotactile deficits may be observed when affective touch stimuli are used, no deficits may be found when emotionally neutral stimuli are presented. Thus, cross-modal integration involving touch may be significantly influenced by social and emotional factors more than other sensory domains (Crucianelli et al., 2016). This is similar to what has been previously discussed regarding Visual–Tactile–Proprioceptive integration. Consistent with this proposal, previous studies have shown that high levels of body dissatisfaction are associated with inaccuracy in tactile distance estimation (e.g., Keizer et al., 2011), stressing a significant influence of interpersonal and affective factors in tactile processing.

Summary of findings

In this systematic review, we aimed to outline the findings of studies on individuals with Anorexia Nervosa and Bulimia Nervosa using multisensory tasks to investigate multimodal integration abilities in these conditions. Based on the available evidence, individuals with AN appear to exhibit abnormalities in the ability to combine inputs from different sensory domains, both in response to body-related (e.g., Provenzano et al., 2019) and non-body-related stimuli (e.g., Chirico et al., 2019). The limited evidence available suggests that these changes persist when information from different spatial frames is combined.

Thus, the studies included in this review suggest that AN may be associated with an inability (or suboptimal ability) to integrate sensory information from multiple sensory domains into a unique and coherent percept, which is a core process in shaping bodily experience. Deficits appear to occur particularly when internal body signals (i.e., proprioceptive, vestibular) must be combined with exteroceptive information (i.e., visual). On the other hand, only limited data have been found on patients with BN, so it is not possible to draw conclusions and make comparisons between the two pathologies.

Limitations

The current review has some limitations that need to be highlighted. First, the limited number of included studies. Only thirteen studies met our inclusion criteria, demonstrating the scarcity of research in this area and the lack of studies focusing on the assessment of MSI abilities in AN and BN. We found that most of the research focused on subclinical or nonclinical conditions and studies that attempted to use multisensory stimulation as a treatment for the somatic affective components (e.g., Artoni et al., 2021; Porras-Garcia et al., 2020; Porras-Garcia et al., 2020). In addition, only one of the included studies considered patients with BN, which does not allow us to make comparisons and draw conclusions about this pathology. Regarding the sample, not all included studies reported potentially relevant sample characteristics such as disease severity, disease duration, diagnostic subtype, or other clinically relevant variables (e.g., comorbidities or medications). Given the paucity of studies, we did not specifically analyze such confounders, which may limit our interpretation.

Further research should better address the role of these critical factors: for example, it may be that greater EDs severity is associated with greater MSI deficits. This hypothesis is supported by studies conducted in subclinical samples: studies have found a relationship between multisensory integration skills, body image, and eating disorder symptoms, with greater deficits being positively associated with greater symptomatology (Tajadura-Jinènez et al., 2022; Mussap & Salton, 2006). In this vein, it may also be the case that deficits in multimodal integration may predict the development of body image-related disorders and individualize individuals at risk for eating disorders. This research will be essential for proposing preventive and early interventions (Perruchoud et al., 2016). In addition, further research is needed to understand how the specific clinical subtype (e.g., restricting, binge/purge subtypes of Anorexia Nervosa) affects multimodal integration ability.

Another striking argument relates to gender differences: most of the studies included in this review focus on female patients. Since Eating Disorders are also increasing in males (Dakanlis & Riva, 2013), further research should include male patients to examine gender differences, thus comparing not only male patients with healthy controls but also females with male patients with the same diagnosis.

Finally, we did not find any neuroimaging and neurofunctional studies that included multimodal tasks: this limited us to hypothesizing and speculating the neurobiological basis of multisensory integration without the possibility of anchoring behavioral findings to robust neuroscientific results. Thus, we encourage future studies to use fMRI techniques to investigate cortical activations during cross-modal tasks to better reveal cortical functional differences between patients and controls.

Conclusions and Further Directions

To our knowledge, this systematic review is the first attempt to systematically investigate the multisensory integration abilities in patients affected by Anorexia Nervosa and Bulimia Nervosa. Crossmodal integration refers to the combination of sensory information from different sensory modalities (e.g., tactile, visual, auditory, proprioceptive, vestibular) and spatial reference frames (egocentric and allocentric) into a unique and coherent percept (Stein, Stanford, Rowland, 2014; Avillac et al., 2004), and constitutes a crucial process for body perception (Berlicchi & Aglioti, 2010).

Body representation and image disturbances have long been recognized as critical factors in the development and maintenance of eating disorders, specifically in Anorexia Nervosa and Bulimia Nervosa (Kearney-Cooke & Tieger, 2012). Indeed, a large body of evidence has demonstrated that patients consistently exhibit disturbances in the way they feel, think, and perceive their bodies. While cognitive and affective body components have been extensively investigated in the literature, the perceptual aspect has received less attention. Therefore, in this systematic review, we summarize the evidence on bodily experience in these conditions by looking at its most fundamental process, multisensory integration. We argue that this is necessary to fully understand the body experience of people with these conditions. The studies included in this review revealed that individuals with Anorexia Nervosa show an inability (or less than ideal ability) to combine multimodal sensory information and information from different spatial frames into a single and coherent percept.

Further research is needed to understand the reasons for the in-depth understanding of multimodal integration abnormalities. Previous research has shown that patients with AN have deficits in the processing of interoceptive signals (see Malighetti et al., 2022), whereas no impairments were found when processing unisensory exteroceptive information (Goldzak-Kunik et al., 2012). This alone could explain the MSI difficulties, as interoceptive information is still biased before integration takes place (Herbert, 2020). Additionally, cortical alterations in regions involved in MSI (i.e., frontal, parietal, temporal areas) might partially account for those results too (Sterzer, 2018). However, we argue that single-level accounts of MSI alterations (e.g., only biological factors) are too reductionist on their own and will only reach their full value when embedded in a more complex, multi-level explanatory framework that can account for the influence of both bottom-up and top-down processes.

We, therefore, propose the Predictive Coding (PP; Friston, 2010) framework for understanding MSI abnormalities in ED. PP views the brain as a "Bayesian prediction machine" that actively constructs percepts. The basic idea is that the brain compares incoming sensory information (likelihood) with internal representations (internal models) based on prior knowledge and beliefs (priors) through an active and iterative process. The discrepancy between expectations and actual sensory data defines the prediction error (PE). According to the “free energy” principle, the PE must be minimized, and this can be done by updating predictions (i.e., adjusting the prediction based on incoming information) or by active inference (i.e., acting to adapt incoming information to predictions; Friston et al., 2010). The strategy adopted depends on the accuracy and reliability (precision) assigned to priors and incoming information: new signals can adjust priors and vice versa, depending on which source is considered the most precise (*Figure 5*). It follows that inappropriate precision weighting (e.g., giving too much or too little weight to either the prior or the likelihood) affects PE gain and the ability to update internal models, leading to erroneous inferences (Sterzer et al., 2018; Quintero et al., 2022). When sensory information is weighted as unreliable, the final output (posterior) is primarily based on priors, in what has been termed the "prior tendency to bind stimuli" (Quintero et al., 2022). This happens for instance when sensory data are noisy, but also as a result of attentional, emotional, and biological factors (Talsma, 2015).

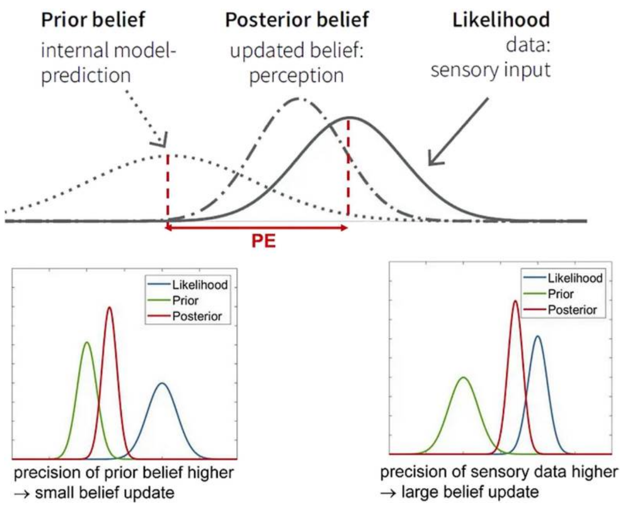

Figure 5. The outcome of the predictive coding process depends on weight (precision) attribution. On the left: when priors are judged to be more precise than incoming sensory information (likelihood), the posterior will be primarily based on priors (i.e., the posterior is shifted towards priors and there is no updating of existing beliefs); on the right: if the likelihood is judged to be more accurate than priors, the posterior will be mainly based on incoming sensory information (i.e., the posterior is shifted toward priors and there is belief update; prior blinding; image from Manjaly & Iglesias, 2020).

In terms of neural implementation, precision, and PE depend on neuromodulators such as acetylcholine, GABA, dopamine, and glutamine (Sterzer et al., 2018; Keeler et al., 2021).

Acetylcholine suppresses PE and regulates its precision, whereas GABA and dopamine determine the influence of PE on the internal model and PE reward respectively; finally, Glutamatergic-N-methyl-d-aspartate receptors (NMDAR) send predictive signals from higher hierarchical levels to lower levels (Sterzer et al., 2018; Keeler et al., 2021). Disruptions in these neuromodulators have been proposed to explain alterations in the inference process in conditions such as psychosis and posttraumatic disorder (Sterzer et al., 2018; Putica et al., 2022).

Alterations in NMDAR receptors (Keeler et al., 2021; Mitchell et al., 2023), as well as the neuromodulators GABA (Bloss et al., 2011), dopamine (Södersten et al., 2016), and acetylcholine (Favier et al., 2020; Riva, Wiederhold & Mantovani, 2019), have been reported in individuals with AN. This imbalance could lead to an altered precision weighting process, resulting in much more weight being given to prior beliefs than to incoming information, and therefore the PE will be considered imprecise (i.e., insufficient to update the internal model). Thus, the MSI posterior will be biased toward priors rather than sensory information, and the PE signaling the discrepancy between the two will not be strong enough to update the internal model. In this sense, individuals with AN may be characterized by an abnormal "prior blinding" tendency. Other factors might also contribute to the bias in the process, such as altered interoceptive signal processing (Herbert, 2020), the different precision attributed to each sensory modality (e.g., visual information might be considered more reliable than others; Perruchoud et al., 2016) as well as biological factors (i.e., genetic and neurobiological changes affecting information processing; Bulik et al., 2022). The resulting weak PE will be thus solved through active inference, where sociocultural and psychological factors may strengthen the internal model (*Figure 6*).

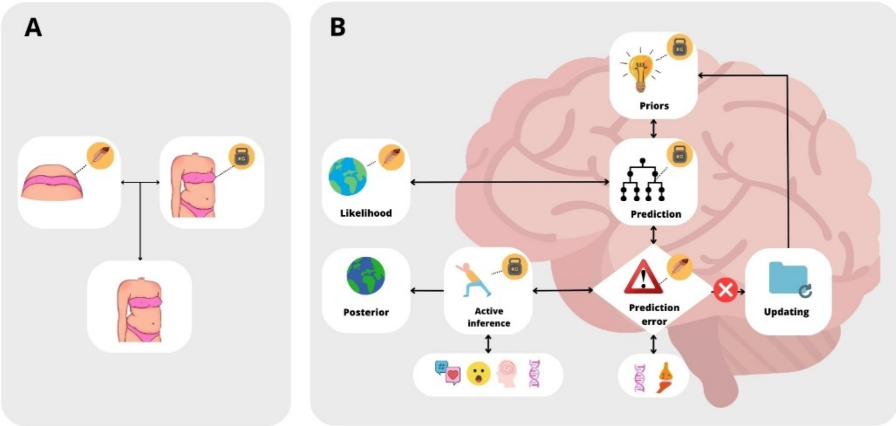

Figure 6. Impaired predictive coding in the context of dual-level multisensory integration. Panel A shows how, when first- and third-person spatial frame signals have to be combined, the integration result is biased towards the latter if a higher level of precision (more weight) is assigned to the allocentric information. Panel B summarizes the critical steps of inference processing when combining information from different sensory domains; changes could occur if more weight is given to priors and predictions than to incoming information, partly due to neurobiological factors. The discrepancy (prediction error) would then be resolved by seeking confirmation of one's predictions through active inference, rather than by updating one's internal models. In this active inference, socio-cultural, emotional, genetic, and neurobiological factors can guide the search for and processing of the information encountered. Therefore, the result (posterior) will be biased and not fully consistent with the original incoming sensory information.

This prior blinding effect has negative consequences when priors are distorted. Patients with EDs do indeed hold maladaptive beliefs (e.g., the ideal of thinness), and neuroscience studies have shown cortical dysfunction in memory-related cortical areas (e.g., distorted body representation in memory; Biezonski et al., 2016; Gadsby, 2017). As suggested by a systematic review of resting-state functional-MRI studies (Gaudio et al., 2016) “several brain regions could be involved in body image disturbances and may sustain an impaired integration between real and perceived internal/external state of one's own body in AN patients” (p. 582). Thus, basing body perception on dysfunctional priors might lead to altered body experience.

In particular, the final posterior requires the integration of information from both egocentric and allocentric spatial frames. The same altered processing could affect both egocentric and allocentric processing. Moreover, when there is spatiotemporal synchrony between information coming from different frames, the information is combined based on the weight of each submodel (Bertoni, Magosso & Serino, 2021). A VR study by Serino et al. (2015) suggests the existence of a primary impairment in the processing of spatial reference frames in patients with EDs, which in turn might alter the final inferential output.

Self-objectification might lead individuals with Eating Disorders to consider allocentric information as more precise than egocentric information, so that all signals are aligned with the dominant frame (Avillac et al., 2005) and to weigh visual information as more reliable compared to other senses. Information as more reliable compared to other senses. Furthermore, as shown by Eich et al. (2012), the use of an allocentric perspective turns off interoceptive signals. Commenting on their results, the authors explain: “The data suggest that adopting an observer [allocentric] perspective is tantamount to literal disembodiment at the neural level. That is, when we choose to relive past events from a perspective outside our body, we shut down the neural circuitry in the insula that is central for monitoring our bodies’ internal states.” (p. 177). As the Allocentric Lock theory suggests (Riva & Gaudio, 2012), people with AN may live in an "allocentric" body in which priors (e.g., beliefs, expectations, memories) have an enormous influence on shaping their experience relative to new incoming sensory information, including interoceptive information. As recently demonstrated, individuals with AN favor interoceptive metacognitive processes (e.g., trusting their own perceived sensations rather than their actual perceptions), disregarding bottom-up bodily input in favor of their previously altered top-down beliefs (Di Lernia et al., 2023). In other words, they experience the wrong body that they expect to experience.

Existing models of EDs tend to underestimate the role of body experience in the development and maintenance of pathology (Dakanalis et al., 2017) although, as discussed in the Introduction, the results of 4-year longitudinal studies involving more than 5,000 individuals have underscored its importance (Dakanalis et al., 2016, 2017).

Based on the data from this review, we suggest that the MSI process may be a critical mechanism in eating disorders and that its interaction with other factors (biological, sociocultural, psychological; Fredrickson & Roberts, 2016; Zipfel et al., 2015) may play a critical role in shaping the pathological outcome. In this framework, PP can be used to predict and understand how all these elements interact to determine a phenomenological outcome with specific characteristics, taking into account individual differences. However, the small number of studies encourages further research to investigate the possible relationship between multisensory integration and eating disorders. This can be done, for example, using multisensory technologies (e.g., VR) and paradigms such as the full-body illusion and the Body Swap illusion (Serino et al., 2016).

Body illusions use multisensory conflicts to promote embodiment over virtual bodies and offer the possibility of targeting body experience from the bottom up. Virtual reality's ability to simulate predictive processing in the brain and its multisensory nature has made this technology a potential ally in the treatment of body misperceptions in patients with Eating Disorders, particularly Anorexia Nervosa (Berg et al., 2019; Zipfel et al., 2015). The underlying idea is that the use of this technology can transform body representation by targeting the underlying mechanisms, i.e. the inferential process in the case of crossmodal integration (Petkova & Ehrsson, 2008; Keizer et al., 2016; Serino, Polli & Riva, 2019; Serino et al., 2016; Riva, Wiederhold & Mantovani, 2019; Riva et al., 2017).

To clinically address MSI dysfunctions we recently suggested a new therapeutic approach—Regenerative Virtual Therapy (Riva et al., 2021) —that integrates VR with different technologies and clinical strategies to regenerate a faulty bodily experience by stimulating the multisensory brain mechanisms combining both exteroceptive and interoceptive stimulation (i.e., visuo-tactile and sonoception respectively; Riva et al., 2021; Ackermann et al., 2001). Furthermore, we propose to integrate the reference frame shift during body illusions, proposing body swapping and/or full body illusions from both egocentric and allocentric spatial frames (i.e., egocentric and allocentric; Brizzi et al., 2023b) to fully target MSI. In this regard, in a recent study, we found that allocentric Full Body Illusion was able to induce embodiment over the fake body (see Brizzi et al., 2023b), altering multimodal integration abilities in healthy individuals: future research should investigate such change in other populations, as well as the impact of allocentric body illusion on factors such as body size estimation, body satisfaction, or body shame.

Data on patients with Bulimia are still too limited to conclude. As previously discussed, we encourage future work to study individuals with BN and to deepen the understanding of this condition to analyze whether multisensory integration deficits are also observed in BN and, if so, whether they have some associations with BN symptoms. This line of research may be relevant not only to better understand BN but also to identify differences and similarities between Anorexia Nervosa and Bulimia Nervosa, as well as why patients tend to transition from one pathology to the other (Yao et al., 2021).

Although multisensory integration occurs at every moment of our lives, surprisingly few studies have focused specifically on this topic, and several questions remain about this very important computational process in the brain. We propose that the study of MSI may provide a piece of the puzzle to better understand EDs. This does not mean that MSI alone will be able to explain complex conditions such as Eating Disorders, but adding this element to the existing biological and social factors involved in the aetiology of such conditions may offer important opportunities to take a step forward in their understanding.

2.2.2 Predicting Anorexia Nervosa treatment efficacy: an Explainable Machine Learning Approach[2]

Introduction

Anorexia Nervosa (AN) is a severe Eating Disorder (ED) marked by extreme self-imposed food restriction, significantly low body weight, intense fear of gaining weight, and a distorted body image. This distortion reflects an altered perception of the body and a dysfunctional relationship between body and self, where physical appearance heavily influences self-worth and identity (Walsh et al., 2022; American Psychiatric Association, 2013). The development of AN arises from a complex interplay of biological, psychological, and sociocultural factors. Genetic variations influence metabolic and appetite-regulating hormones like leptin and dopamine (Barakat et al., 2023). Dysfunctional thought patterns about body weight, perfectionism, and novelty-seeking personality traits further increase vulnerability (Strober, 2004; Brizzi et al., 2023). Sociocultural pressures, including thinness ideals and parental attitudes toward food, also play a significant role (Garner & Garfinke, 1980; Bell and Cooper, 2005).

The interplay of these factors contributes to AN's chronicity and severity, with studies showing that 19%-26% of individuals meet diagnostic criteria even after 20-30 years (Andres-Pepina et al., 2020). This chronic nature makes AN a life-threatening mental health condition with severe physical and psychological implications. Recent research showed that AN affects up to 3% of young women and has the highest mortality rate of any psychiatric disorder, with approximately 5% of patients dying within four years of diagnosis (Frank et al., 2024; Auger et al., 2021). These epidemiological statistics portray AN as a public health emergency, particularly given that lifetime prevalence ranges from 0.5% to 3.5% in women and 0.1% to 2.0% in men (Nagata and Golden, 2022). The situation has worsened following

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[2] This study has been published: Brizzi, G., Pupillo, C., Sajno, E., Boltri, M., Brusa, F., Scarpina, F., Mendolicchio, L., & Riva, G. (2025). Predicting anorexia nervosa treatment efficacy: an explainable machine learning approach. *Journal of Eating Disorders*, *13*(1), 97. https://doi.org/10.1186/s40337-025-01265-3.

the COVID-19 pandemic (Boltri et al., 2024), which resulted in a 48% increase in hospital admission rates to specialized ED units compared to previous years (Boltri et al., 2024).

In response to these concerning trends and the multifaceted nature of AN, the current situation presents significant challenges for healthcare systems worldwide. AN remains a challenging disorder to comprehend and treat, given its complex etiology and diverse manifestations, and the rising demand for healthcare providers and therapeutic interventions has placed strain on existing services. This pressing situation has steered the ED research field, particularly in anorexia, towards more efficient identification of outcome predictors and treatment efficacy factors. The goal is to strategically allocate limited resources to maximize clinical impact and help the greatest number of individuals effectively (Mehler et al., 2023; Kazdin et al., 2017).

Longitudinal studies investigated predictors of treatment outcomes in AN. For instance, Fichter and colleagues (2017) identified Body Mass Index (BMI) at admission and Eating Disorder Inventory Maturity Fears subscale at admission as critical factors in determining the successful recovery, intended as the absence of AN diagnosis - in 112 patients. However, these types of studies are difficult to conduct due to high costs, low power, high attrition rates, and testing of specific or limited hypotheses (e.g. a limited set of predictors), leading to difficulties in replication and limited study comparability (Frank et al., 2024).

In recent years, technological advances have allowed for more sophisticated and effective techniques than clinical longitudinal research, thanks to Machine Learning (ML). ML facilitates the development of predictive models that can be used to test hypotheses, make inferences from data, and employ flexible, data-driven approaches to maximize predictive power (Fardouly et al., 2022; Sajno et al., 2023). This study specifically focuses on supervised ML methods, where models are trained on labeled datasets containing input-output pairs with known outcomes. This approach involves selecting predictors based on existing literature and clinical expertise, defining an outcome label such as treatment effectiveness, and developing a model able to predict this label based on selected features (Fardouly et al., 2022). In other words, supervised ML models detect patterns and relationships that traditional analysis might not detect. Supervised ML has been applied in emerging use cases in EDs domain, including risk factor identification, monitoring of patients, and predicting treatment response and prognosis in clinical populations (for a review, see Ghosh et al., 2024).

In the mental health research field, one line of research is applying ML models to predict treatment outcomes and identify critical factors linked to clinically positive outcomes (Jankowsky et al., 2024). For example, ML has been used to predict treatment outcomes for depressive disorder (for a review, see Sajjadian et al., 2021). Chekroud et al. (2016) employed supervised ML to predict patients' responses to antidepressant medication by analyzing clinical variables, including baseline symptom severity, treatment history, and sociodemographic information. In the field of cognitive rehabilitation for Mild Cognitive Impairment and dementia, ML techniques have been applied to predict disease progression, conversion from MCI to dementia, and rehabilitation outcomes starting from neuropsychological tests and sociodemographic data (Grassi et al., 2019).

In the EDs research field, current research has primarily concentrated on two areas: (i) identifying biomarkers through neuroimaging (e.g., Lavigno et al., 2015) and (ii) detecting at-risk individuals (e.g., Arold et al., 2023). For instance, Merhbene and colleagues (2024) reviewed the use of ML and Natural Language Processing methods to predict AN symptom from social media posts and comments, reporting relatively good performance levels (F1-score ranging from 0.67 to 0.93). Frank and colleagues (2023) developed a ML model to predict BMI at a 6-month follow-up in a sample of individuals with AN treated in a 6-day per week partial hospital program, finding that BMI change from admission to discharge was the most important predictor, strongly correlating with BMI at follow-up (r= 0.55), while clinical questionnaire scores (e.g., State-Trait Anxiety Inventory, Beck Depression Inventory-II) were less predictive. Sandoval-Araujo and colleagues (2024) applied ML to distinguish between typical and atypical AN using BMI, reinforcing its role as a key diagnostic parameter. Another line of research instead used ML methods to classify individuals with a history of AN at two stages of recovery from healthy controls using brain magnetic resonance images, observing differences in cortical thickness and gray matter volume across several regions (i.e., insula, lateral orbitofrontal, and temporal pole; Arold et al., 2023). Similarly, Lavignino and colleagues (2015) identified six brain regions (i.e., cerebellum white matter, choroid plexus, putamen, nucleus accumbens, the diencephalon, and the third ventricle) to be relevant in distinguishing individuals with AN from healthy controls.

While ML applications in EDs, particularly AN, are emerging, their integration into clinical practice remains limited. Moreover, a major gap persists in studies investigating the key variables that influence treatment outcomes and long-term recovery trajectories. This underscores the need for broader ML applications to support clinical decision-making, treatment development, and personalized intervention strategies in AN care.

The present study aims to address this gap by expanding ML applications focusing on understanding factors that influence treatment outcomes in AN. Specifically, this research employs supervised ML techniques with two primary objectives:

- Create a model to predict the effectiveness of ED treatment in a cohort of hospitalized patients affected by AN,

- Identify the most influential physical and psychological variables for predicting positive treatment outcomes, specifically in terms of weight recovery.

A deeper understanding of the critical factors contributing to effective intervention programs can help target the core aspects influencing treatment outcomes. This allows for a more strategic allocation of limited resources (e.g., financial, personnel, and physical space) to enhance overall treatment outcomes and reach a broader population. Moreover, this approach offers valuable insights into AN mechanisms, stressing key variables that play a pivotal role through a data-driven perspective.

Methods

Data source

Data for this study were retrieved from the study by Brusa and colleagues (2023) . It contains clinically relevant physical and psychological parameters assessed before starting the rehabilitation program at the IRCCS Istituto Auxologico Piancavallo (Italy). The dataset contains information related to 72 severe patients (68 females, 4 males) with a diagnosis of AN (54 restrictive, 18 binge-purge subtypes) admitted to a multidisciplinary hospitalization program for EDs between August 2021 and July 2022. Inclusion criteria were: (a) a primary diagnosis of AN, (b) a BMI at admission equal or lower to 17 kg/m^2, indicating moderate to extreme severity, and (c) compliance with the rehabilitation program. *Table 1* presents sample descriptives. Patients were exposed to a multidisciplinary treatment, proposing both individual and group activities (for a more detailed explanation of the treatment, see Supplementary Materials - *Table 8* -and the original study by Brusa et al., 2023). Clinically relevant parameters were assessed at the beginning of hospitalization (T0) and the end of the rehabilitation program (T1).

	Mean (sd)	Minimum	Maximum
Age	24.11 (12.41)	13	66
Duration of Illness (years)	10.14 (12.53)	0	58
Age first diagnosis (years)	16.23 (6.41)	10	50
BMI (admission)	14.13 (1.58)	9.73	16.9
BMI (discharge)	14.49 (1.45)	10.22	17.6
Hospitalization length (days)	35.83 (9.07)	21	59

Table 1. Sample descriptives. BMI = Body Mass Index.

Because of the severity of patients (BMI mean = 14.13, sd = 1.58) and the short treatment length (Days mean = 35.83, sd = 9.07) we preliminary performed a paired sample t-test to investigate significant differences in BMI before and after the treatment. The analysis showed a significant difference, with the BMI ad admission being significantly higher than the BMI at the discharge (*Table 2*).

		Student's t	df	p	Mean Diff (SE)	Cohen's d
BMI (admission)	BMI (discharge)	-3.92	71.0	< 0.01	-0.35 (0.09)	-0.46

Table 2. Paired sample t-test. The table presents the paired sample t-test results to investigate differences between BMI at admission and discharge. SE = standard error, Diff = difference, df = degree of freedom.

Procedure

Procedure and results reporting were conducted based on Flanagin et al. (2024) and Serino et al. (2017).

Study Design and Outcome Measure

We developed and evaluated ML models to predict treatment success for AN through binary classification of ΔBMI (i.e., weight improvement). Models were developed and trained to predict two different classes reflecting patients' changes in BMI from admission to discharge (ΔBMI), where class 1 indicated weight recovery or stability (ΔBMI ≥ 0; 53 subjects) and class 0 indicated weight loss (ΔBMI <0; 19 subjects). The choice of using BMI as an index of treatment effectiveness is based on prior research (Kaplan et al., 2009; Makhzoumi et al., 2017; Sandoval-Araujo et al., 2024). Notably, our decision to consider BMI maintenance (no change) as a positive outcome is supported by research showing that severe anorexia (BMI <15) and the restrictive subtype may have no change pre-post treatment in the short term (Toppino et al., 2022). Indeed, in severe cases of AN, maintaining weight can be a critical first step toward recovery: studies indicate that patients with extreme weight loss often experience significant physiological and psychological challenges that make immediate weight gain difficult. Then, stabilizing weight can prevent further health deterioration and provide a foundation for gradual recovery (Maurel et al., 2024).

Features

The database contains clinical, physical, and psychological parameters commonly assessed in clinical practice. Below are presented the main measures, whereas detailed information is provided in Supplementary Materials (*Table 5, Table 6*).

Psychological Variables

- The Body Uneasiness Test (BUT; Cuzzolaro et al., 2006) is a 71-item questionnaire to assess body-related discomfort. It comprises two main subscales: subscale A refers to weight phobia, body image concerns, avoidance, compulsive self-monitoring, detachment, and depersonalization from the body (34 items), whereas subscale B measures worry related to different body parts (37 body areas). Examples of items of scale A include: “I spend a lot of time in front of the mirror” and “I feel I am fatter than others tell me”, whereas scale B asks participants to rate how much they hate different body areas such as height, arms, and stomach. This questionnaire has been validated in the Italian language, with a Cronbach’s alpha between 0.69 and 0.90 (Cuzzolaro et al., 2006).
- The Eating Disorder Inventory-3 (EDI-3; Clausen et al., 2010) is a 91-item questionnaire that assesses three ED-specific pathological symptom categories (drive for thinness, bulimia, body dissatisfaction) and nine general symptom categories (low self-esteem, personal alienation, interpersonal insecurity, interpersonal alienation, interoceptive deficits, emotional dysregulation, perfectionism, asceticism, maturity fears); additionally, 6 composite scales can also be calculated to characterize better the condition (eating concerns composite, ineffectiveness composite, interpersonal problems composite, affective problems composite, overcontrol composite, global psychological maladjustment). Examples of items include “I eat sweets and carbohydrates without feeling nervous” and “I think my stomach is too big”.
- The EDI-III has been validated in Italian language with Cronbach's alpha values for the subscales in ranging from 0.70 to 0.94.

- The Psychological General Well-Being Index questionnaire (PGWBI; Dupui, 1984) is a 22-item questionnaire to assess Quality of Life (HRQoL). It comprehends six subscales: anxiety, depression, positivity and well-being, self-control, general health, and vitality. Examples of items are “How often were you bothered by any illness, bodily disorder, aches or pains during the past month?” and “Did you feel depressed during the past month?”. It has been validated in the Italian language with Cronbach's alpha coefficients ranging from 0.92 to 0.94.
- The Symptom Checklist-90 (SCL-90; Sarno et al., 2011) is a 90-item questionnaire to assess nine symptomatologic dimensions: somatization; obsessive-compulsive behaviours and thoughts, interpersonal sensitivity, depression, anxiety, hostility, phobic anxiety, paranoid ideation, and psychoticism. Items are rated on a 5-point Likert scale from 0 (not at all) to 4 (extremely). Examples of items include rating how much participants were bothered by “headaches” and “feeling others are to blame for most of your troubles”. The questionnaire was validated in Italian, showing Cronbach's alpha coefficients between 0.70 and 0.96.
- The Frost Multidimensional Perfectionism Scale (FMPS; Frost et al., 1990) is a 35-item questionnaire assessing five dimensions of perfectionism, namely personal standards, concern over mistakes, parental expectations, doubting of actions, and organization. Examples of items include “I feel that I have made a lot of mistakes in my life" and "If I fail at work/school, I will be a failure as a person”. The questionnaire has been validated in the Italian language, showing Cronbach's alpha ranging from 0.86 to 0.89.

Physical Variables

- The Bioelectrical impedance analysis (BIA; Kahlil et al., 2014) is a method used to estimate body composition focused on the amounts of body fat and muscle mass.

This technique relies on measuring the body’s impedance, namely the body's opposition to the flow of an electric current (i.e., resistance and reactance). From this parameter, it is possible to calculate extracellular water, body cell mass, and phase angle.

The final features set consisted of 52 features, including questionnaire subscale scores and physical parameters assessing patients' state at the beginning and the end of the hospitalization. For this study, only parameters at the beginning of the treatment program were considered.

A more in-depth explanation of predictors (features) is available as Supplementary Material.

The model did not include demographic variables based on Frank and colleagues (2024).

Data Preparation and Feature Selection

The dataset was initially examined for quality and completeness. Missing values were imputed using the K-Nearest Neighbors Imputer, which has shown robustness in handling missing data in clinical datasets (Batista & Monard, 2003). All features were scaled to the same values using StandardScaler, which is considered a necessary practice to improve the accuracy of ML model predictions (de Amorim et al., 2023). The Variance Inflation Factor (VIF) was calculated for each predictor variable to assess multicollinearity. No variables exhibited a VIF greater than 10, indicating that multicollinearity was not a significant concern in our dataset (Hair et al., 2010).

Machine Learning Pipeline

ML pipeline (see Figure 1) started with data preprocessing and cleaning with subsequent delta BMI label calculation. A Dummy Classifier (DC) was initially generated as a baseline model to establish a performance benchmark for randomness. In addition, Linear

Discriminant Analysis (LDA) was applied to compare classification performance with the other models (Graf et al., 2024).

Subsequently, six supervised ML algorithms were trained based on ones commonly used in the EDs research field: specifically, Decision Tree (DT), Random Forest (RF), Gradient Boosting (GB), Support Vector Machine (SVM), Logistic Regression (LR), and k-Nearest Neighbors (kNN) were tested based on Gosh and colleagues (2024).

The dataset was randomly split into a 70/30 ratio, with 70% allocated for training to allow the models to learn underlying patterns and 30% reserved for testing to evaluate their generalization ability on unseen data. This split follows standard ML practices, balancing the need for sufficient training data while ensuring a robust test set for performance assessment (Gholamy et al., 2018). 5-fold and 10-fold cross-validation with 5 repeats were performed for each algorithm to measure the models' performance. This process allowed the assessment of model stability and generalizability across different data subsets. Following the cross-validation phase, hyperparameter optimization for all six algorithms was performed by using three main techniques: Randomized Search, Bayesian Search, and Grid Search (Yu & Zhu, 2020). This phase aimed to refine the parameters of each model to achieve optimal performance. After this, a new cross-validation on the optimized models was performed to assess the performance improvement.

Based on optimization results and cross-validation processes, the two best-performing models were selected for final testing on the held-out test set. Importance features analyses were performed for the best model to identify the most important predictors. Finally, to enhance model interpretability, SHAP (SHapley Additive exPlanations) was utilized to understand the contribution of individual features to the model's predictions.

Model Evaluation

The evaluation metrics considered for each phase of the training and testing set were accuracy (i.e., the ratio between the correctly classified samples and the total number of samples), precision (i.e., the ratio between correctly classified samples and all samples assigned to that class), recall (i.e., sensitivity or True Positive Rate, indicating the ratio between correctly classified positive samples and all samples assigned to the positive class), specificity (i.e., the ratio between correctly classified negative samples and all samples classified as negative), F1 score (i.e., harmonic mean of precision and recall), and Area Under the Curve - Receiver Operating Characteristic (AUC-ROC - i.e., ROC curve summary metric that reflects the ability to distinguish between classes, shows the overall diagnostic accuracy). These metrics were selected as they are the most widely used in binary classification in clinical research (Hicks et al., 2022), including in EDs (Sandoval-Araujo et al., 2024; Gosh et al., 2024). Confusion matrix was also generated to provide a detailed breakdown of the model predictions. Finally, the area under the curve precision-recall (PR-AUC) was assessed to address potential imbalances between classes and obtain an additional metric of overall performance (Saito & Rehmsmeier, 2015).

Model Validation

A repeated stratified K-fold cross-validation was employed to evaluate the model effectively. This splits the data set into multiple folds to train and test the model iteratively, providing a more reliable performance measure than a single training-test split. The K-fold variant splits the data into K subsets, trains the model on K-1 folds, and tests it on the remaining fold, repeating this process K times. Stratification ensures that the proportion of positive and negative samples is consistent across folds, which is critical for unbalanced data sets because it preserves class distributions. It has been seen to be one of the most suitable cross-validation types for small clinical datasets with multi-characteristic subjects, ensuring a balanced tradeoff between bias (errors from overly simplistic models that do not fit the data) and variance (errors from excessively complex models that overfit the data) (Wilimitis et al., 2023; Tougui et al., 2021). In addition, it has been seen that smaller K values (10, 5, 3) for small sizes offer a practical compromise, balancing computational efficiency and reliability of performance estimates (Tougui et al., 2021).

Feature Importance Analysis

Feature importance analysis was performed using the feature_importances_ attribute from scikit-learn to specifically evaluate individual predictors' impact on the best performing model and extract the 10 most influential features. These importance scores were computed as each tree's mean and standard deviation of the impurity decreased. Specifically, higher relative importance scores reflected features that are most relied on by the model to make predictions.

In addition, the SHAP (SHapley Additive exPlanations; Guidotti et al., 2018), Explainable AI (XAI) method was used to make the results more interpretable. SHAP was used because it assigns an importance value to each feature in the model output and is designed to be applied a posteriori to any type of ML model (Lundberg and Lee, 2017); the 20 most relevant parameters are extracted by default (Lundberg & Lee, 2017). In this context, Tree.Explainer algorithm was used since it is suitable for tree models such as Random Forest. SHAP values also provide a deeper understanding of the contributions of characteristics to individual predictions. SHAP summary plots were created for the overall model and separately for the two AN subtypes (0 = restrictive, 1 = binge-purge). This subtype-specific analysis was conducted solely as an additional post-hoc interpretability using SHAP values. No additional ML training was performed for the subtypes because the limited sample size precluded the development of separate ML models for each subtype.

Each patient was represented by a single point for each feature in the graph. The x-axis coordinate of each point was determined by the SHAP value, and the points were stacked along each feature to show their density. The features were sorted by the average absolute value of the SHAP values for each feature. Color was used to indicate the original value of a feature; red and blue indicate the high or low of the individual feature, respectively. The gray vertical line of the decision graph represents the baseline value of the model.

To compare and integrate the results of these two methods, it is essential to note that SHAP values provide a measure of how much each feature contributes to the model's output for a particular prediction, indicating both positive and negative impacts. In contrast, feature importance rankings generally focus on the overall importance of each feature in the model, providing only those that impacted positively. Consequently, discrepancies in the order of importance between the two methods may arise.

ML algorithms training and testing were carried out in Python v. 3.10.12, using Google Colab v. 0.0.1a2. We used the following Python packages: numpy, pandas, matplotlib, scikit-learn, seaborn, scipy.stats, scikit-optimize, and shap.

Figure 1 shows the ML pipeline.

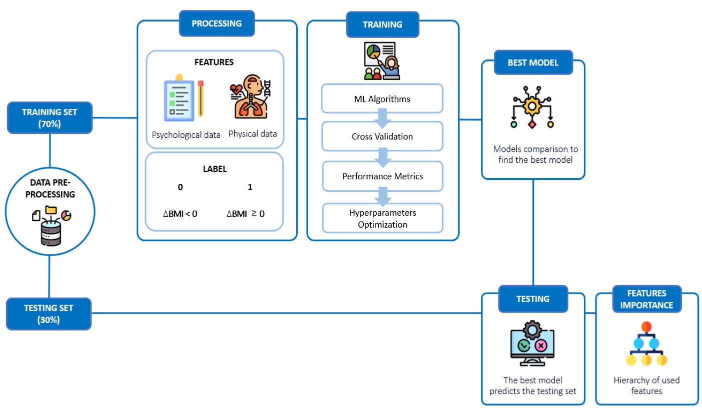


Figure 1. Machine Learning pipeline. The figure graphically summarizes the machine learning steps.

Results

ML performance evaluation during training and testing to predict delta BMI

The six trained ML algorithms ten folds cross-validation performance is reported in *Table 2*. Notably, all models outperformed our benchmark for randomness, namely DC model (AUC-ROC = 0.50) and LDA (accuracy = 0.31; Dhamnetiya et al., 2022). DC and LDA classification reports are reported as Supplementary Material.

	Decision Tree	***Random Forest***	***Gradient Boosting***	***Support Vector Machine***	***Logistic Regression***	***k-Nearest Neighbors***
Accuracy	0.70 (0.18)	0.70 (0.15)	0.71 (0.18)	0.74 (0.09)	0.58 (0.22)	0.67 (0.19)
AUC-ROC	0.61 (0.23)	0.65 (0.27)	0.65 (0.27)	0.62 (0.30)	0.57 (0.31)	0.65 (0.26)
Precision	0.80 (0.19)	0.75 (0.14)	0.81 (0.18)	0.74 (0.09)	0.71 (0.21)	0.74 (0.16)
Recall	0.79 (0.23)	0.91 (0.15)	0.82 (0.20)	1.00 (0.00)	0.71 (0.26)	0.84 (0.20)
Specificity	0.43 (0.45)	0.14 (0.33)	0.44 (0.47)	0.00 (0.00)	0.24 (0.40)	0.18 (0.36)
F1-Score	0.77 (0.18)	0.81 (0.12)	0.79 (0.15)	0.85 (0.06)	0.69 (0.20)	0.78 (0.16)

Table 2. Evaluation metrics of the 10-fold with 5 repeats cross-validation for the six algorithms. The values are expressed as mean values and their standard deviation in brackets. AUC-ROC=Area Under the Curve - Receiver Operating Characteristic

The best hyperparameters were found with Bayesian Optimization, which obtained similar values to the other two methods and is the most robust technique. As shown in *Table 3*, the best-performing algorithms trained with the fitted hyperparameters were Decision Tree (DT) and Random Forewst (RF).

	Decision Tree	*Random Forest*
Accuracy	0.72 (0.20)	0.76 (0.15)
AUC-ROC	0.68 (0.23)	0.67 (0.23)
Precision	0.85 (0.17)	0.88 (0.12)
Recall	0.75 (0.26)	0.81 (0.23)
Specificity	0.60 (0.44)	0.60 (0.44)
F1-Score	0.77 (0.21)	0.81 (0.14)

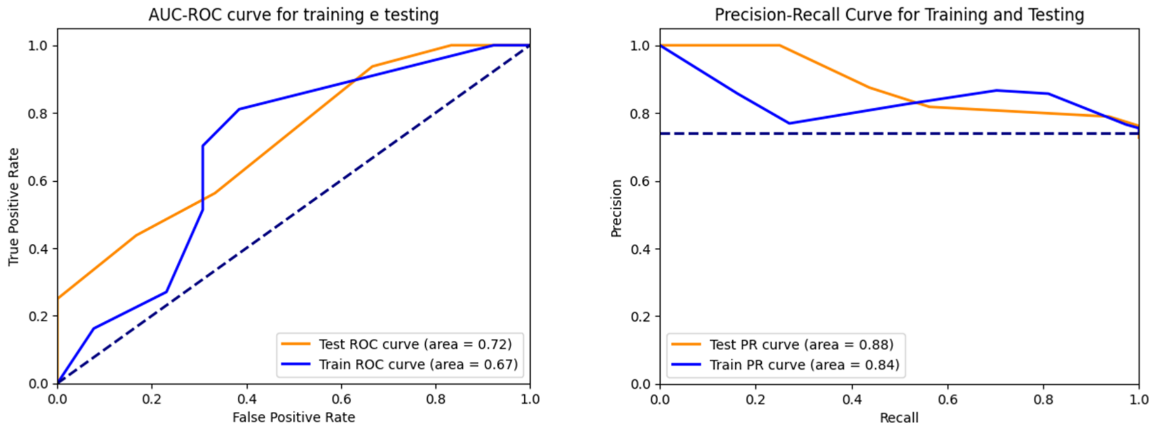
Table 3. Evaluation metrics of the 10-fold with 5 repeats cross-validation for the two optimized models: Decision Tree and Random Forest. The values are expressed as mean values and their standard deviation in brackets. AUC-ROC=Area Under the Curve - Receiver Operating Characteristic.

The testing phase was conducted exclusively on the two best-performing models, DT and RF, which were identified based on their superior performance during training. To assess their generalization ability, we evaluated these models on a previously unseen 30% hold-out test set from the original dataset. This test set was not used during training, ensuring that the evaluation reflects how well the models can classify new data in our binary classification. The results of the final best model - RF - are presented in *Table 4*: its results show an accuracy of 0.77, highlighting the model's ability to correctly classify most of the cases in the test set.

Random Forest - Test		
	Class 0 (negative Δ BMI)	*Class 1 (0 or positive Δ BMI)*
Accuracy	0.77	
AUC-ROC	0.72	
Precision	0.67	0.79
Recall	0.33	0.94
Specificity	0.33	0.33
F1-Score	0.76	0.86

Table 4. Evaluation metrics of the testing set for the optimized Random Forest (RF) model. The table shows the results for both binary classes. AUC-ROC = Area Under the Curve - Receiver Operating Characteristic.

To evaluate the RF performance, its ability to predict class 1 and 0 were tested. The AUC-ROC of 0.72 indicated a fair discrimination without overfitting and outperforming the training curve (AUC-ROC = 0.67; *Figure 2a*). The curves' shapes indicate that the model performs consistently better than random chance across various classification thresholds. *Figure 2b* presents the Precision-Recall (PR) curves for training and testing. The PR-AUC values for testing (0.88) and training (0.84) are notably high, indicating robust performance in balancing precision and recall.



(a) **(b)**

Figure 2. Visual comparison of a performance model for the training and testing set for Random Forest. The blue lines represent the training curves, the orange lines represent the testing curve, and the dashed lines of a random classifier. A higher curve represents a better performance of the model to be acceptable, it must exceed the dotted lines. The first figure represents the AUC-ROC curve (a). The AUC-ROC curve shows the relationship between the true positive rate and the false positive rate. The second figure represents the Precision-Recall (PR) curve (b). The PR curve shows the relationship between precision and recall. AUC-ROC = Area Under the Curve - Receiver Operating Characteristic.

The model correctly identified expected positives (precision = 0.79) and true positives (recall = 0.94). However, it showed difficulties in identifying true negatives (specificity = 0.33). Similarly, the confusion matrix (Figure 3) showed that the model accurately classified 15 out of 16 positive cases (True Positives) but struggled with identifying negative outcomes (Class 0), misclassifying 4 out of 6 as positives (False Positives). Despite the 4 false positives, the high precision (0.79) is explained by the large number of true positives (15) relative to false positives (4). The high recall and precision for Class 1 suggest that the model is highly reliable in predicting positive BMI changes, which are critical for assessing treatment success. On the other hand, the high false positive rate and low specificity is given by the imbalance of the two classes, as the negative class is lower than the positive class (Thölke et al., 2023).

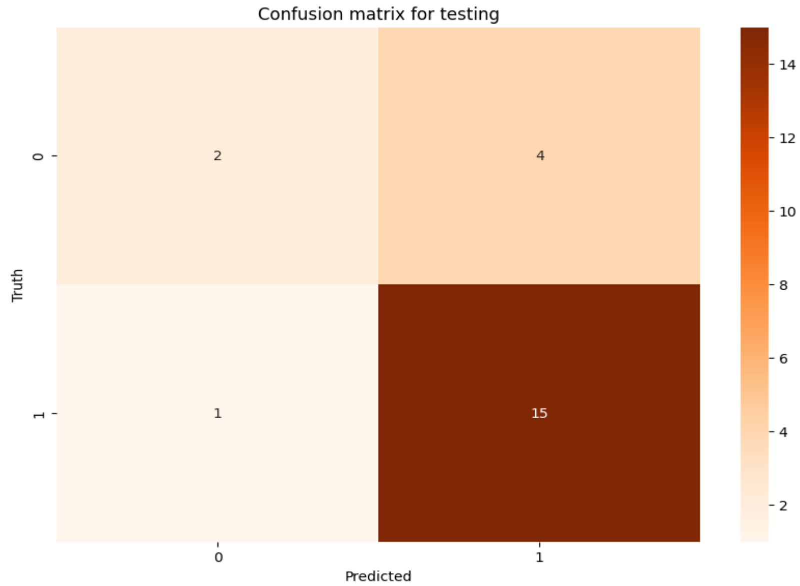


Figure 3. Confusion matrix of the testing set. The picture shows the four basic characteristics for evaluating a classification model. In this case, it concerns the confusion matrix of the best model (Random Forest) for the testing set. 1 indicated weight recovery or stability (ΔBMI $\geq$ 0) and 0 indicated weight loss (ΔBMI <0). In the first row, the first cell indicates the true negatives (number of patients correctly classified that their delta BMI has worsened) and the adjacent cell the false positives (number of patients misclassified with improved or unchanged delta BMI, known as type I error), while the second row shows the false negatives (number of patients who were misclassified with improved or unchanged delta BMI but actually had negative delta BMI, known as type II error) and true positives (number of patients who were correctly classified as patients to whom delta BMI was positive or unchanged), respectively.

Predictors Importance

Initially, the importance of the features of the optimized RF model was evaluated using feature importance analysis, which showed the 10 most important model predictors for the training set. BUT-PST, EDI3-PA, and EDI3-IPC resulted as the top three most influential parameters (*Figure 4*).

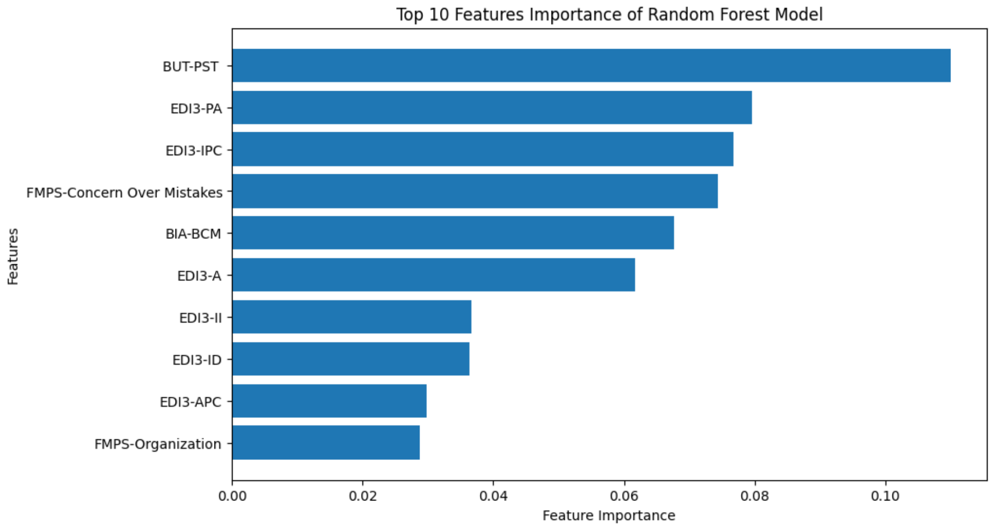


Figure 4. Scikit-learn-based feature importance rank for predicting class 1 (0 or positive delta BMI). The features importance plot shows the 10 most important predictors of weight recovery and/or stability. BUT= Body Uneasiness Test, EDI3 = Eating Disorder Inventory 3, FMPS= Frost Multidimensional Perfectionism Scale, BIA= Bioelectrical impedance analysis. BUT-PST= Positive Symptom Total, EDI3-PA=Personal Alienation, EDI3-IPC= Interpersonal Problems Composite, BIA-BCM= Body Cell Mass, EDI3-A= Asceticism, EDI3-II= Interpersonal Insecurity, EDI3-ID = Interoceptive Deficits, EDI3-APC= Affective Problem Composite.

To further understand the impact of features on individual predictions, the SHAP technique was applied. The overall SHAP summary plot (*Figure 5*) highlighted BMI (admission) as the most impactful feature, in addition to EDI3-EDRC and EDI3-GPMC.

Comparing the Scikit-learn-based feature importance rank and the SHAP outputs, EDI3-PA, EDI3-IPC, FMPS-Concern Over Mistakes remained in the top 10 predictors, while BUT-PST and EDI3-A were still present but in lower positions.

A more detailed a posteriori analysis was performed on the two subtypes of AN, i.e. restrictive (R) (*Figure 6a*) and binge-purge (BP) (*Figure 6b*). In both conditions, BMI at admission emerged as the most relevant predictor, as observed in the overall SHAP model. Specifically, low-to-medium initial BMI predicted an equal to zero or positive ΔBMI. No differences emerged when comparing the R and the overall SHAP model, whereas differences emerged when considering the BP model. Here, features showed different feature rankings despite the variables being the same.

Figure 5. Summary plot of SHAP-calculation for the 20 highest-ranking features. Features are sorted by their mean absolute SHAP value in descending order, with the most important variables at the top. Each dot corresponds to one patient in this study. This plot shows how the different variables of each patient affect the prediction of the RF model towards class 1 (0 or positive delta BMI). Positive SHAP values (to the right) indicate features that increase the likelihood of a positive BMI change, while negative SHAP values (to the left) indicate features that decrease this likelihood. Instead, the gradient of colors indicates positive (red) or negative (blue) values compared to the original feature values for each patient. The plot is based on the RF model with all features included for all 72 patients. BUT = Body Uneasiness Test, EDI3 = Eating Disorder Inventory 3, FMPS

= Frost Multidimensional Perfectionism Scale, BIA = Bioelectrical impedance analysis, SCL90 = Symptom Checklist-90, PGWBI = Psychological General Well-Being Index questionnaire, BMI = Body Mass Index, EDI3-EDRC = Eating Disorder Risk Composite, EDI3-GPMC = General Psychological Disadaptation Composite, EDI3-IPC = Interpersonal Problems Composite, BIA-PA = Phase Angle, EDI3-MF = Maturity Fear, EDI3-PA = Personal Alienation, EDI3-OC = Obsession Composite, BUT-A = Avoidance Behavior, EDI3-IA = Interpersonal Alienation, EDI3-II = Interpersonal Insecurity, EDI3-A = Asceticism, EDI3-LSE = Low Self-Esteem, BUT-PST = Positive Symptom Total, BUT-BIC = Body Image Concerns, EDI3-DT = Drive for Thinness.

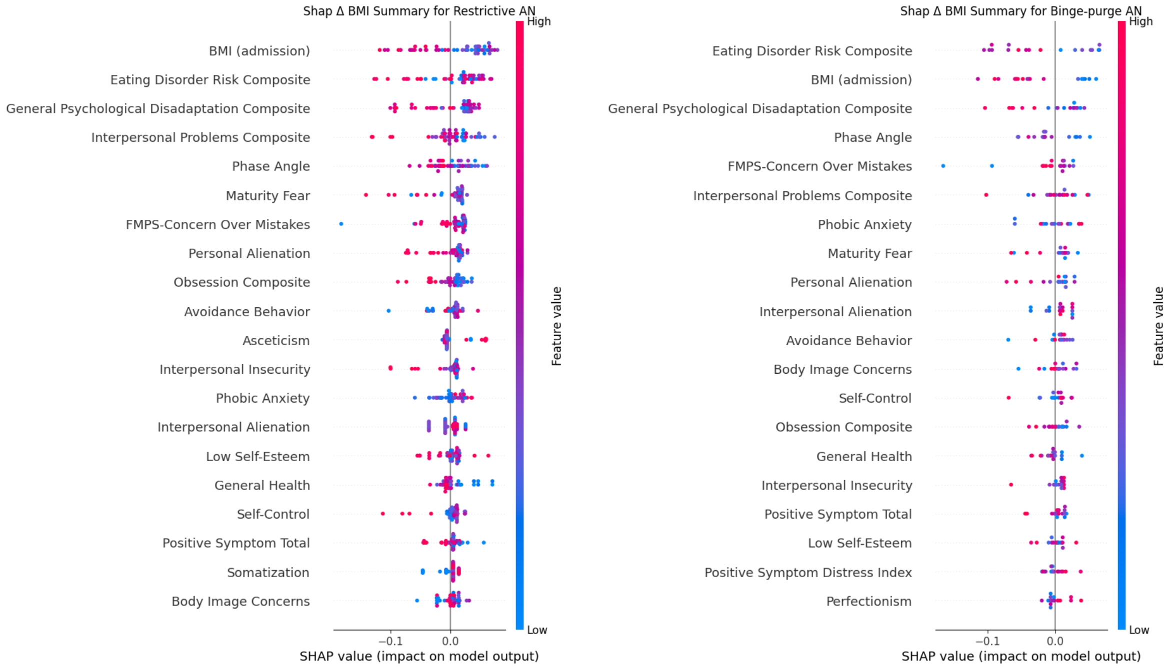


Figure 6a, 6b. Summary plot of SHAP-calculation for the 20 highest ranking features for subtypes AN. Plot shown for restrictive AN (a) and binge-punge AN (b). Features are sorted by their mean absolute SHAP value in descending order with the most important variables at the top. Each dot corresponds to one patient in this study. Positive SHAP values (to the right) indicate features that increase the likelihood of a positive BMI change, while negative SHAP values (to the left) indicate features that decrease this likelihood. Instead, the gradient of colors indicates positive (red) or negative (blue) values compared to the original feature values for each patient. The plot is based on the RF model with all features included for all 72 patients. Body Uneasiness Test = BUT, Eating Disorder Inventory 3 = EDI3, Frost Multidimensional Perfectionism Scale = FMPS, Bioelectrical impedance analysis = BIA, Symptom Checklist-90 = SCL90, Psychological General Well-Being Index questionnaire = PGWBI, Body Mass Index = BMI, Eating Disorder Risk Composite = EDI3-EDRC, General Psychological Disadaptation Composite = EDI3-GPMC, Interpersonal Problems Composite = EDI3-IPC, Phase Angle = BIA-PA, Maturity Fear = EDI3-MF, Personal Alienation = EDI3-PA, Obsession Composite = EDI3-OC, Avoidance Behavior = BUT-A, Asceticism = EDI3-A, Interpersonal Insecurity = EDI3-II, Interpersonal Alienation = EDI3-IA, Low Self-Esteem = EDI3-LSE, Positive Symptom Total = BUT-PST, Body Image Concerns = BUT-BIC, Positive Symptom Distress Index = BUT-PSDI, Perfectionism = EDI3-P.

Discussion

The primary aim of this study was to develop a ML model to predict weight recovery or stabilization in a cohort of AN inpatients. Results from this study showed ML good performance levels (accuracy = 0.77, AUC-ROC = 0.72, and PR curve = 0.88), similar to previous studies (AUC-ROC values between 0.49 and 0.93, and accuracy between 0.59 and 0.86; Gosh et al., 2024, Espel-Huynh et al., 2021, Haynos et al., 2023). Despite differences in outcome measures, predictor variables, and performance metrics, the results of this study remain within the performance range reported in the literature, highlighting the potential clinical utility of this model in the context of eating disorders.

The secondary aim of this study was to identify which variables better predicted weight recovery, as a proxy of successful treatment. Scikit-learn feature importance extraction (Breiman, 2001) and SHAP values (Orlenko & Moore, 2021) were used to identify predictors at the global and individual levels respectively. Interestingly, results were consistent: overall predictors were also reflected at the individual level, thus reinforcing the robustness of results (Tjoa & Guan, 2021). The subsequent section goes into more detail concerning the three most important weight stability and recovery predictors. To conclude, we critically discussed the implications of integrating ML into clinical practice.

This study represents a preliminary, proof-of-concept effort designed to highlight the potential of ML methods in the field of EDs research. The following sections will explore the model's most significant predictors to conclude with a critical evaluation of the advantages and challenges associated with applying ML in clinical settings.

Predicting Weight Recovery or Stability

Body-Self Relationship

Scikit-learn features importance and SHAP analyses identified BUT score as a significant predictor of weight stability and recovery. In particular, the Positive Symptom Total (BUT-PST), Body Image Concerns (BUT-BIC), the overall Positive Symptom Distress Index (BUT-PSDI), and body-related concerns and dissatisfaction with own body image (BUT-A) emerged as critical factors. This aligns with early Bruch's (1974) insights, according to which AN interventions should carefully consider how patients perceive and relate to their bodies to be effective in the long term.

A large amount of evidence showed that AN is fundamentally characterized by a distorted experience of one's body. This Body Image Disturbance goes beyond mere visual (mis)perception, representing a profound disconnection between the actual physical state and the subjective experience of their body at perceptual, emotional and cognitive levels (Brizzi et al., 2023a; Brizzi et al., 2023b; Artoni et al., 2021). Specifically, research has shown that patients with AN report high levels of body dissatisfaction and body-related distress, which are reinforced by the internalization of unhealthy beauty standards (Artoni et al., 2021). Concerns still remain regarding perceptual alterations: while some studies reported individuals with AN significantly overestimate their body dimensions compared to healthy controls (Sattler et al., 2020), others have found no such perceptual distortion (Provenzano et al., 2019). Such inconsistency may partly stem from methodological differences across studies - e.g., different assessment tools ranging from explicit questionnaires to implicit measures - as well as limited carefulness in capturing bodily experience complexity.

In fact, how we experience our body depends on both emotions and beliefs, but also on how we process and integrate information from inside (interoceptive) and outside our body (exteroceptive). Recent studies revealed deficits in patients with AN both in processing inner body information (Lucherini et al., 2022) and at the level of integration of exteroceptive and interoceptive information (Brizzi et al., 2023). This favors the idea of perceptual alterations that may reinforce body image disturbance, creating a self-reinforcing cycle of distorted body experience.

Further investigation of these perceptual mechanisms could reveal novel patterns and inform therapeutic approaches. For instance, impaired interoceptive awareness might create a cascade effect where disconnection from internal bodily signals leads to distorted cognitive interpretations, such as feeling bloated despite no physiological basis, ultimately contributing to body dissatisfaction.

Despite these insights into the multifaceted nature of body experience, standard intervention protocols in hospital settings tend to neglect the role of the body in AN, prioritizing the work on food-related behaviors and weight recovery through dietary management (Artoni et al., 2021). While this remains essential, evidence seems to suggest this focus alone may be insufficient for comprehensive recovery. From this perspective, Then, it is not surprising that, to date, there are no superior treatment options for AN. Established interventions—including Cognitive Behavioral Therapy (CBT) and Family-based therapy—show similar outcomes, with limited success in achieving clinically significant improvements (Gann et al., 2022). Some authors have suggested that this therapeutic ceiling may stem from insufficient attention to body experience in conventional treatments (Artoni et al., 2021; Brizzi et al., 2023). In response, an emerging line of research is exploring the integration of body image-centered protocols into AN treatment. These innovative approaches encompass multiple strategies: psycho-educational sessions (e.g., reasoning about body-checking behaviors, or social media use; Cash & Hrsabosky, 2003; Mahon and Hevey, 2023), meditative practices (e.g., yoga, meditation; Ruzzito et al, 2021; Sala et al., 2023) or self-monitoring journaling exercises following Cognitive Behavioral Therapy Enhanced approach (CBT-E; Danielsen et al., 2016). Initial findings suggest that addressing altered body-self relationships positively influences recovery outcomes. Notable initiatives such as the Body Project (Stice and Presnell, 2007) and The Body Wise (Mounfold et al., 2014) have further advanced this approach by developing experimental body-focused protocols specifically for AN treatment.

Recently, technology-based treatments have been also proposed, including Mirror Exposure (Porras-Garcia et al., 2021) and Body Swapping (Serino et al., 2019) in Immersive Virtual Reality (IVR) environments. Such approaches use multisensory technology to place patients in bodies different in shape and weight from real ones, with the primary goal of proposing behavioral experiments that would not be possible in physical reality. For instance, in IVR Mirror Exposure paradigms, patients embody a normal-weight body and look at themselves in a virtual mirror from a third-person perspective (Porras-Garcia et al., 2021). This experience was observed in the fear of gaining weight (Porras-Garcia et al., 2021). Similarly, during Body Swapping procedure patients are asked to embody a normal weight body (BMI = 18.5), but this time from a first-person perspective (Serino et al., 2019). Interestingly, this experience has been observed to reduce body distortion, as the swap into a virtual body helped patients to re-establish a connection with their physical bodies (Serino et al., 2019). Recently, our research group proposed two different protocols in this direction: the study by

Malighetti al colleagues (2020) used a combination of IVR body swapping and mirror exposure into different bodies while asking patients to recall positive, negative, and neutral autobiographical memories depending on the body size (overweight, underweight, and normal-weight respectively), whereas the study by Brizzi and colleagues (pre-print) asked patients to recall what each part of her bodies was able to do for them in terms of enjoying full activities (i.e., functional mirror exposure). Following this trend, Regenerative Virtual Therapy (RVT; Riva et al., 2021) has been proposed. It is an innovative therapeutic approach that combines principles from neuroscience, psychology, and advanced technology to restructure faulty bodily self-representations. What makes this proposal particularly interesting is the combination of multisensory technologies to reshape both the inner and outer body self-perception, brain-stimulation techniques and mindfulness practices.

Drawing from Cognitive Behavioral Therapy (CBT) principles, Immersive Virtual Reality (IVR) approaches recognize the pivotal role of behavior in influencing emotional states and thought patterns. Just as psychological disorders often involve maladaptive behaviors that reinforce dysfunctional emotions and cognitions, IVR provides a unique platform for behavioral modification. By enabling controlled behavioral interventions in virtual environments, IVR facilitates bottom-up therapeutic change, where behavioral alterations can catalyze cognitive restructuring (Di Natale et al., 2024).

The findings from this study underscore the critical importance of integrating body-focused interventions into AN treatment protocols to optimize weight recovery and maintenance outcomes. Innovative technologies like IVR, when combined with traditional therapeutic approaches, offer unique opportunities to address the complex interplay between emotional, cognitive, and perceptual components of body experience.

Social and Interpersonal Factors

The feature importance analysis revealed two other two key predictors in addition to body-self relationship: the EDI3-PA (Personal Alienation) and EDI3-IPC (Interpersonal Problems). This aligns with previous studies showing that interpersonal difficulties and relationship style (e.g., Non-assertive and Friendly-submissive interpersonal style) influence AN symptomatology onset and maintenance (Carter et al., 2012; Martini et al., 2022; Jones et al., 2015). Notably, such a result was observed both when considering qualitative data (Cardi et al., 2018) and quantitative (Ung et al., 2017; Carfagno et al., 2024).

The importance of interpersonal relationships for mental health is well stressed by Sullivan's interpersonal theory (Sullivan,1954), according to which social interactions are fundamental for positive human functioning and dysfunctional relationships significantly increase psychopathology risk (Brown and Harris, 2012). Moreover, they are the focus of AN cognitive interpersonal maintenance model proposed by Schmidt and Treasure (2006), which stresses the role of relationships in pathology onset and maintenance. According to this theoretical framework, anorexic symptoms are maintained intrapersonally by beliefs about the positive function of the illness, and interpersonally by both positive and negative reactions elicited from close others by the physical presentation and behaviors associated with AN (Schmidt & Treasure, 2010; 2013). Then, symptoms such as food avoidance might be understood as a strategy to address the need to avoid close relationships that might evoke intense negative emotions. This may be even more the case in Western cultures, where food and eating are inherently social activities: shared meals are often at the heart of social interactions, celebrations, and family gatherings, making eating more than just food and nutrition, but a vital part of social bonding and community.

Following this perspective, Lacan (Recalcati, 2007) proposed that AN should be understood as a manifestation of a profound struggle with desire and identity, intricately linked to the subject's relationship with the Other (i.e., namely the symbolic representation of societal norms, familial expectations, and interpersonal relationships; Cosenza, 2023). That is, AN might be not merely a struggle with food, but it is a response to Other's demands and desires: food refusal can be then conceptualized as a form of resistance against the symbolic order and the expectations it entails (Abinzano, 2021). Importantly, this might also, in some way, reflect their resistance to treatment and lack of trust in care personelle and programs (Abbate-Dagaet al., 2013).

In light of all these considerations, Cognitive Behavioral Therapy (CBT), the Maudsley Model of Anorexia Nervosa Treatment for Adults (MANTRA; Allison et al., 2021; Loomes & Bryant-Waugh, 2021) and Multi-family (MFT-AN; Baudinet et al., 2023) therapeutic approaches include activities specifically targeted to address social and interpersonal difficulties (Koskina & Schmidt, 2019). Using strategies such as role-playing and behavioral experiments on one hand, and identity exploration and group activities on the other hand, these approaches try to work on the social component of AN. The idea is to allow patients to explore alternative identities, practice and train social skills, and explore alternative behaviors and beliefs. In hospital settings, social activities include psychoeducation groups and peer-discussions. For example, the individuals enrolled in the study by Brusa and colleagues (2023) participated in various rehabilitative activities with intrinsic relational and socializing value (i.e. group discussion, team-work, brainstorming ideas on specific topics, etc).

The MEDverse proposal (Cerasa et al., 2022) represents a conceptual framework that merges VR and augmented reality (AR) technologies within the metaverse to create immersive therapeutic environments tailored for mental health treatment. For example, it is possible to envisage social activities in the metaverse. Such activities might range from role-playing to engaging in conversations about food and body image with virtual characters, behavioral experimentals while practicing eating in virtual social settings, to group therapy sessions with avatars representing other patients and therapists. The technology's principal advantage lies in its capacity to generate a profound sense of presence and embodiment (Riva, 2012), enabling patients to emotionally and cognitively engage with therapeutic content in a way that transcends traditional interventions.

This heightened sense of immersion manifests through two crucial psychological mechanisms: first, the "place illusion", where patients genuinely feel present in the virtual environment, and second, the "plausibility illusion", where they process and respond to virtual events as if they were real (Slater, 2009). These mechanisms, combined with the capability to induce body ownership illusions through multisensory integration, create a powerful therapeutic platform where patients can safely explore and challenge themselves.

Through carefully designed virtual social scenarios, patients can practice interpersonal interactions in a controlled environment that feels authentically engaging yet remains therapeutically safe. The technology facilitates graduated exposure to challenging social situations, from intimate family meals to broader social gatherings, allowing individuals to develop and refine their social skills while managing anxiety and eating-related behaviors simultaneously. The immersive nature of these experiences, combined with real-time feedback and professional guidance, creates a powerful platform for addressing social isolation, improving communication patterns, and rebuilding damaged relationships – elements that are often central to the maintenance of eating disorders but challenging to address in traditional therapeutic settings (Treasure & Schmidt, 2013). Moreover, the virtual environment can be populated with avatars representing various social roles (family members, peers, colleagues), enabling patients to work through specific interpersonal challenges while developing more adaptive social interaction. The underlying idea is that "exposure to one’s problems and pain as they are experienced in the lives of the others facing you can bring about change of an unforeseen kind with far-reaching consequences" (Schlapobersky, 2016; Lipsits and Markowirz 2013).

The findings from this study underscore the critical importance of integrating social relationship work into AN treatment to optimize weight recovery and maintenance outcomes. Even in this context, technologies like IVR offer unique opportunities to address interpersonal challenges through direct experiential learning. The immersive nature of IVR enables patients to engage in social scenarios in real time, bypassing the limitations of traditional therapeutic approaches that rely heavily on mentalization and recall abilities. This is particularly valuable as individuals with AN often struggle with abstract cognitive processing and may benefit more from immediate, embodied experiences.

Machine Learning in Clinical Practice: Pros and Cons

In the last few years, ML has emerged as a powerful analysis approach for predicting treatment outcomes and understanding complex patterns in patient data. ML indeed offers several advantages over traditional statistical approaches. First, the latter is primarily used to confirm or refute specific hypotheses and may be more susceptible to overfitting issues when dealing with complex and multidimensional datasets (Chekroud et al., 2021), while supervised ML focuses on prediction and provide robust internal validation of model performance through techniques such as k-fold cross-validation, which helps mitigate overfitting concerns and improves generalizability (Wang, 2021). Second, ML offers greater flexibility in handling diverse data types and model structures.

Supervised ML can be fine-tuned through various parameters and hyperparameters to optimize performance for specific feature types and research questions (James et al., 2013). Furthermore, ML excels at processing high-dimensional data, allowing it to consider numerous clinical and nonclinical variables simultaneously (Breiman, 2001), and it can identify complex, nonlinear relationships among variables without requiring predetermined assumptions (LeCun et al., 2015).

A critical challenge in ML applications for clinical decision-making is the risk of misclassification. Misclassifying patients as likely responders when they are not (false positives) could result in the continuation of ineffective treatments, delaying more suitable interventions. Conversely, incorrectly predicting non-response (false negatives) could lead to the denial of beneficial treatments to patients, impacting their recovery trajectory. These risks underscore the need for rigorous model evaluation and can be mitigated through careful model selection, robust validation techniques, and post hoc explanation methods (Yang et al., 2024). It is imperative to acknowledge that ML models should be regarded as decision support systems, wherein the ultimate decision rests with healthcare professionals to ensure patient-centered care.

In conclusion, the adaptability and flexibility of ML allow researchers to tailor their analyses to the unique characteristics of patient data, potentially uncovering new predictors, and to be able to use multidimensional data considering the multifaceted nature of the disorder. This is particularly useful in the AN context, where, as previously seen, multiple factors, physiological markers to psychological traits, and environmental influences can contribute to treatment outcomes. Finally, this data-driven approach has the potential to reveal unexpected connections and patterns in AN data, potentially leading to new insights into the etiology and treatment. In this regard, future studies could also consider non-clinical parameters (e.g., questionnaires on social aspects) and anamnestic factors (e.g., family history of mental health difficulties) to better understand their impact and possible links between them.

However, supervised ML also presents some important limitations. Many of them are like traditional statistics. Both methods can be affected by data quality issues, such as selection bias or measurement error, which can lead to misleading results or poor generalizability. This means that data might be not generalizable across different populations, such as individuals who seek help and those who do not (Fardouly et al., 2022). Additionally, while ML often requires large datasets for optimal performance (Ravidran & Kokjohn, 2023), traditional statistics can also benefit from larger sample sizes to increase statistical power and precision (Button et al., 2013). Lastly, a specific challenge for many ML models in some application areas, such as healthcare, is their "black box" nature (Guidotti et al., 2021). Unlike traditional statistical methods, which often provide interpretable coefficients or odds ratios, complex ML algorithms can produce highly accurate predictions without offering clear explanations for their decision-making processes (Rudin, 2019). This lack of transparency can be problematic in clinical settings, where understanding the rationale behind predictions is crucial for trust and implementation. To address this limitation, the field of explainable AI (XAI) has emerged (Gupta et al., 2024). XAI aims to make the decision-making processes of ML models more understandable (Gunning et al., 2019). XAI techniques can provide explanations of model behavior and creation (global level) or individual predictions (individual level, e.g., individual patient), which can be implemented as early as during model creation or used later as posthumous explanations (Guidotti et al., 2021). These insights are particularly important in clinical applications, where interpretability can have a significant impact on the acceptance and effective use of ML models by physicians and patients (Dwivedi et al., 2023).

Limitations

This study is situated within the emerging field of research leveraging ML to evaluate treatment effectiveness in mental health (e.g., Del Fabro et al., 2023). In recent years, ML techniques, particularly supervised learning models, have been increasingly used to enhance clinical decision-making and optimize treatment selection in psychiatric disorders, including depression, schizophrenia, and bipolar disorder (Koutsouleris et al., 2022; Le Glaz et al., 2021). However, despite the growing interest in data-driven approaches, it is essential to recognize certain limitations that may impact the interpretation and generalizability of present findings.

First, the limited sample size and imbalance between the two groups being analyzed. However, our sample size aligns both with previous studies in the field (Cerasa et al., 2015) and with the minimal number of participants suggested by Figueroa et al. (2012) for reliable ML evaluation. Additionally, several methodological strategies were implemented to address such possible limits (e,g., repeated stratified k-fold cross-validation, multicollinearity check, and precision-recall (PR) curve). Future research should validate the model on a larger and more heterogeneous sample to confirm its clinical utility. In this regard, we recommend researchers from different fields collaborate and combine large international datasets to fully exploit ML potential (Luo et al., 2016). While we did not preregister this study due to its exploratory nature, adopting open science practices, such as data sharing and preregistration through platforms like the Open Science Framework, can enhance transparency, and reproducibility, as well as the collective effort to advance the field.

Second, we focused on change in BMI as an index of improvement based on Franket et al. (2024). Even though BMI is considered the primary target of AN hospitalization programs, other parameters might be considered as an index of successful treatment (e.g., psychological well-being). Additionally, we conceptualized weight stabilization (ΔBMI = 0) at the same level as an improvement since, in severe conditions and short interventions, the most important aspect is that patients do not lose additional weight and start to stabilize their weight and then improve. This is based on Couturier and Lock (2006) who reported that the mean time to AN remission for weight is 11.3 months.

Third, we did not have a follow-up measure as it is not foreseen in the rehabilitation program to have this information. However, the timeframe for assessing treatment success presents a challenge, with some research indicating that the clinical outcome of treatment for AN should be evaluated more than two years post-treatment completion (Gowers & Smyth, 2004). Although this can be seen as a limitation, it reflects the reality of clinical settings: everyone is unique, just as the expression of their symptoms is, making it impossible to predict the rehabilitation path a person will undertake after discharge. This makes it difficult to maintain a connection with the person for potential follow-ups. Indeed, there are various contexts in which a person might find themselves after discharge, such as communities, hospitals, day hospitals, or returning home. This would make it challenging both to collect and to generalize follow-up data after discharge.

Additionally, in line with the research question, in this study, we focused on psychological and physical features. However, there might be other factors that might influence the treatment outcome, such as the presence of comorbidities, pharmacological treatment, and treatment duration, among others. Future research might consider additional parameters with larger datasets.

Lastly, the present study identifies predictors of treatment efficacy, but it does not explore how these predictors relate to specific therapeutic techniques or treatment outcomes. Thus, we encourage future research to explore ML use to match individuals with the most appropriate interventions based on their unique characteristics.

Conclusions

The ML potential in psychiatry has generated a great deal of enthusiasm in recent years. This study used ML to predict weight recovery in patients affected by AN attending a multidisciplinary intensive rehabilitation program starting from psychological and physical body parameters. Results revealed that body-self relationship and interpersonal difficulties play a pivotal role in weight restoring, suggesting that therapeutic interventions should focus more on psychological aspects, rather than purely nutritional interventions. If such sensitive topics could be difficult to tackle previously, technology offers new techniques through innovative techniques such as Body Swapping and activities: this would allow to address altered body experience and interpersonal difficulties respectively in immersive and engaging ways. This approach could also take into account the ego-syntonic typical of this disorder, i.e., the patients' difficulty in perceiving reduced food intake as a problem, and its complexity, which is often not centered exclusively on food. By acknowledging these factors, treatment efficacy can be maximized, ensuring that limited resources are strategically used to achieve meaningful clinical outcomes. We argue that this promising area of research could benefit from researchers from different fields working together to create large international datasets that could make a significant contribution to realizing the potential of ML, with the ultimate aim of helping as many people as possible.

Data availability statement

The dataset and the code are available at https://github.com/chiara-pupillo/ML-AN/blob/9aa9db289f758f59215e4c8c162047e90da057db/CP_MAL_AN.ipynb

2.3 Conclusions

This chapter introduces the second protagonist of this project: Eating Disorders, specifically Anorexia Nervosa and Bulimia Nervosa. After clinical definitions of these conditions, the chapter presents the core starting point of this thesis: altered body experience that characterizes patients affected by Anorexia and Bulimia may stem from a deficit in the way in which information is combined through a multisensory integration process.

A systematic review of the literature supported this perspective, giving me the possibility to introduce my proposal. I applied the Predictive Coding framework to explain how multisensory integration processing can be impaired, discussing different possible levels at which this process can be impaired, leading to a distorted bodily experience. Disruptions can happen both at the level of single sensory modality processing (e.g., inner body perception), when information is combined (e.g., a different precision attributed to egocentric and allocentric information), or when bottom-up information is combined with top-down priors (e.g., cognitive penetrability).

In the second part of the chapter, I showed the key role of the body determining Anorexia Nervosa successful treatment using Machine Learning techniques. This research stressed the importance of the purpose of this research project: developing new Anorexia Nervosa treatments able to work on the multisensory body.

The next step is the understanding of what type of tool(s) and technique(s) might be more suitable to reach this goal.

3. Virtual Reality

In the previous chapter, we found support for the idea that altered body experience might be associated with a suboptimal multisensory predictive process and that body experience plays a pivotal role in EDs successful treatment. Then, a technology capable of reproducing the brain's predictive multisensory process was needed to deeply work on bodily experience. This chapter will present Virtual Reality (VR) as a suitable tool in this regard. Here, its main psychological features will be presented: namely, it is a cognitive, simulative, and embodied technology (Riva, Wiederhold & Mantovani, 2019). These features make VR a tool to provide transformative experiences, able to change people's minds and ways to relate to their bodies and the world (Gaggioli, 2016). The chapter will then go through some experiments in which VR experiences were used to assess and manipulate body experience.

3.1 Virtual Reality from a Psychological Perspective

We are used to hearing about Virtual Reality as a technology made up of complex hardware and software systems. However, it's also possible to view VR through a psychological lens, allowing us to truly grasp its potential. The subsequent sections will explain this idea, based on Riva, Wiederhold, and Mantovani (2019).

3.1.1 Cognitive Technology

VR serves as a powerful cognitive technology by closely mirroring the brain's predictive processing. As previously discussed, the brain constantly constructs and updates internal models of the world, anticipating incoming sensory information to minimize prediction errors (Friston, 2010). Similarly, VR maintains a model of the user's body and adjust the sensory information to user's responses. Through multisensory inputs and real-time interactions, VR provides a platform for studying how the brain forms, adjusts, and reacts to these internal models (Riva et al., 2017, 2019). This technology allows researchers to manipulate these predictive mechanisms by designing controlled environments where sensory information and user actions can be finely tuned, enabling a deeper understanding of how expectations shape perception and behaviour. By simulating the brain's anticipatory processes, VR has significant potential for applications ranging from learning enhancement to therapeutic interventions, particularly in areas involving cognitive distortions or maladaptive mental models, eating disorders (Riva et al., 2017, 2019).

3.1.2 Simulative Technology

As a simulative technology, VR replicates real or imagined experiences, allowing users to engage in scenarios that would otherwise be impractical, impossible, or unethical to experience in real life. This makes it a valuable tool for psychological research and therapy, where immersion in specific environments can facilitate learning, behavior change, and emotional processing.

In therapeutic settings, VR simulations are used for exposure therapy, where patients with anxiety disorders or phobias can confront feared stimuli in a controlled, safe environment. The flexibility of VR enables the customization of these simulations to meet individual needs, providing a personalized approach to psychological intervention. This makes VR not only a simulative but also an adaptive tool that can be tailored to simulate experiences such as entering different bodies as compared to real ones.

3.1.3 Embodied Technology

VR as an embodied technology fundamentally aligns with the principles of embodied cognition, which posits that cognition is deeply intertwined with the physical body and its interaction with the environment. Embodied cognition emphasizes that the mind does not operate in isolation but is shaped by sensorimotor experiences within specific contexts and for specific purposes. VR, by simulating multisensory environments, provides an interactive space where the mind and body can engage with virtual stimuli, making it an effective tool for studying and influencing embodied experiences (Riva et al., 2017).

In the context of embodiment, which refers to the sensation of having and controlling a body, VR offers unique advantages. Embodiment is constructed through the integration of multisensory inputs (such as visual, tactile, and proprioceptive information) that create a cohesive representation of the self (Riva et al., 2017). VR can manipulate these inputs, creating compelling illusions of body ownership, self-location, and agency—the key components of embodiment. For example, in virtual environments, users can experience body ownership over avatars or virtual body parts as their movements are mirrored and synchronized within the VR simulation (Brizzi et al., 2023). This allows for the creation of body illusions like those induced by the Rubber Hand Illusion (RHI), where participants feel ownership over a virtual or artificial body (Serino et al., 2019).

Furthermore, VR transcends mere observation by allowing users to actively interact with a virtual world, creating a dynamic sense of presence and immersion. Presence, or the feeling of "being there" in the virtual environment, is a critical feature of VR that enhances the embodied experience (Riva et al., 2017, 2019). This immersive quality is driven by VR's ability to predict and respond to users' sensory and motor actions in real-time, which is analogous to how the brain constructs a predictive model of the body and space through multisensory integration. In essence, VR mirrors the brain's process of predictive coding, where the brain constantly anticipates and adjusts to incoming sensory information to minimize prediction errors (Brizzi et al., 2024).

As an embodied technology, VR is not just a tool for simulating real-world environments; it can also be used to reconfigure body perceptions and sensorimotor experiences. Through the manipulation of multisensory stimuli, VR can alter body representations, extend body boundaries, or even replace bodily experiences, making it a powerful medium for therapeutic interventions. For example, in clinical settings, VR has been used to treat disorders related to body image and embodiment, such as in eating disorders where distorted body perceptions are prevalent. By providing controlled, immersive environments, VR can offer patients new ways to experience and alter their body representation, facilitating changes in cognition and behavior.

3.2 Virtual Reality as a Transformative Medium

3.2.1 Transformative Experiences

In the journey of human experience, there are specific moments with the power to redefine who we are and how we understand ourselves and the world around us. Such moments can be defined as transformative experiences.

Transformative experiences are those that bring about profound changes in the self, both epistemically and personally (Gaggioli, 2016). Such experiences challenge existing worldviews, prompting individuals to reconsider how they perceive reality, themselves, and their place in the world. Notably, such experiences transcend the simple acquisition of knowledge; they prompt a fundamental restructuring of one’s entire being, often leading to a reimagined self. They spark a shift in perception that is both epistemic—transforming what we know—and personal, influencing how we experience ourselves (Gaggioli, 2016).

The transformative nature of these events lies in their ability to invite epistemic expansion—the acquisition of new knowledge that fundamentally changes one's framework for understanding (Gaggioli, 2016). This is not simply learning a new fact or skill; it involves a more profound reordering of one’s mental and emotional architecture (Gaggioli, 2016). For example, a disorienting event or a major life transition, such as a personal loss, spiritual awakening, or an encounter with a new culture, can act as a catalyst for this kind of deep change, shaking previously held beliefs and expanding the individual's capacity for self-reflection and growth.

Philosophers like L.A. Paul (2014, 2015) argue that transformative experiences are unpredictable and deeply personal. They cannot be fully understood or anticipated until they are lived through. For instance, becoming a parent is not only a life-changing event but also a personally transformative experience, as it alters one's values, priorities, and self-concept in ways that are impossible to comprehend until the experience is lived. These experiences mark significant crossroads, where individuals may find themselves on a path toward a new understanding of life, one that transcends their previous conceptions of reality and self.

In this light, transformative experiences are not simply moments of change—they are catalysts for self-realization and personal evolution, unlocking new dimensions of being and understanding that fundamentally alter one's relationship to the world (Gaggioli, 2016).

Transformative experiences hold significant promise in the context of addressing various psychopathologies, as they can promote shifts in perspective and self-understanding: in therapeutic settings, eliciting transformative experiences can facilitate healing and promote personal growth by enabling individuals to confront and reframe their struggles (Gaggioli, 2016).

The intentional prompting of transformative experiences in the context of psychopathologies can significantly enhance therapeutic outcomes: by facilitating shifts in perspective, promoting empathy and self-awareness, challenging cognitive rigidity, and fostering healing and growth, they can empower individuals to navigate their mental health challenges with newfound strength and understanding. This approach addresses the symptoms of psychopathology but also encourages a holistic transformation of the self, leading to overall improved well-being and quality of life.

3.2.2 Transformative Experiences in Virtual Reality

VR stands as a revolutionary medium for facilitating transformative experiences, uniquely positioned to immerse users in first-person, subjective encounters that are often beyond the reach of traditional forms of media. In VR, individuals are not mere observers; they become active participants in dynamic narratives, engaging deeply with new perspectives and realities that challenge their existing understandings. This immersive quality fosters an emotional and visceral connection to experiences that would otherwise remain abstract or distant.

The transformative potential of VR is further enhanced by its ability to create a strong sense of presence—the sensation of truly "being there" within the virtual environment (Slater, 2002). This sense of presence intensifies the connection between the user and the immersive world, making the experiences feel immediate and real. When individuals feel physically present in an alternate reality, they are more likely to engage authentically with the scenarios presented to them (Slater, 2022). This engagement allows for a full exploration of new identities and experiences, leading to shifts in self-perception and understanding that can be both profound and lasting (Gaggioli, 2016).

Moreover, VR facilitates epistemic expansion, broadening users' understanding of what is possible in terms of identity and experience. Through immersive simulations, individuals can encounter and explore aspects of existence that challenge their previous notions of self and reality (Gaggioli, 2016). For example, stepping into the shoes of another person—whether that be someone from a different cultural background or a fictional character with extraordinary abilities—offers insights that are often difficult to obtain through traditional learning or introspection. Such encounters enable users to question their assumptions and broaden their horizons, leading to transformative shifts in their worldviews.

As users navigate these virtual environments, they are prompted to confront scenarios and identities that they may not encounter in their everyday lives. This engagement with alternate realities encourages a deeper examination of personal beliefs and values, fostering growth and self-discovery (Gaggioli, 2016).

One of the possible application fields in this regard is the use of VR to manipulate body-self experience. Indeed, VR has the unique ability to alter Body Self Consciousness, namely, it can reshape the sense of agency—the feeling of control over one's actions—self-location, or the perception of one's body's position in space, and body ownership, the sensation of identifying with a particular body (Park & Blanke, 2019).

Research has shown that VR can effectively induce out-of-body experiences and manipulate the concept of body ownership thanks to paradigms as body illusions. For instance, by employing carefully crafted visual and sensory feedback, users may feel as though they have exited their own bodies, observing themselves from an external vantage point (Brizzi et al., 2024). This phenomenon, referred to as embodiment, exemplifies altered bodily self-consciousness and serves as a powerful tool for exploring the boundaries of self-identity and body perception. Through these immersive experiences, users gain insights into the fluidity and adaptability of their sense of self (Riva, 2018).

Such manipulations disrupt conventional experiences of identity and invite users to reconsider their relationship with their bodies: by engaging with these alternate perceptions, individuals can experience transformative shifts in how they understand and relate to themselves, ultimately reshaping their self-concept and emotional responses.

3.3 Manipulating Bodily Self-Consciousness in Virtual Reality

Once we have understood which technology could be best suited to transforming such an intimate experience as that of one's own body and what are its core principles, the chapter will go on to show two examples of experimental studies in which VR has been used to transform how individuals subjectively experience their body. In the first study that will be presented, VR is used to modify body satisfaction and body perception in both male and female subjects by proposing a first-person perspective full body illusion. Similarly, the second study will focus on female participants – moved by the previous study results – and wants to investigate the effect of a full body illusion experience on body perception and satisfaction introducing also the investigation of spatial perspective role (i.e. egocentric Vs allocentric) in which the embodied experience is presented.

The software used for these experiments were created by me during my PhD.

3.3.1 Gender differences in bodily experience: Insights from virtual reality body illusion [3]

Introduction

Body illusions offer profound insights into understanding body experience and its underlying mechanisms, serving as a powerful lens through which the intricate relationship between physical self-perception and identity can be explored (Vankerckhoven et al., 2023). In the last years, technological advances allowed the development of advanced paradigms for proposing bodily illusions that can cleverly modify core components of Bodily Self-Consciousness, namely the sense of owning a body (ownership), the sense of being in a body and occupying a specific physical space (self-location), and the sense of having control over the body (agency; de Vignemont, 2020). Specifically, technology allowed the transition from the classic rubber hand to making subjects experience a fake rubber hand as their own (Rubber Hand Illusion (Botvinick & Cohen, 1998), to the use of whole mannequins that make people perceive a completely artificial body as their own (Full Body Illusion; Ehrsson, 2022; Preston et al., 2015).

Furthermore, the availability of low-cost technology has enabled more sophisticated techniques to emerge. In particular, the use of Virtual Reality (VR) has made it possible to create convincing, high-fidelity graphics for the proposal of Full-Body Illusions in which individuals identify with entire virtual bodies (Blanke & Metzinger, 2009; Preston et al., 2015; Scarpina et al., 2019). Immersive VR (IVR) experiences have outperformed traditional, non-digital techniques in terms of their effectiveness in promoting the identification of artificial bodies (or body parts). This progress opened new avenues for understanding the complex relationship between human cognition and the perception of

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one's physical self. In this regard, researchers have developed paradigms where the artificial body presented in IVR can be drastically different from the user's actual body, a process referred to as Full Body Illusion (FBI) (Petkova & Ehrsson, 2008; Serino et al., 2019). During FBI, individuals can experience having a different body - such as one that is thinner, taller, larger, or smaller than their actual body (Petkova & Ehrsson, 2008; Serino et al., 2019; Serino, Pedroli, et al., 2016). This possibility provided profound insights into the malleability of body representation.

The multisensory integration process (MSI)

The core principle underpinning body illusions is the reliance on the body's Multisensory Integration Process (MSI). Indeed, body representation is developed and updated through an MSI process where concurrent spatial and temporal information coming from different sensory modalities are unified into a coherent and unique percept (Brizzi, Sansoni, Di Lernia, et al., 2023; Brizzi, Sansoni, & Riva, 2023). Body illusions fully exploit MSI: the phenomenon of embodiment - namely the identification with an artificial body experienced through body illusions - is promoted by synchronous multisensory stimulation where sensory information from the artificial and real bodies are spatially and temporally congruent (Blanke & Metzinger, 2009; Costantini & Haggard, 2007; Petkova & Ehrsson, 2008). Typically, embodiment induction requires that the virtual body is presented from a first-person perspective so that the visible virtual body and the hidden physical body are aligned (i.e., they have the same self-location), and they are congruently stimulated in the same body region at the same time (i.e., synchronous visuo-tactile stimulation) or synchronized in terms of movements (i.e., visuo-motor synchronization; Blanke & Metzinger, 2009; Spanlang et al., 2014). The illusion strength is instead usually reduced when the stimulation is applied without temporal and spatial synchronization between what the individual sees (i.e., the virtual body being touched on the abdominal area) and feels (i.e., the real body not being touched, being touched in another body area, or with perceivable delay; Blanke & Metzinger, 2009; Keenaghan et al., 2020; Spanlang et al., 2014). Despite synchronous and asynchronous stimulation remaining widely used as experimental and control conditions respectively (e.g., Di Lernia et al., 2023), recent studies observed that proved that a certain level of visualtemporal mismatch does not affect the illusion (Burin et al., 2018) or even a complete mismatch between visuomotor feedback (Burin et al., 2020).

Virtual reality body-focused interventions

Groundbreaking studies revealed that IVR-based Full Body Illusion (IVR-FBI) significantly altered body perception, leading to perceptual and affective alterations (Keizer, Van Elburg, et al., 2016; Scarpina et al., 2019; Serino et al., 2019). In this context, we refer to BS as a subtype of full-body illusion where there is no correspondence between the user's body and the artificial one (Petkova and Ehrsson, 2008). For example, the embodiment of a thinner virtual body was found to increase body satisfaction in females (Porras Garcia et al., 2019; Preston & Ehrsson, 2018), whereas the embodiment of an obese body was found to trigger body dissatisfaction and anxiety (Porras Garcia et al., 2019; Preston & Ehrsson, 2014a, 2018). Similarly, it was observed that body size estimation changed significantly towards the virtual body after the FBI in samples of female participants (Keizer, van Elburg et al., 2016; Serino et al., 2019). Moreover, the study by Preston and colleagues (2018) showed that owning an obese body decreased body satisfaction, and owning a slimmer body increased body satisfaction in females. These findings led to the proposal of using this procedure for manipulating and correcting the body experience of patients affected by disorders characterized by altered relationships between the self and the body. In particular, FBI has been used to alter body experience in patients with Eating and Weight disorders such as Anorexia Nervosa and Obesity (Serino, Scarpina et al., 2016). For example, in women suffering from Anorexia Nervosa, exposure to a normal-weight body has been shown to reduce the overestimation of body size typically reported by those suffering from the disorder, thereby contributing positively to the healing and recovery process (Keizer, Van Elburg et al., 2016; Serino et al., 2019; Serino, Scarpina et al., 2016). Similarly, female patients affected by obesity and healthy controls reported significant changes in the estimation of their abdomen circumference after embodying a slim body according to the artificial body measures (Keizer, van Elburg, et al.,2016; Serino et al., 2019). Overall, IVR-BS emerged as a valuable tool for addressing altered body experience in two core components: the ability to accurately assess one's body size and spatial awareness (the perceptual component), and the emotions and sensations associated with one's body (the emotional component; Cash, 2000; de Vignemont, 2010; Longo et al., 2009).

Gender differences and virtual reality body-focused interventions

Nevertheless, significant questions remain to be answered before fully integrating IVR-based body-focused procedures in clinical practice, particularly regarding how different genders might respond to these experiences. A substantial proportion of previous research indeed predominantly focused on female subjects and patients grappling with eating and body image disorders. Notably, this applies not only to conditions with a higher prevalence in women such as Anorexia Nervosa, but also to pathologies with a higher prevalence in men, such as obesity (Muscogiuri et al., 2023). For instance, studies using IVR-BS to treat obesity primarily focused on females (Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Scarpina et al., 2019), so it is not clear whether this body-focused intervention might be beneficial also for males. This understanding is crucial to tailor effective treatments and maximize the therapeutic potential of IVR in the area of body representation and experience. This becomes even more critical in light of the growing body of research that suggests that body-self issues are not exclusively female concerns: men tend to experience a critical relationship with their bodies too, which can lead to distress and problems in various areas of life, from social to psychological (Eisenberg et al., 2006; Neumark-Sztainer et al., 2006). Hence, understanding the transformative potential of FBI to alter body-self relationships requires a nuanced appreciation of gender specific similarities and differences (Eisenberg et al., 2006; Talbot & Mahlberg, 2023). This is also considering data demonstrating that body size misestimation and dissatisfaction are widespread across the population, highlighting a widespread propensity, even among non-clinical populations, to overestimate one's body width and to be dissatisfied with one own body (Eisenberg et al., 2006; Talbot & Mahlberg, 2023). This misperception and affective state are not merely a benign cognitive bias: they have profound implications, entwined with various facets of an individual's psychological well-being, and even the onset and maintenance of disordered eating behaviors. In other words, it is not enough to recognize that such illusions can alter body perceptions: it is essential to understand the magnitude and direction of these changes, and how they may affect men and women differently. The development of therapeutic and preventive interventions aimed at improving body image and promoting mental health might benefit greatly from this understanding, as interventions can then be tailored to be universally effective and flexible enough to be adapted to specific demographic groups or individuals. Then, this study investigated how body size perception and body satisfaction changed after IVR-BS in males and females. To this end, we developed a gender specific version of the currently used Virtual Reality Full Body Illusion and investigated how this procedure affected body self-experience from affective (i.e., body satisfaction) and perceptual (i.e., body size estimation) levels.

Methods

Participants

A total of 43 participants participated in the experiment (21 males and 22 females), according to the sample size calculation (G*Power) for repeated measures ANOVA with within-between interactions (alpha = 0.05, beta = 0.8, effect size f = 0.25, number of groups = 2, number of measures = 3, correlation among measures = 0.5) and based on previous research (Preston & Ehrsson, 2018; Serino et al., 2019). We included only healthy participants with no current diagnosis of psychopathological and/or neurological conditions based on self-reported information. Participants completed the General Health Questionnaires before starting the study to assess their psychological well-being. Three participants (two females and one male) were removed from subsequent analysis because of scoring GHQ higher than 14, indexing possible psychological distress. Then, the final sample consisted of 20 males and 20 females. *Table 1* reports the final sample descriptives.

Sample Descriptives

	Gender	BMI	Age	Real_w	Real_h	Real_s	GHQ
Mean (sd)	Female	20.9 (1.76)	25.3 (3.03)	80.4 (11.60)	93.8 (8.01)	99.9 (6.40)	12.8 (2.21)
	Male	23.1 (1.99)	26.6 (3.76)	101 (5.25)	106 (4.88)	118 (8.30)	11.7 (2.35)
Minimum	Female	18.4	20.0	63.2	76.9	90.0	7.00
	Male	19.4	20.0	86.8	94.2	103	7.00
Maximum	Female	24.4	32.0	102	109	110	14.0
	Male	27.4	33.0	110	113	132	14.0

Table 1. Sample descriptives. The table displays a detailed breakdown of average age, waist, hips and shoulders circumferences mean values, Body Mass Index (BMI), and General Health Questionnaire (GHQ) scores, segmented by gender, including both mean values and standard deviations.

Procedure

Participants were first asked to sign the informed consent form and were then introduced to the experimental procedure and technology. They were asked to complete initial questionnaires (i.e., sociodemographic information, Body Image State Scale, and General Health Questionnaire) and to estimate the circumference of three different body parts in a randomized order (i.e., hips, waist, and shoulders, according to the Body Size Estimation task procedure; BES). They were then presented with IVR experience - i.e., FBI. Participants wore the headset and were asked to look around the virtual room. They saw a body and were instructed to align themselves with the virtual body (the instruction was as follows: "Can you see a virtual body in the room? Perfect, now align yourself with the virtual body as if you were about to enter the body"; Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Di Lernia et al., 2023). Once the gender-matched virtual and physical body locations coincided, participants were instructed to look down and focus on their abdominal area (the instruction was as follows: "Now, you have just to look at your belly"). To promote embodiment over the virtual body, the experimenter stimulated the abdominal area of the avatar and the participants' real body with the controller, while the same stimulation was applied to the avatar. After 120 s of visual-tactile stimulation (based on Preston & Ehrsson, 2014b), they were asked to complete the Embodiment Questionnaire to assess embodiment strength and had to estimate a second time to estimate the circumferences of three body regions (Body Size Estimation task) and rate their body satisfaction (Body Image State Scale). The procedure was administered twice to all participants in counterbalanced order, providing both synchronous and asynchronous visuo-tactile stimulation to avoid possible order effects. Consequently, the study used a mixed design with two factors: the participants' gender (male or female) and the different assessment times (body satisfaction and body size estimation at the baseline, after the asynchronous, and synchronous virtual experience).

General Health Questionnaire (GHQ)

The General Health Questionnaire 12 (GHQ-12; Politi et al., 1994) is a non-clinical instrument designed to gauge an individual's overall psychological well-being. It serves as a preliminary screening tool, not for diagnosis but to assess general mental health. The questionnaire consists of 12 items that ask questions about the respondent's recent experiences and feelings. This self-administered questionnaire comprises 12 items, which inquire about a person's recent feelings and experiences. Respondents indicate their agreement with each item using a Likert scale that ranges from 0 (more than usual) to 3 (much less than usual). A score of 19 or above is considered a potential indicator of psychological distress. The GHQ-12 addresses various aspects of wellbeing, such as enjoyment of daily activities, problem-solving capacity, feelings of unhappiness and depression, loss of self-confidence, and general happiness. The Italian adaptation of the GHQ-12 was developed at the University of Verona using a back-translation method and has repeatedly been validated and confirmed as a reliable tool (Piccinelli et al., 1993). GHQ-12 was used as a screening for psychological distress so that only participants with a total score higher than 14 (indexing the absence of distress) were then included in the analysis.

Full Body Illusion in Virtual Reality

Participants initiate the virtual experience by donning a head-mounted display, specifically the Oculus Quest 2. Within the virtual environment, they view an avatar and are instructed to align their physical body with the virtual gender-matched one to ensure the real and virtual bodies are spatially congruent. Following this, the experimenter uses a controller to touch the avatar's abdomen—simultaneously replicating this touch on the participant's actual body. This dual stimulation lasts for 120 s (Preston & Ehrsson, 2014b). There are two methods used in this visuo-tactile stimulation to ensure the illusion happens and provide a control condition: synchronous, where the stimulation of the real and virtual bodies is temporally and spatially aligned, and asynchronous, where there is no such alignment and a delay of approximately 10 s separates the visual and tactile input (based on Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Di Lernia et al., 2023). The sequence in which the participants receive synchronous and asynchronous stimulation is counterbalanced to eliminate any potential bias from the order of presentation. The virtual avatars were designed based on prior studies, using Makehuman software to represent a normal-weight body (waist-to-height ratio equal to 0.4606; Di Lernia et al., 2023; Keizer, Van Elburg, et al., 2016; Serino, Pedroli, et al., 2016). *Fig. 1* shows the body parameters (see Keizer et al., 2016a, b; Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Serino et al., 2019; Di Lernia et al., 2023).

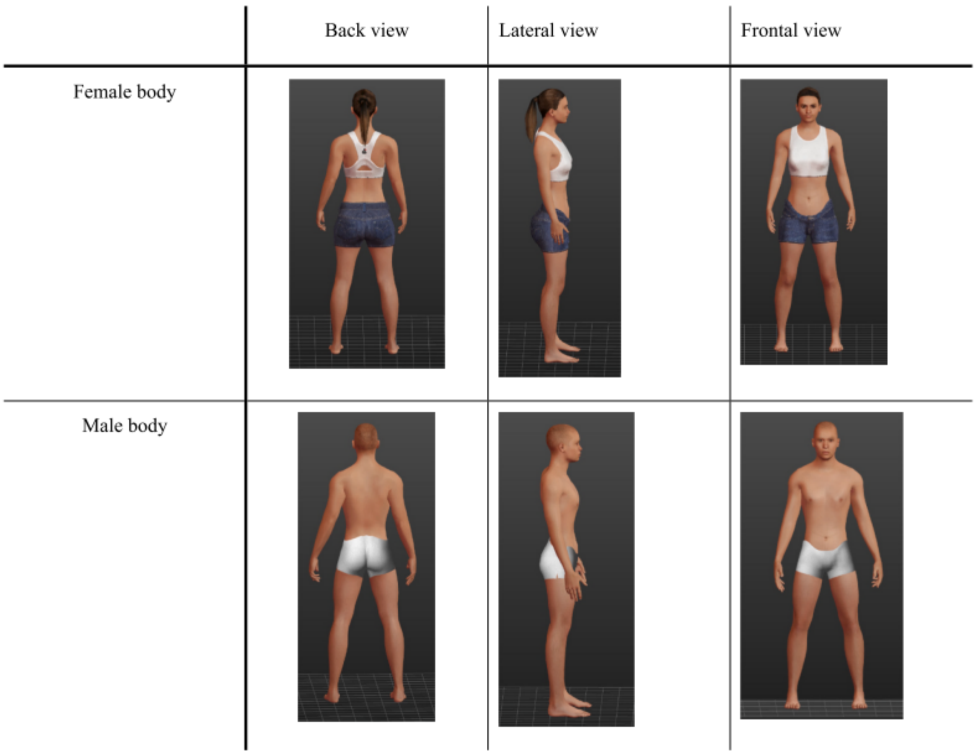

Fig. 1. Avatar parameters. Height = 160.54, age = 25, front chest distance = 26.58, bust circumference = 82.99, underbust circumference = 66.57, waist circumference = 73.95, nape to waist = 38.34, waist to hip = 19.01, shoulder distance = 14.14. The same measures were used for the male body (Keizer et al., 2016a, b).

Embodiment Questionnaire (EQ)

An adapted version of the Embodiment Questionnaire developed by Piryankova and colleagues (2004) was administered at the end of the two virtual experiences (synchronous vs. asynchronous visual-tactile stimulation) to assess the effectiveness of this procedure in inducing an illusory sense of virtual body ownership (Di Lernia et al., 2023; Serino, Pedroli, et al., 2016). The EQ consists of 15 self-reported items on a 7-point Likert scale assessing the perception of the illusion in terms of ownership (e.g., “I felt like the virtual body was my body”), selflocalization (e.g., “I felt like I was inside the virtual body”) and agency (e.g., “I felt like I had power over the virtual body”). This version of the questionnaire has been used in previous research in Italian samples (Di Lernia et al., 2023; Serino, Pedroli, et al., 2016). Following the methodology of previous research (e.g., Di Lernia et al., 2023), we proposed the paper-based questionnaire immediately after the IVR experience.

Body Size Estimation (BES) task

The Body Size Estimation task was developed to investigate the perceptual component of how individuals perceive their body size. The task requires estimating the circumference and/or width of different body parts (e.g., hips, waist, and shoulders) using a string. Based on previous research (Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Di Lernia et al., 2023), participants had to estimate the circumference of the above-mentioned body parts by placing a piece of rope in a circle/oval on the floor. Subsequently, the estimate of each body area is compared with the subject's actual measurement to obtain a measure of accuracy (i.e., the ratio between the estimation and the actual measure; Farrell et al., 2005). Each body part was estimated separately and in counterbalanced order. This can be considered an implicit task for body representation assessment as it requires participants to recall in memory their body dimensions and reproduce them with a string (Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016, 2019).

Body Image state scale (BISS)

The Body Image State Scale is a self-reported questionnaire to assess state body image (Bardi et al., 2021; T. Cash et al., 2002). It comprises 6 items and answers are rated on a 9-point Likert-type scale. Each item starts with the sentence “At this moment, I feel” [e.g. “At this moment, I feel (extremely dissatisfied to extremely satisfied) with my physical appearance"]. The score is an average of each element. Higher scores indicate higher body satisfaction.

Analysis and Results

Analyses were run in Jamovi. For the Body State Satisfaction Questionnaire, we derived an aggregate score (BISS_Tot) by averaging the responses across items for each experimental condition. Similarly, we assessed accuracy in the Body Size Estimation task by computing the ratio of participants' estimations to the actual measurements of each body part (Accuracy), again considering each condition separately (based on Serino, Pedroli, et al., 2016). Outliers were defined as values lying >2.5 standard deviations from the mean in either direction. No outliers were detected. We looked at skewness and kurtosis (threshold +/− 2.5) to evaluate the distribution of BISS and Accuracy scores; results indicated no deviations from normality. Regarding the Embodiment Questionnaire, we computed mean scores for each subscale, applying a similar protocol for outlier detection and exclusion—values were discarded if they were more than two standard deviations away from the mean, in either direction. Then, a set of analyses was planned specifically aimed at answering our research questions: 1) investigating gender differences at the baseline on body estimation accuracy and body dissatisfaction, and 2) see if and how males and females change their body satisfaction and perceptual accuracy level after the FBI experience.

Embodiment Questionnaire

First, we wanted to evaluate differences in embodiment strength across conditions. We performed a non-parametric paired t-test (Wilcoxon test) to compare embodiment strength after synchronous and asynchronous stimulation, observing significant differences across all EQ subscales. Notably, values after the synchronous stimulation were overall higher than after the asynchronous one. *Table 2* shows the mean and standard deviation of each EQ subscale and t-test results, and comparisons (Serino, Pedroli, et al., 2016).

	N	Mean	SE
Sync_Own	40	3.48 (0.487)	0.0769
Async_Own	40	1.69 (0.477)	0.0754
Sync_Loc	40	3.88 (0.836)	0.1322
Async_Loc	40	1.70 (0.544)	0.0860
Sync_Ag	40	2.42 (0.626)	0.0990
Async_Ag	40	1.11 (0.265)	0.0419

Wilconox Test

				95% CI		
	W	p	Mean Diff (SE)	Inferior	Superior	Effect Size
Sync_Own – Async_Own	820	< .001	1.78 (0.078)	1.61	1.94	1.00
Sync_Loc – Async_Loc	820	< .001	2.13 (0.116)	1.88	2.38	1.00
Sync_Ag – Async_Ag	666	< .001	1.50 (0.106)	1.25	1.75	1.00

Table 2. Wilcoxon test comparing illusion strength after synchronous and asynchronous stimulation. The table reports the descriptives for each subscale of the Embodiment Questionnaire (EQ) and Paired-Sample T-Test results. Sync = synchronous stimulation; Async = asynchronous stimulation; Loc = location; Own = ownership; Ag = agency; SE = standard error; Mean diff = Mean Difference.

Body Satisfaction (BISS) at the baseline

An independent sample t-test was used to examine differences in body satisfaction between genders at the baseline, before the body illusion. The analysis revealed a significant difference between genders ($t\ (26.4) = -6.51$, $p < 0.001$; Cohen's $d = -2.06$). Specifically, the female BISS mean value was lower for females than males (the mean for females was equal to 3.92 (0.53), whereas the mean for males was equal to 4.80 (0.23)). Then, result suggested that young women tended to be more dissatisfied with their bodies as compared to men.

Body Satisfaction (BISS) changes after Full Body Illusion

A repeated measures ANOVA was performed to examine the impact of body illusion on body satisfaction in male and female participants. We considered Condition (baseline, synchronous, asynchronous) as within factor, Gender (male, female) as between factor, and Body Satisfaction (BISS score) as the independent variable. Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. Subsequently, post hoc analyses with Bonferroni correction were conducted to investigate within gender variations. We observed a significant main effect of Condition ($F(2, 76) = 17.5$, $p < 0.001$, $\eta 2 = 0.045$) and Gender ($F(1, 38) = 33.6$, $p < 0.01$, $\eta 2 = 0.38$), as well as a significant interaction effect Gender*Condition ($F(2,76) = 11.4$, $p < 0.01$, $\eta 2 = 0.02$; *Figure. 2*). Post-hoc comparisons revealed that females changed their satisfaction level both after synchronous and synchronous stimulation as compared to baseline, whereas no differences were observed for males did not. *Table 4* reports post-hoc results.

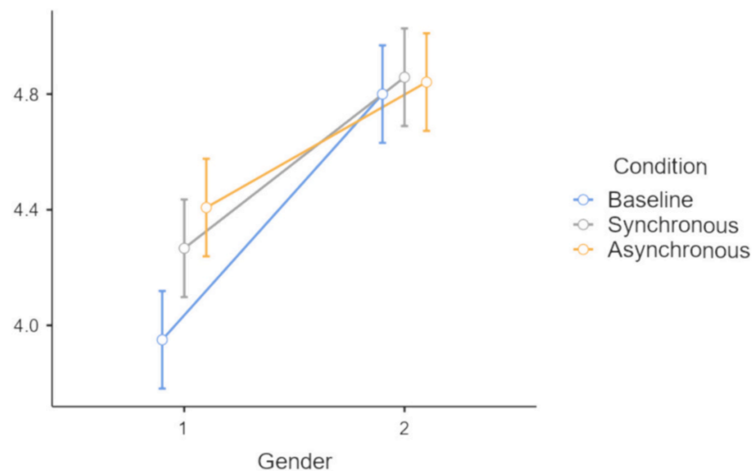

Figure 2. BISS changes in females and males across conditions. 1 = females, 2 = males.

Condition	Gender		Condition	Mean Diff (SE)	df	t	$p_{bonferroni}$
Base	Female	-	Sync	-0.316 (0.062)	76.0	-5.095	< .001
		-	Async	-0.457 (0.062)	76.0	-7.363	< .001
	Mal	-	Sync	-0.058 (0.062)	76.0	-0.939	1.000
		-	Async	-0.041 (0.062)	76.0	-0.669	1.000
Sync	Female	-	Asyncs	-0.140 (0.062)	76.0	-2.268	0.393
	Male	-	Async	0.016 (0.062)	76.0	0.270	1.000

Table 4. BISS changes within genders. The table presents post-hoc comparison within gender to investigate changes in BISS scores across conditions. Base = baseline; Sync = synchronous stimulation; Async = asynchronous stimulation.

Body Size Estimation (BES) at the Baseline

An independent sample t-test was performed to investigate gender differences in the Body Size Estimation task at baseline for each body area. The analysis revealed that there were no significant differences between males and females in the estimation of waist and shoulder circumferences whereas differences emerged when considering hips estimation. *Table 3* presents analysis results. Then, even though both males and females tended to overestimate their body dimensions (values >0), females tended to overestimate their hips more than male.

	Group	N	Mean	SE
Accuracy_shoulders	Female	20	1.18 (0.130)	0.029
	Male	20	1.12 (0.139)	0.031
Accuracy_waist	Female	20	1.30 (0.182)	0.040
	Male	20	1.21 (0.124)	0.027
Accuracy_hips	Female	20	1.24 (0.134)	0.029
	Male	20	1.08 (0.092)	0.020

Independent Samples T-Test

		Statistic	df	p		Effect Size
Accuracy_shoulders	Student's t	1.23	38.0	0.227	Cohen's d	0.389
Accuracy_waist	Student's t	1.81	38.0	0.079	Cohen's d	0.571
Accuracy_hips	Student's t	4.31	38.0	< .001	Cohen's d	1.363

Table 3. Results of independent sample t-test for BES performance at the baseline. The table details the comparative analysis of gender-based differences in body dimension accuracy across different body areas.

Body Size Estimation (BES) after Full Body Illusion

A repeated measures ANOVA was performed to examine the impact of body illusion on body satisfaction in male and female participants separately. We considered condition (baseline, synchronous, asynchronous) and body areas (shoulders, hips, waist) as within factors, gender (male, female) as between factor, and accuracy in body estimation (BES task performance) as the independent variable. The greenhouse-Geisser correction was applied when the assumption of sphericity was violated. Subsequently, post hoc analyses with Bonferroni correction were conducted to investigate within gender variations. Results revealed a main significant effect of Condition ($F(2, 76) = 18.006$, $p < 0.001$, $\eta2 = 0.015$), Body Area ($F(2, 76) = 12.923$, $p < 0.001$, $\eta2 = 0.090$) and Gender, ($F(1,38) = 7.76$, $p = 0.008$, $\eta2 = 0.089$) as well as a significant interaction effect Condition*Gender*Body Area ($F(4,152) = 3.858$, p =

0.005, $\eta 2 = 0.006$). *Figure. 3* shows three way interaction results. Post hoc analysis within each gender revealed a significant change in hip estimation in female participants after both synchronous and asynchronous conditions as compared to the baseline. Specifically, the comparison between the baseline and synchronous conditions revealed a significant mean difference of 0.082 (SE = 0.017, $t(228) = 4.857$, $p < 0.01$), and the comparison between baseline and asynchronous condition comparison showed a significant mean difference of 0.079 (SE = 0.017, $t(228) = 4.651$, $p < 0.01$). A significant change was instead observed for males in waist estimation only after synchronous stimulation as compared to baseline (difference = 0.068, SE = 0.017, $t(228) = 4.033$, $p = 0.011$).

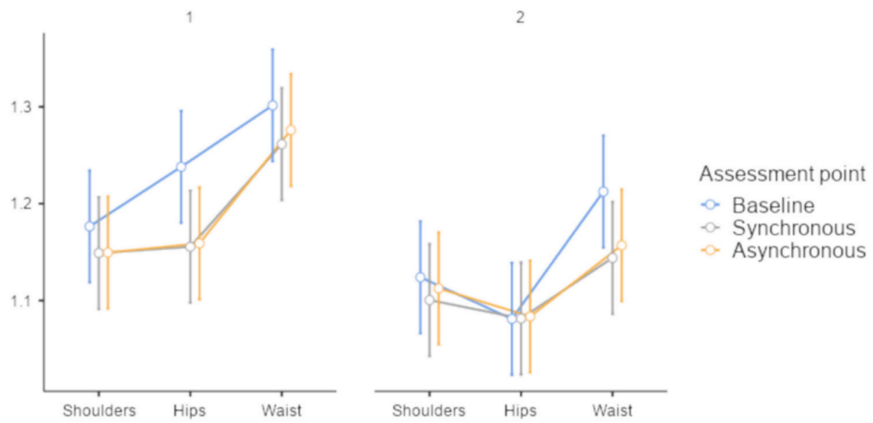

Figure. 3. BES changes across different body areas and conditions. The plot shows how females (1) and males (2) changed their body size estimation across conditions divided for different body areas.

Discussion

This study investigates how FBI into a different normal-weight body alters body representation from perceptual and emotional viewpoints in a sample of healthy male and female participants. Unlike previous studies, the current research emphasizes similarities and differences in body experience across genders, specifically concerning body size estimation and body satisfaction.

Gender Differences at the Baseline

Body Satisfaction

The first result of this study showed that females tended to be more dissatisfied with their bodies as compared to males. This is in line with a wide body of literature (Pingitore et al., 1997; Quittkat et al., 2019), indicating that women generally report heightened levels of body dissatisfaction and experience greater pressure to conform to certain aesthetic standards as compared to men, especially within Western cultures (Santhira Shagar et al., 2021). Then, even though males are growingly exposed to messages promoting idealized body types, the effects of such messages seem to be not as deeply rooted or impactful as they are for females. This may partially relate to differences in self-serving approaches.

Specifically, previous research suggested that men tend to adopt selfenhancement and self-protection strategies which could bolster their self-esteem, finding alternative sources of self-worth outside the body domain (e.g., achievements, personal strengths, non-appearance-related qualities (Brennan et al., 2010; Burlew & Shurts, 2013; Grossbard et al., 2009; Voges et al., 2019). On the other hand, Brennan et al. (2010) observed that men tend to be quieter about their body negativity as compared to females, even though they still struggle with their bodies. In this regard, future research could employ implicit measures of body satisfaction, which may circumvent explicit measures biases (e.g., social and response biases). For instance, body satisfaction implicit measures might include Relational Responding Task (Glashouwer et al., 2018), and Implicit Association Tests (Preston & Ehrsson, 2018; Velkoff & Smith, 2020). Nonetheless, socio-cultural determinants might contribute to gender differences in body satisfaction. Indeed, the cultural role of female and male bodies was not the same. Traditionally, the female body was depicted as a symbol of beauty and desire – i.e., it was objectified – leading females to self-objectify themselves (Calogero et al., 2010; Fredrickson & Roberts, 2016; Rollero & De Piccoli, 2017). Specifically, girls' bodies have been seen as objects whose main goal is to appeal to the observer and be in line with societal ideals. Notably, high degrees of self-objectification have a profound effect on how one experiences one's own body, adversely affecting both body-self relationship as well as psychological well-being more broadly (Calogero et al., 2005, 2010; Fredrickson & Roberts, 2016; Riva et al., 2015; Rollero & De Piccoli, 2017; Winn & Cornelius, 2020). Conversely, the male body has historically been under-examined, with the masculine form typically linked to attributes of power, proficiency, and achievement (Lefkowich et al., 2017). This might lessen the Self-Objectification process and downplay the importance of physical appearance in males, shifting the focus toward other parameters such as performance and social standing (Lefkowich et al., 2017). On the other hand, recent studies highlighted the escalating male pursuit of muscular physiques (Eik-Nes et al., 2018a). That is, males in recent years seem to desire to be more muscular and/or perceive to be not muscular enough (Blashill et al., 2020). However, research revealed that excessive preoccupation with a one's perceived appearance is a broader concept as compared to the drive for muscularity (see Blashill et al., 2020). Consequently, while global and general measures of body satisfaction may be effective for evaluating females, they may not be as suitable for exploring male body-self relationships. The idea that body satisfaction might assume different facets depending on gender is supported by previous studies revealing that only girls associated body dissatisfaction with the concept of self-esteem (Furnham et al., 2002). This would imply using different tools to assess the level of body satisfaction based on the specific sample of interest (e.g., the Drive for Muscularity Attitudes Questionnaire for a male sample; Morrison and Harriman, 2005). Recent studies have attempted to construct tools capable of accounting for both thinness and muscularity, proposing assessment tools that displayed a series of 3D bodies modified along these two parameters (Arkenau et al., 2020; Steinfeld et al., 2020). Participants were asked to respond by marking the body that best reflected their real body and their ideal body, where the discrepancy provided an index of body satisfaction in line with the classic procedure of Figure Rating Scales (Arkenau et al., 2020; Steinfeld et al., 2020). On one hand, this approach allows standardized measures for both males and females, whereas on the other these are non-immersive 3D tools (Arkenau et al., 2020; Steinfeld et al., 2020) that are not able to discriminate the influence of the two specific factors, so that separate and specific scales might be developed. This implies that body satisfaction is a complex construct that necessitates the use of gender-specific assessment instruments and methodologies. Currently, we are facing a notable shift in societal norms and attitudes, with the male body increasingly subject to objectification processes as well (Bocarsly et al., 2023). This suggests that although objectification may have been internalized by males to a certain extent, its full impact remains to be thoroughly examined in the current sociocultural corner. Given the crucial role of objectification in the development of an altered body-self relationship, future longitudinal studies might involve young boys to track and understand the potential long-term effects of this trend, twinning that which has been historically observed for females.

Body Size Estimation

A second important finding from this study refers to the body estimation abilities, namely in the accuracy with which people estimate their body dimensions. In line with previous research, we observed that both males and females misestimate their body dimensions, with an overestimation tendency (Martynov et al., 2020). However, what is innovative about the present study is related to gender differences across different body areas. We found that females tended to overestimate the hips size more than males. Again, this may be related to socio-cultural standards of beauty that emphasize hip size and shape as critical elements of the female form. These standards glorify body types that are typically slender and curvaceous at the hips, a beauty ideal not typically applied to men (Singh & Young, 1995). Building on this concept, the process of self-objectification could result in a cognitive bias wherein women view their bodies through the prism of societal expectations. Moreover, hips are a focal point of femininity and attractiveness, and this can lead to a heightened awareness and critical assessment of their own body in comparison to these ideals (Singh & Young, 1995). For males, instead, we observed that they tended to overestimate the waist circumference significantly more than females. Parallel to what emerged for females, this is in line with the societal ideal body for men, which demands a developed musculature (particularly the upper body) and leanness to produce a “v” shaped torso (Gruszka et al., 2022). Then, while both genders may overestimate their body dimensions, what makes our findings particularly intriguing is the observed gender differences concerning body areas that are socially and culturally regarded as symbols of femininity and masculinity. Assuming the absence of perceptual deficits, results seem to suggest that socio-cultural factors and emotional aspects drive the observed overestimation. A more in-depth analysis would benefit from investigating the precise relationship between the perceived size of specific body areas, the level of satisfaction with these regions (using tools like the Body Area Satisfaction Scale), and the degree of Objectification to specifically verify this hypothesis. Notably, some research observed that women were more likely to misperceive themselves as overweight, while men were more likely to perceive themselves as underweight (Weng et al., 2023; Griffiths et al., 2015). The authors discussed their findings referring to possible intervening variables such as BMI, age, media exposure, and social comparison. Whereas in our study BMI and age were not significantly different between groups, a future analysis might consider whether social media use might influence body size estimation abilities. It might be that girls tend to use social media to be exposed to images of girls with a body that conforms to the beauty standards of thinness, while boys use social media to look at a different kind of content, hence this might have an effect on their body perception.

Body Representation after Full Body Illusion

Body Size Estimation Task

Concerning the change in body representation after the FBI, data revealed that females changed their hips estimations after both synchronous and asynchronous stimulation as compared to the baseline. Our findings align with prior studies indicating that experiencing embodiment through a simulated body can influence perceptions of object size, including one's own body. This result can be explained by referring to the predictive coding framework of brain functioning and Virtual Reality technology functioning (Millidge et al., 2021; Talsma, 2015). Specifically, when participants engage with a virtual body that doesn't match their anticipated body expectation (priors), there is a conflict between the incoming sensory information and the brain's prediction (prediction error); to reconcile this, the brain adjusts its representation of the body to align with the new multisensory inputs (Pedroli, et al., 2016; Riva, 2018; Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016). As a result, individuals might tend to overestimate their body dimensions because they build their representation on inaccurate expectations and priors (Brizzi, Sansoni, Di Lernia, et al., 2023). However, when they swap into a different body through multisensory immersive technology, like Virtual Reality, the prediction error prompts the brain to update the body representation (Brizzi, Sansoni, Di Lernia, et al., 2023; Brizzi, Sansoni, & Riva, 2023; Serino et al., 2019). On these bases, Virtual Reality seems to be able to modify the body memory, at least temporarily. This idea that embodiment over an artificial body significantly affects body perception was found in previous research involving healthy participants and patients affected by body image disturbances such as Eating and Weight Disorders (i.e., Anorexia Nervosa and obesity; Keizer, Van Elburg, et al., 2016; Scarpina et al., 2019; Serino, Scarpina, et al., 2016). Following these results, research has recently focused on the development of procedures exploiting Virtual Reality body illusions to correct dysfunctional body-self relationships and facilitate the recovery journey. For instance, FBI has been effectively employed to assess and treat body image distortions in females with Anorexia Nervosa (Ferrer et al., 2020; Porras Garcia et al., 2019; Porras-Garcia, Serrano-Troncoso, et al., 2020) and obesity (Scarpina et al., 2019). These results underscore the potential of Virtual Reality as a transformative tool. This is because of specific features of this technology: it is immersive, cognitive, and simulative, namely that it can mirror the brain's predictive functions and then has the potential to impact the bodily information processing pathways (Riva et al., 2017, 2019). These are the reasons why IVR has been proposed to be the core of a new transdisciplinary research field - embodied medicine - whose main goal is the use of multisensory and immersive technologies to alter the body experience by replacing multisensory bodily contents with synthetic ones (Riva et al., 2017, 2019). Notably, the efficacy of this approach seems to be higher when there is crossmodal congruency between the real and the virtual world. This is because multisensory integration of spatially and temporally congruent crossmodal signals is at the basis of how our experiences, including the body. This explains why changes in body estimation were primarily observed after synchronous stimulation (Blanke, 2012; Brizzi, Sansoni, Di Lernia, et al., 2023; Ehrsson, 2012; Rossi Sebastiano et al., 2022). However, the literature provides mixed findings concerning the exact mechanisms behind the effects of synchronous and asynchronous stimulation on body size estimation. If the most of studies highlighted the importance of spatial and temporal synchrony between the virtual and real environments to drive change (Malighetti et al., 2022), the present study and previous research found different results. For instance, Van Der Hoort and colleagues (2011) found that the overestimation of object sizes after experiencing a small body occurred through synchronous visuo-vestibular as well as through asynchronous visuo-tactile stimulation. Similarly, Keizer and colleagues (2016) found that the embodiment of a virtual body altered body size estimation irrespective of the type of stimulation. Here, the authors suggest that processing information from other sources of input (e.g., proprioception, interoceptive signals, tactile information) might allow for a more holistic experience of the body, which in turn might enhance body size estimation accuracy (Keizer, Van Elburg, et al., 2016). Other authors, instead, suggested that change after asynchronous stimulation was linked to the weight attributed to visual information during the predictive process (Thaler et al., 2018). If these hypotheses are true, embodiment might then not be necessary to observe changes. This aligns with our results and previous research (e.g., Serino Pedroli, et al., 2016; Serino, Scarpina, et al., 2016), where changes in body estimation were detected despite low levels of embodiment in the synchronous condition (around the mean value of a scale ranging from “totally disagree” to “totally agree”). This aligns with the suggestion by Longo and colleagues (2008): the authors performed a psychometric evaluation of embodiment measures, observing a mean value of around 0 (on a scale ranging from − 3 to 3). From their discussion, embodiment should not be perceived as a binary state but rather as a progressive process assessed along a continuum. On the other hand, previous research (e.g., Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Keizer et al., 2016a, b; Di Lernia et al., 2023) considered embodiment successfully induced in light of significant differences between synchronous and asynchronous stimulation. That is, what seems to matter is the difference across conditions and multisensory stimulation. Notably, other parameters might account for contrasted findings, such as the software and the experimental setting, among others. For instance, it might be that the graphic quality or the realism of the avatar significantly impacts the illusion experience and then the observed change (Mottelson et al., 2023). In this regard, it might be important to use similar approaches in future research to make results comparable and drive conclusions. Further research is needed to discern whether this synchrony is an absolute prerequisite for any perceptual change, or if it is merely a beneficial factor that amplifies the effect of change. On the other hand, differently from female participants, we found males changed waist estimations only after synchronous stimulation. This might be attributed to gender-specific approaches to processing body-related information and the varying levels of concern over the body. Previous research indicates that women generally place a greater emphasis on appearance, leading to a higher investment in contemplating and attempting to modify their bodies as compared to men (Quittkat et al., 2019). Consequently, it might be that males tend to have a more rigid and less malleable body, making their body representation more resistant to alteration through multisensory stimulation. Subsequent research should specifically investigate body representation malleability and its relationship with body investment. Moreover, future studies might consider exploring the cumulative effects of repeated FBI: this would aim to determine whether sustained and repeated sessions could lead to any significant modifications in body size estimation and overall body representation also among males. It may be possible to conduct a repeated measures study in which several FBI sessions are offered several times. Furthermore, comparisons could be made between the effects of exposure to a normal-weight body (as is the case in procedures with female patients) and/or to a muscular body. Such a procedure could clarify whether the lack of change in men is related to the use of the specific avatar or the duration of exposure. Another reason that might partially explain our finding might be related to the embodiment process: males may tend to experience the illusion less than females, which in turn translates into a different body estimation change. This might be because body illusions are based on multisensory conflicts, and previous studies reported gender differences in multisensory tasks (Collignon et al., 2010). However, as described above, other findings observed body experience changes both before synchronous and asynchronous stimulation, namely with and without embodiment or at least independently on the level of embodiment. That is, it is not clear whether the embodiment is necessary for body perception to change, or whether visual information alone might promote changes (Maselli & Slater, 2013; Pavone et al., 2016; Tieri et al., 2017). It might also be that the difference between females and males related to the virtual body. That is, it might be that the difference between the virtual body and the real one in the case of girls was sufficiently similar to promote greater identification. In contrast, for males the differences might be too vast for this projection process to occur. However, this hypothesis is disconfirmed by evidence suggesting that virtual bodies are embodied equally strongly regardless of their similarity to the real body - e.g., bodies of own- and other-race (Banakou et al., 2016; Pyasik et al., 2023), smaller and larger size (Tambone et al., 2021), different genders (Tacikowski et al., 2020), bodies of historical figures that do not resemble own bodies at all (Banakou et al., 2018). However, going more into detail about our previous finding, data revealed that the body size estimation differed across genders for specific body areas. Specifically, females significantly changed the estimation of their hips after the illusory experience, whereas males changed significantly their waist estimation only after synchronous stimulation. Specifically, we found that the body areas typically considered emotionally salient to each gender (the hips for women and the waist for men) are the ones that change the most following FBI (Zavorsky et al., 2007). It might be that the most critical and emotionally charged areas may also be the most malleable and susceptible to multisensory manipulations. To date, studies on body illusions involving individuals affected by Anorexia Nervosa revealed that patients tend to show a more flexible body representation than healthy controls, so they tend to experience the illusion strongly and their body representation can be easily influenced by external stimuli (Keizer et al., 2014). In light of the body-self alteration that characterizes this condition, it might be body areas that are particularly emotionally salient tend to be more susceptible to modifications and alterations. Notably, previous authors suggested that when we ask individuals to judge the dimension of body parts, perhaps we are measuring the perceptual dimension together with the feelings, concerns, and preoccupation about those body parts, affecting the judgment itself (Riva, 2018; Riva & Dakanalis, 2018). However, further and specific research is needed to confirm this hypothesis. An interesting result is that alterations were reported in the body areas of the avatar that were visible to the participants. Unlike other studies, we did not observe changes in the estimation of shoulder circumference, which was not visible in the avatar since the participants' attention was directed to the hips and waist (as presented in the procedure section, the task of the participants was to look at and focus on the abdominal area). This finding aligns with the idea that visual information plays a key role in shaping our perception —meaning that sight may carry more weight in the predictive process compared to other sensory information (Alexi et al., 2018). However, exact mechanisms need to be better investigated. For instance, the observed changes might be due to a serial dependency bias due to the exposure. In addition, more refined mechanisms, such as a change in the multisensory integration process, might have an influence too. On one hand, the short-time effects observed in body estimation change after the illusion seems to provide evidence for the first hypothesis (Keizer, Van Elburg, et al., 2016). Conversely, the enduring effects noticed in clinical populations following multiple exposures might suggest that while single-session effects may be attributed to cognitive biases, repeated engagements with the illusion might induce more profound and lasting changes (Porras-Garcia, Ferrer-Garcia, et al., 2020). Follow-up assessment measures can be additionally used to assess this aspect.

Body satisfaction

The last finding from this study relates to body satisfaction change after FBI. We observed that the exposure to a virtual body did not significantly change body satisfaction in male participants, whereas an improvement was found for females independently of the stimulation. This gender difference seems to be consistent with data related to body size estimation. Then, we observed congruence between the emotional and perceptual components (Ramos et al., 2019). This might be related to the avatar used: unlike previous studies (Preston & Ehrsson, 2018), we presented a slim body that was comparable for both males and females. However, it is possible that such a body type is not particularly desirable for males, who might idealize a more muscular body (Eik-Nes et al., 2018b; Frederick et al., 2005). Therefore, this paradigm might not be optimal for studying male body experience. However, studies using muscular bodies in line with sociocultural standards found resistance to change in body satisfaction at both an implicit and explicit level (Preston & Ehrsson, 2018). A speculative explanation could concern the flexibility with which body representation changes in males and females: as mentioned earlier, it could be that females tend to fluctuate more in their level of body satisfaction than males. This aligns with the findings of a meta-analysis showing that merely observing ideal bodies (for example, in images or social media posts) can significantly alter body satisfaction in females by triggering comparison mechanisms (Grabe et al., 2008). Hence, there may be a different susceptibility and suggestibility to body-related stimuli across genders, although further and more specific research is required (Arkenau et al., 2022). Another possible explanation of this finding could be related to baseline differences: since males started from a higher level of body satisfaction, changes might be less pronounced. Moreover, the same intervening variables explaining baseline satisfaction differences might play a role, including both methodological choices (e.g., the use of explicit measures) as well as psychological factors (e.g., women tend to rely more on self-critical strategies when evaluating their physical appearance, whereas men tend to rely more on self-hopeful strategies; Franzoi et al., 2012). It is also possible that resemblance to the avatar and the level of embodiment impact such change (Preston & Ehrsson, 2018). For instance, greater subjective similarity to the avatar might result in less change or higher levels of embodiment might be associated with greater change.

Limitations and Future Research

This study confirmed previous findings related to gender differences in body-self relationships and provides novel insights into the effects of body illusions on body representation. However, some caveats should be considered in the interpretation of our data. First, a larger sample size is needed to verify the reproducibility of our results. Second, this study focused on bodily perceptual and emotional components, but other factors might be better investigated to understand their role in determining a change and gender differences, such as objectification level or self-esteem among others. Future studies might include also these possible intervening variables to see if and how they influence body change. Another limitation relates to the experimental tools: in line with previous research (e.g., Keizer et al., 2016a, b; Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Di Lernia et al., 2023), participants could not move and the avatar was static. This is why we did not assess cybersickness and motion sickness in this study. However, the brain seems more responsive to human action than static images, with possible implications on body representations (Cazzato et al., 2012; Peuskens et al., 2005). This insight opens new avenues for future research, particularly in exploring the potential of inducing embodiment with an avatar through visuomotor integration - where the virtual body's movements are synchronized with the participant's movements – seeing whether discomfort during the VR experience might emerge as a critical factor that could limit VR efficacy. Notably, the static nature of the proposed experience might explain the low levels of embodiment we observed in both in synchronous and asynchronous conditions. Indeed, similarly to previous works that used the same procedure (Serino et al., 2019; Serino, Pedroli, et al., 2016; Serino, Scarpina, et al., 2016; Keizer et al., 2016a, b; Di Lernia et al., 2023) participants overall reported low embodiment levels around the mean value. However, specific parameters and cut-offs to better determine whether embodiment can be considered reached are needed. This even because in the case of virtual full-body illusion, the first-person perspective was shown to be sufficient to induce embodiment without any kind of synchronous multisensory stimulation (Maselli & Slater, 2013; Pavone et al., 2016; Tieri et al., 2017), asynchronous visuotactile, and even visuomotor, stimulation might not be sufficient to disrupt the embodiment (Keenaghan et al., 2020; Maselli & Slater, 2013). Then, future research might include a different control condition, such as visual-only stimulation – i.e., observation of the virtual body without any tactile/motor stimulation. This type of research might elucidate mechanisms underlying changes both after synchronous and asynchronous stimulation. For example, it might be that mere visual exposure might induce changes because individuals tend to rely more on visual information compared to others. Lastly, we used explicit measures to assess embodiment and body satisfaction (Preston & Ehrsson, 2018). Since self-reported explicit results might be biased due to social and desirability biases, future research might then consider including implicit measures. For instance, the Relational Responding Task (Glashouwer et al., 2018) or the Implicit Association Tests (Preston & Ehrsson, 2018; Velkoff & Smith, 2020) can be used for assessing body satisfaction, whereas skin conductance and temperature (Palomo et al., 2018) can be used to measure embodiment strength. This can also better elucidate whether embodiment was successfully induced, ideally solving the issue of determining embodiment strength with questionnaires that do not present a specific cut-off to determine whether the illusion occurred.

Conclusions

The results of this study underscore the potential of Virtual Reality to create immersive, embodied, and multisensory environments. IVR can effectively alter the body's affective and perceptual experience, distinctly in males and females. The small changes observed in males, however, suggested that they can benefit from interventions when reflecting their specific needs. Research is needed to understand how to design effective body illusion experiences for males. In this regard, it might be possible to investigate whether repeated exposure to FBI might affect male body experience by using longitudinal studies. Another point to highlight is providing useful recommendations for practitioners and policymakers interested in implementing IVR-based interventions for body image concerns. In this regard, it should be noted that the opportunity provided by IVR to work on the Self-body relationship is unparalleled, as it allows the individual to inhabit a body different from their own. While in the field of clinical psychology, this exercise has traditionally been proposed through imaginative techniques, having access to an embodiment process capable of engaging all the subject's sensory channels would significantly enhance the opportunity to undergo an experience so transformative as to influence one's sense of bodily satisfaction. Finally, it ought to be underlined that the use of virtual reality tools can generate ethical problems, considering for example the fact that using virtual reality entails the risk of cybersickness. Concerning this phenomenon, symptoms may include headache, nausea, dizziness, visual fatigue, and disorientation. Despite these ethical implications, it is important to underline that measures to prevent or reduce the possible onset of cybersickness are easily applicable. For example, to obtain important results in terms of improving one's body satisfaction, it may be enough to use IVR for a very short time. From this perspective, therefore, it is as if IVR, requiring minimal effort from the subject, manages to achieve maximum output. This research area is poised to deepen our understanding of the bodyself relationship, offering insights for the development of solutions for both men and women grappling with body-self concerns. Addressing this aspect is crucial for psychological health and preventing mental health disorders such as Eating Disorders (Cash & Brown, 1987; Dakanalis et al., 2016). On these bases, IVR interventions might indeed offer support before dysfunctional or pathological behaviors. In other words, such a stance not only promises to improve individual well-being but also aims to preempt the development of severe psychopathological conditions.

3.3.2 Playing With Spatial Frames: Altering the Body Matrix Through Multisensory Egocentric and Allocentric Body Illusions [4]

Introduction

Body Illusions delve into the phenomena where individuals perceive an artificial body – or body part - as a part of their bodies (Petkova al., 2008). In other words, body illusions allow individuals to embody an artificial body or body part, where embodiment (Serino et al., 2019) refers to the "sensations that arise in conjunction with being inside, having, and controlling a body" (Kilteni et al., 2012; pag. 374). Critically, Body Illusions alter Body Self-Consciousness in its core components, namely a) the feeling of owning a body and the experience of a body as one's own (body ownership), b) the perception of where the self is located (self-location), which can be divided into body location (the sense of where the body is located in space) and first-person perspective location (the sense of where my first-person perspective is located in space), and c) the feeling of control over one's body (agency; Blanke, 2012; Longo et al., 2008; Liou et al., 2024). Then, this type of procedure provided valuable understanding into how our brains construct, maintain, and update our body representation based on sensory input it received (Kilteni et al., 2015) and offered the unique opportunity to investigate the relationship between the body, the mind, and the sense of self (Gallagher, 2014).

From Rubber Hand to Body Swapping

The classic example of Body Illusion is the Rubber Hand Illusion (RHI; Botvinick and Cohen,1998). During the RHI, participants' real hand is hidden from view while a rubber hand is placed in their line of sight; the spatial and temporal synchronous stimulation of both hands leads individuals to incorporate the artificial hand into their body representation. That

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is, when there is correspondence between what individuals see (the rubber hand being stroked in a specific position) and feel (the real hand being stroked in the same position), individuals perceive the fake hand as part of their own body (i.e., synchronous stimulation). Embodiment strength diminishes when the same stimulation is applied without spatio-tempoal correspondence (individuals see the rubber hand being stroked, but no tactile stimulation is applied on their real hand; i.e., asynchronous stimulation).

Building upon this multisensory conflict principle, researchers encompassed entire bodies, leading to the development of Full Body Illusion (FBI). FBI showed that synchronized multisensory stimulation (e.g., visuo-motor, visuo-tactile) induced a person to embody an entire mannequin (or virtual body) when viewed from a first-person perspective. The intriguing concept of Body Swapping (BS) emerges as a further extension of FBI: BS procedures introduced a significant difference between the artificial and individuals' real bodies. That is, during BS, individuals embody a fake body that significantly differs from their real one (e.g., it is taller, or slimmer; Petkova and Ehrsson, 2008; Serino et al., 2016, 2019). Such paradigms revealed the malleable nature of body experience and the key role of multisensory integration in shaping how we experience our bodies.

Research demonstrated that after participants swapped into different bodies, their bodily experience underwent substantial changes, in line with the artificial body. For instance, when individuals embody smaller or larger bodies, they align their actions and spatial awareness accordingly to the virtual body (e.g., they adjust their movements based on the dimensions of the artificial body to perform reaching tasks, and their body size estimations of different bodily areas changed based on the proportions of the artificial body; van Der Hoort and Ehrsson, 2016; Tajadura-Jiménez et al., 2017; Serino et al., 2020).

Spatial Frames and Body Illusion

In addition to the embodiment decrease caused by asynchronous multisensory stimulation, the strength of Body Illusions is influenced by other factors, such as the humanoid shape of the body or body part, and the distance of the artificial body from the real body, for which Peripersonal Space is a critical constraint (Lloyd et al. 2007; Preston et al., 2013). In this regard, Petkova et al. (2011) compared the embodiment of a mannequin presented from a first-person perspective (1PP; the body fell within participants' Peripersonal Space boundary) with that when the mannequin was viewed from the third-person perspective (3PP; the body fell outside participants' Peripersonal Space boundary), finding evidence of a genuine body illusion only in the 1PP condition. Then, the authors suggested that the first-person visual perspective would represent a fundamental constraint of the full-body illusion (Petkova et al., 2011). The contemporary philosophy of mind supports the idea that the conscious self is associated with a first-person perspective and that all conscious experiences are essentially anchored to this spatial frame (Liou et al., 2024). However, the availability of sophisticated technologies like Virtual Reality (VR) allowed the development of paradigms that challenged this mainstream view.

Out of Body Experience and Allocentric frame

Neuropsychological and neuroscientific research revealed that body representation requires the coherent integration of multisensory information from both egocentric (i.e., 1PP) and allocentric (i.e., 3PP) spatial frames (Brizzi et al., 2023). This is particularly evident in neurological pathologies (Blanke et Mohr, 2005): for instance, conditions with alterations in cortical brain areas responsible for integrating multisensory information as the temporo-parietal junction, inferior parietal lobule, insula, and cingulate cortex (Lopez, 2016, Lopez et al., 2012), showed that it is possible to perceive oneself as dislocated from the spatial origin of the visual perspective and see one's body from an observer, third-person perspective (Out of Body Experiences; OBE). Then, some authors suggested that Body Illusions can be induced even when the body is observed from a third-person perspective under appropriate multisensory conditions (Pomes and Slater, 2013; Debarba et al., 2015; Gorisse et al., 2017). OBE experience was experimentally replicated in healthy individuals (Out of Body Illusions; Droit-Volet et al., 2022; Ehrsson, 2007, Lenggenhager et al., 2007). Here, participants wear virtual reality headsets fed by a camera that records their real bodies from a 3PP (e.g., they observed their bodies from the back; e.g., Lenggenhager et al., 2007; Aspell et al., 2009). Research revealed that participants experienced a shift - or "drift" - in their sense of self-location towards the body they observed in the video when there was multisensory congruency between the observed body and the real one (Mayer et al., 2008; Blanke, 2012), and more recent studies found similar embodiment levels when presenting Body Illusion from 1PP and 3PP (Preston et al, 2015; Liou et al, 2024).

3PP Body Illusion was then used to better understand the role of visual perspective on body experience (Kilteni et al., 2013; Banakou et al., 2013; Petkova et al., 2011). However, in most of these experiments participants see an avatar's body from a typical 1PP within their peripersonal space when glancing downward (1PP), and see a distant, tall mirror reflecting the avatar's body and face when looking up (3PP; Preston et al., 2015). This approach, however, limited the ability to fully compare pure egocentric (1PP) and allocentric (3PP) perspectives. Additionally, the focus of these studies was more on the sense of ownership rather than on the broader concept of Body Self-Consciousness.

Body Illusion from First and Third Perspectives: Clinical Application

Body experience is a multifaceted construct comprising three related yet independent components: (a) an affective dimension involving the emotional attitudes individuals held towards their own body, (b) a cognitive dimension representing the beliefs and thoughts individuals hold about their bodies, and c) a perceptual dimension, referring to the subjective experience of one's body size and shape (Cash & Deagle, 1997; Riva, 2018; Schilder Paul, 1935; Slade Peter D, 1988).

Research has identified disruptions across these three bodily components in individuals diagnosed with Eating Disorders (EDs), especially Anorexia Nervosa (AN; Artoni et al., 2021; Rosewall, Gleaves, et al., 2020). The Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-5, 2013) refers to this aspect as a "disturbance in the way in which one's body weight or shape is experienced" underscoring the deep influence of the body subjective experience on this condition. Systematic and meta-analytical reviews sustain that those individuals affected by AN exhibit heightened body dissatisfaction and preoccupations, as well as a distorted overestimation of body size and shape as compared to general population (Glashouwer et al., 2019; Mölbert et al., 2017; Rosewall, Gleaves, et al., 2020). Remarkably, such distortions are among the most enduring symptoms of disordered eating and play a crucial role both in the emergence and maintenance of maladaptive weight-loss practices (Boehm et al., 2016; Grilo et al., 2019; Irvine et al., 2020). Consequently, acknowledging and addressing the complex dynamics between body experience and self-perception has emerged as a fundamental aspect for proposing AN successful preventive and treatments (Irvine et al., 2020).

Recent meta-analyses have looked at the effectiveness of different treatments for AN, without finding conclusive evidence in favor of one treatment as compared to other. Van den Berg and colleagues (2019) investigated the efficacy of different treatments from 17 randomized controlled trials (RCTs). The comparison between different therapeutical approaches to AN – i.e., psychodynamic or psychoanalytic therapy, cognitive behavioral therapy, interpersonal therapy, family therapy, social skills training, motivational interviewing, as well as combinations of these – and control conditions revealed no significant advantage for any approach in terms of weight gain, eating disorder pathology, or quality of life improvements. Murray and colleagues (2019) broadened this inquiry through another meta-analysis encompassing 35 RCTs, observing no advantage when comparing specialized treatments and comparator interventions. These outcomes have encouraged further investigation into the limitations of current AN treatments and highlighted potential avenues for refinement. Specifically, some advocate for a more nuanced attention to the body and the subjective experience of the body (Gardner & Garfinkel, 1997; Irvine et al., 2020). In response to these findings, a flourishing trend in research has emerged that emphasizes the development of body-centered protocols and experiences.

Examples of this attempt are represented by Mirror Exposure (ME; Delinsky & Wilson, 2006) and Virtual Reality Body Swapping (VR-BS; Serino et al., 2019). ME involves patients confronting their reflection to directly challenge and modify the negative cognitions and emotions associated with their body (Delinsky & Wilson, 2006). By engaging with their reflected image, individuals are encouraged to adopt an allocentric perspective (third-person perspective), viewing their bodies from an external viewpoint and use positive words to describe and relate with it. This method aims to diminish avoidance behaviors and reduce anxiety and distress related to the body, fostering self-compassion and acceptance (Delinsky & Wilson, 2006). VR-BS is a relatively new technique which uses VR Body Illusion to correct altered body perception. It involves inducing embodiment from an egocentric perspective (first-person perspective), thus allowing individuals to own a different body as compared to the real one (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2019). This method has been shown to significantly alter Body Self-consciousness, correcting body size misestimation in non-clinical populations as well as patients affected by different eating and weight disorders, at least temporarily (Di Lernia et al., 2023; Keizer et al., 2016; Petkova & Ehrsson, 2008a; Serino et al., 2019).

Building on these methodologies, the research team led by Porras-Garcia (2021) introduced a novel approach: the Virtual Reality-Based Body Exposure. This technique synergizes VR and embodiment strategies with mirror exposure. Indeed, in their studies participants engaged in a mirror-like exposure in virtual reality while embodying a virtual body that was incrementally adjusted in Body Mass Index (BMI) towards a healthier range (Porras-Garcia et al., 2021). Throughout the sessions, individuals were encouraged to articulate their perceptions and emotional responses to their avatar's appearance, covering all aspects from head to toe. These studies observed a significant decrease in the fear of weight gain and emotional components of body disturbances, as measured by self-reported measures (Porras-Garcia et al., 2021).

The Current Study

The differential effects of egocentric versus allocentric perspectives on full body illusion are not fully understood, particularly in the context of emerging technologies. Virtual Reality Body Swapping from an egocentric spatial reference frame has been shown to alter body perception (Serino et al., 2019), whereas experiences akin to looking in a mirror from third person perspective have been found to influence the cognitive and emotional aspects of body experience (Porras-Garcia et al., 2021). However, there is a lack of in-depth research on how different viewpoints in full-body illusion experiences affect embodiment, self-perception and behavioral outcomes in virtual environments. That is, it is still not known if and how egocentric and allocentric body experience specifically influence body experience. Then, this study wanted to investigate

- (RQ1) how different spatial perspectives contribute to Body Self-Consciousness, meaning if there are differences in embodiment strength when presenting body illusion from a first versus third person perspective

- (RQ2) how different spatial perspectives contribute to perceptual body representation, so if spatial perspectives influence the perceptual component of body image

To reach this goal, embodiment and body size estimation accuracy were measures before and after swapping into a virtual body presented from egocentric and allocentric spatial frames. We hypothesized that BS from both 1PP and 3PP altered body self-consciousness and perceptual bodily experience.

This understanding might advance the development of body-focused interventions by underscoring the necessity of incorporating both egocentric and allocentric perspectives in prevention and therapeutic treatments to address the multifaceted nature of body experience comprehensively.

Methods

Participants

Power analyses were performed using G*Power. Based on a predicted effect size of f = 0.25 (Keenaghan et al., 2020), an error equal to 0.05, and a desired power of 0.8, to perform a repeated measures ANOVA with three assessment times, the analysis suggested a sample size equal to 28. A total of 32 healthy female participants took part in the experiment (Age = 39.09 sd = 15.41; BMI =20.74 sd = 1.42; BES = 34.93 sd = 6.45). Participants comprises university students and were partially recruited through snowball sampling method by the experimenters. All participants had normal or corrected-to-normal vision, and none of them self-reported the presence of past or current neurological and/or psychopathological conditions. The study was approved by the ethical committee of the Catholic University of Sacred Heart. All participants provided informed consent to participate in this study.

Egocentric Body Swapping Illusion

Participants were asked to wear a head-mounted display (Oculus Quest 2). In the virtual environment, they observed a virtual body and were asked to align themselves with it so that their position (self-location) and that of the avatar matched (Are you in a room? Can you see the virtual body? Good, now I ask you to align yourself perfectly with it). Their task was simply to look at their belly and focus on the abdominal part of the virtual body. Then, the experimenter touched the virtual body on the abdominal part of the virtual and real bodies with the controller for 90 s. The visual-spatial congruence of this stimulation was used to induce embodiment in the virtual body (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2019). That is, participants saw the abdominal area of the avatar touched by a ball and felt the same tactile stimulation applied to their physical body by the experimenter with the controller. The virtual avatar was designed based on prior studies, using Makehuman software to represent a normal-weight body (waist-to-height ratio equal to 0.4606; BMI = 18.5; (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2019). This experience allowed to induce embodiment from a first-person/ egocentric perspective. Figure 1 shows some screenshots from the immersive experience.

Allocentric Body Swapping Illusion

Resembling what was described for the Egocentric condition, participants wore a head-mounted display (Oculus Quest 2) to immerse themselves in a virtual environment in which they were proposed with a virtual body positioned in front of them. They were instructed to stand in front of this artificial body, akin to standing before a mirror, closely observe it, and focus on its abdominal area. This study diverged from previous research that employed Out-of-Body Experiences: indeed, in this study the virtual body was positioned approximately 50 cm away, placing it reasonably within the participants' Peripersonal Space, the space immediately around the body. This is relevant as consistent research revealed that individuals tend to include in their body representation objects and tools that fall within this spatial region (Canzonieri et al., 2013). As previously explained, the experimenter touched the virtual body on the abdominal part of the virtual and the participants' body with the controller for 90 s with visual-spatial congruence to induce embodiment (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2019). The body used for this condition was consistent with that used in the egocentric condition so that only the visual perspective was manipulated. This experience allowed to induce embodiment from a third-person/ allocentric perspective. *Figure 1* shows some screenshots from the immersive experience.

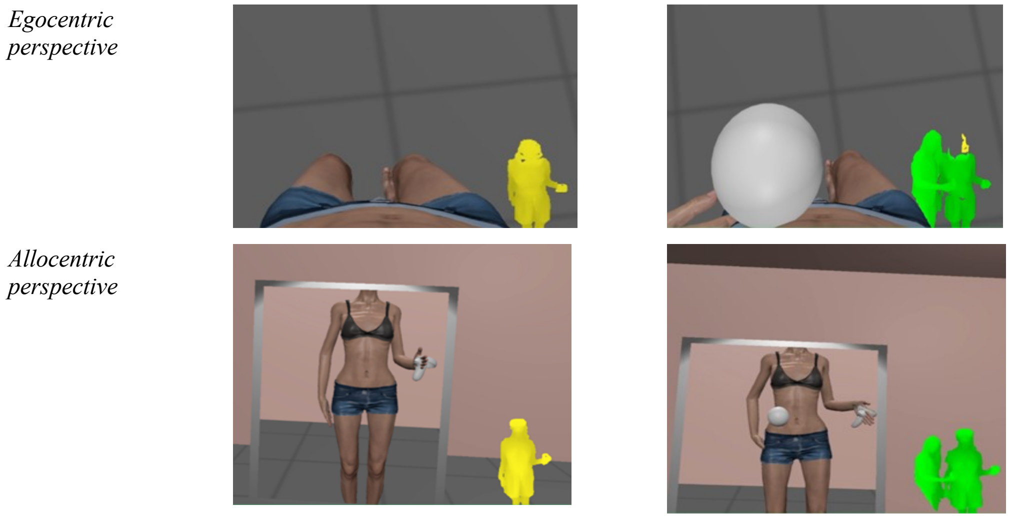

Figure 1. Software. The image shows what participants see inside the virtual environment in the egocentric condition (upper part) and in allocentric condition (lower part). The right panel shows the experimenter applying the visuo-tactile stimulation to the real and virtual body.

Embodiment Questionnaire (EQ; Serino et al., 2016)

An adapted version of the embodiment questionnaire proposed by Piryankova and colleagues (2014) was administered at the end of the two virtual experiences (egocentric vs. allocentric) to assess the embodiment strength over the virtual body (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2016). The EQ consists of 15 self-reported items on a 7-

point Likert scale. It assesses participants' core body- self-consciousness components, namely ownership over the virtual body (e.g., I felt like the virtual body was my body), correspondence between the virtual and real bodies in terms of self-location (e.g., I felt like I was inside the virtual body) and agency (e.g., I felt like I had power over the virtual body). Scoring involved calculating the mean for each subscale item (Piryankova et al., 2014). The questionnaire was proposed after both 1PP and 3PP immersive experience in order to assess and compare embodiment strength across conditions.

Body Esteem Scale (BES; Cecil & Stanley, 1997; Confalonieri E et al., 2008).

The Body Esteem Scale comprises 23 items, and respondents indicate their degree of agreement on a 5-point Likert scale ranging from 0 (never) to 4 (always). Nine negative items were reverse scored. Mendelson et al. (2001) found a solution for three factors: Attribution, Weight, and Appearance. The first factor, Appearance, refers to general feelings about appearance (items 7*, 9*, 11*, 13*, 21*, 23), the second factor Weight refers to satisfaction with weight (items 4*, 8, 10, 18*), while the third-factor Attribution refers to the perception of the evaluation attributed by others to one's body (items 2, 5, 12, 20; Confalonieri et al., 2008). The questionnaire was proposed in paper-based format. This task was used to assess emotional body component in order to control for possible intervening variables in the analyses.

Body Size Estimation Task (BES; (Farrell et al., 2005))

The Body Size Estimation task was a behavioral task developed to investigate the perceptual component of body representation, namely how individuals perceive their body size. It requires estimating the circumference of three different body parts (i.e., hips, waist, and shoulders) using a string without looking at the own body (Di Lernia et al., 2023; Serino et al., 2019). Then, the estimate of each body area is compared with the subject's real measurement to obtain a measure of body estimation accuracy (i.e., misestimation). This task was used to assess bodily percentual component before and after body illusions. BES was not proposed in the virtual environment in line with previous studies (Di Lernia et al., 2023; Serino et al., 2019).

Procedure

Prior to start the study, participants provided informed consent. They were familiarized with the experimental procedure and the technology. In a first phase, participants completed sociodemographic information and filled out the Body Esteem Scale. Subsequently, they were asked to estimate the circumferences of three body areas (the hips, waist, and shoulders) as part of the Body Size Estimation task. In the second phase of the experiment, participants were presented with the Body Illusion. They had to wear the headset and, depending on the condition, would either align with the avatar to experience embodiment from a first-person perspective (Egocentric condition) or stand in front of it as though looking in a mirror from a third-person perspective (Allocentric condition). Participants' task was to observe and focus on the avatar's abdomen area in both conditions. To induce embodiment, the experimenter synchronized touch on the avatar's abdomen and the participant's corresponding area with the controller for 90 seconds (synchronous visuo-tactile stimulation; Serino et al., 2016; Keizer et al., 2016). After this, participants completed the Embodiment Questionnaire to assess their level of embodiment with the virtual body and again performed the Body Size Estimation task. This procedure was conducted twice so that each participant experienced both the Egocentric and Allocentric conditions. As a consequence, the study used a within-subjects design with three assessment points (Baseline, Egocentric, and Allocentric). The order of condition presentation was counterbalanced to control for order effects. At the end of the experiment, participants real body measures were assessed. The session ended with a debriefing session to address any questions or curiosities the participants might have. The total study time was approximately 20 minutes. *Figure 2* presents a schematic representation of the procedure.

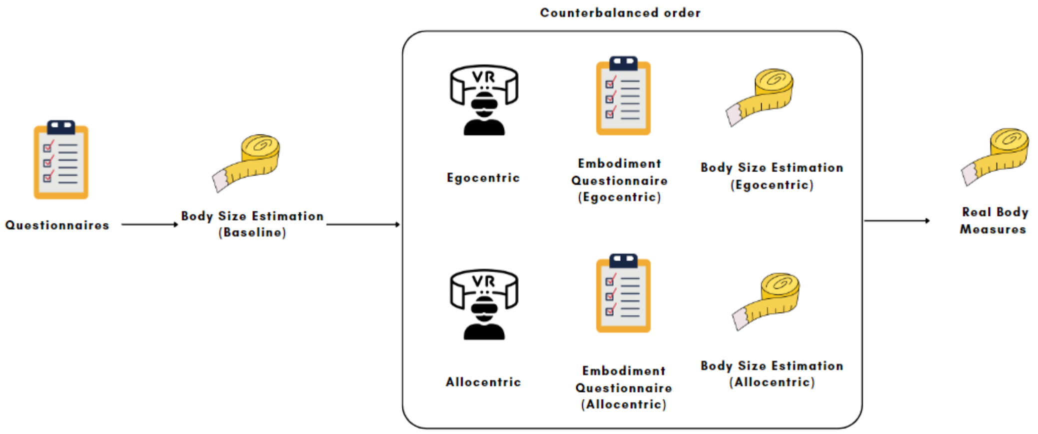

Figure 2. Procedure.

Analysis and Results

Pre-processing of Data

Analyses were performed in R studio. Embodiment Questionnaire (EQ) scores were intended to be the mean score of items under the same factor (i.e., ownership, agency, and self-location; Serino et al., 2019)). Performance on the Body Size Estimation (BES) task was analyzed by calculating the percentage of misestimates for each body part (Misestimation), following the equation suggested by previous research (Serino et al., 2019):

$$\text{Percentage of Misestimation} = \left(\frac{\text{Estimated Size} - \text{Actual Size}}{\text{Actual Size}}\right) \times 100$$

Then, a negative value in Misestimation score indicated an underestimation, whereas a positive value represented an overestimation of one's body area circumference. Values above and below 2 standard deviations from the mean were excluded from the analysis for EQ and Misestimation, defined as outliers. Shapiro-Wilk test was used to check for normality. *Table 1* presents descriptives of main variables of interest.

	Mean (sd)	Min	Max	Skewness	Kurtosis
Base_ratio_s	8.82 (11.63)	-9.30	33.47	0.60	-0.61
Base_ratio_v	18.29 (12.91)	-14.28	45.98	-0.11	-0.18
Base_ratio_f	13.79 (7.69)	1.53	33.66	0.71	0.01
Allo_ratio_s	1.55 (6.44)	-11.76	18.80	0.26	0.27
Allo_ratio_v	14.73 (13.00)	-13.97	45.62	0.34	-0.20
Allo_ratio_f	9.03 (8.45)	-13.72	26.93	-0.02	0.33
Ego_ratio_s	1.15 (5.94)	-12.15	15.99	0.00	0.27
Ego_ratio_v	13.67 (10.80)	-2.19	35.96	0.20	1.00
Ego_ratio_f	6.88 (12.21)	-18.83	32.79	0.04	0.56
EQ_Ego_Ownership	4.13 (0.84)	2.22	5.77	0.08	-0.73
EQ_Ego_Location	4.85 (0.96)	2.75	6.5	0.16	0.59
EQ_Ego_Agency	3.42 (1.25)	1.00	5.5	0.13	1.14
EQ_Allo_Ownnership	3.49 (0.87)	1.88	5.44	0.05	0.52
EQ_Allo_Location	4.00 (1.20)	1.5	7	0.34	0.23
EQ_Allo_Agency	2.51 (1.04)	1.00	4.5	0.01	1.17

Table 1. Descriptives of Body Size Misestimation and EQ in Egocentric and Allocentric conditions. The table presents mean values (Mean), standard deviations (sd), minimum value (min), maximum value (max), skewness (skew) and kurtosis. Base = baseline, Allo = Allocentric, Ego = Egocentric, s = shoulders, v = wais, f = hips.

Embodiment: Egocentric Vs Allocentric Spatial Frame

To investigate embodiment differences across conditions, a paired sample t-test was used to compare embodiment strength assessed by the EQ between the two conditions (i.e., Egocentric and Allocentric; Serino et al., 2016; Serino et al., 2018). Table 2 presents the results of the analysis. Significant differences emerged between the conditions in all subscales (all p-values were below 0.01). Looking at mean values (*Table 2*), we observed that embodiment strength was overall higher in the Egocentric as compared to the Allocentric condition.

		t	df	p	d
EQ_Egocentric_Ownership	EQ_Allocentric_Ownership	3.74	31	< .001*	0.75
EQ_Egocentric_Location	EQ_Allocentric_Location	3.29	31	0.002*	0.78
EQ_Egocentric_Agency	EQ_Allocentric_Agency	4.11	31	< .001*	0.78

Table 2. Paired-sample t-test to evaluate Embodiment across Conditions. The table shows the results of the paired samples t-test to examine the differences between the mean EQ scores in the Allocentric and Egocentric conditions for each subscale. Df = degree of freedom, d = Cohen's d, t = t statistic. Significance level (*).

Body Size Estimation Change: Egocentric Vs Allocentric

To investigate if and how perceptual body experience changed after body illusion presented from different spatial perspectives, we used a two-step approach.

Firstly, changes in Misestimation across conditions were examined. A repeated measures ANOVA was performed on a Linear Mixed Model (LMM) which included Condition (i.e., Baseline, Egocentric and Allocentric) as fixed effect, and Body Esteem score (BES_Tot) as covariate. This is because the possible impact esteem with own body might have on body image (Kékes Szabó, 2015; Mendelson et al., 2002).

To account for intra-individual variations and non-independence of data, we included random intercepts and slopes for both 'Condition' and 'BES_tot', nested within the participant identifier 'ID' (Bates et al., 2015; Barr et al., 2013). The model was specified as follows: Misestimation ~ Condition + BES_tot + (Condition + BES_tot |ID). Results are presented in *Table 3*. Analysis revealed that Misestimation level varied significantly across conditions and was influenced by individual differences in body esteem at baseline.

	F (df)	p	η2
(Intercept)	68.81 (1, 239)	< 0.001*	
Condition	10.87 (2, 239)	< 0.001*	0.08
BES_Tot	7.97 (1, 30)	0.008*	0.21

Table 3 ANOVA considering the effect of the Condition on Misestimation. The table shows ANOVA results conducted on Linear Mixed Model to investigate the effect of Condition on Misestimation while controlling for Body Esteem at baseline and inter-subject variability. Df = degree of freedom. Significance level (*).

Post-hoc analysis with Bonferroni correction was used to better examine differences between conditions. Results (see *Figure 3*) showed that participants in both the Egocentric and Allocentric conditions exhibited significantly lower levels of Misestimation than those in the Baseline condition, and there were not significant differences between Misestimation in the Allocentric and Egocentric conditions. Specifically, there was a significant difference between the Allocentric and Baseline conditions (mean difference= -4.42, SE = 0.14, t (239) = -3.19, p = 0.004, Cohen's d= -0.47), with the Allocentric condition showing a lower ratio compared to the Baseline condition (see *Table 1*). Similarly, a significant difference was observed between the Baseline and Egocentric conditions (mean difference = 6.13, SE = 1.37, t (239) = 4.48, p < 0.001, d= 0.66), with the Baseline condition demonstrating a higher ratio than the Egocentric condition (see *Table 1*). However, no significant difference was found between the Allocentric and Egocentric conditions (mean difference = 1.78, SE = 1.38, t (239) = 1.29, p = 0.59).

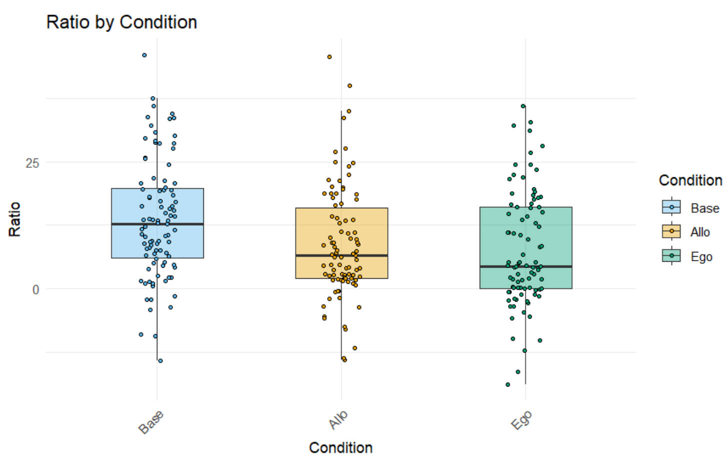

Figure 3 Misestimation across Conditions. The graph shows Misestimation mean values and corresponding standard deviations across different conditions. Base = baseline, Allo = Allocentric, Ego = egocentric.

To better characterize results, we investigated how the estimation accuracy of each body area varied across conditions. Following the same approach as before, a repeated measures ANOVA was performed on LMM. Specifically, fixed effects included the interaction between body areas (Body) and conditions, whereas the total score on the Body Esteem Scale (BES_tot) was included as a covariate. Random effects were also included to account for repeated measures design. Based on the suggestion by Bates and colleagues (2015) and Barr and colleagues (2013), the model was specified as follows: Misestimation ~ Body × Condition + BES_tot + (Condition*BES_tot |ID) (Barr et al., 2013; Douglas Bates et al., 2018).

The analysis revealed a significant effect of Condition ($F(2,233) = 14.07$, $p < 0 .001$, $\eta2$ = 0.11), Body ($F(2,233) = 39.74$, $p < 0.001$, $\eta2 = 0.25$), and Body Esteem ($F(1, 30) = 7.38$, $p = 0.01$, $\eta2 = 0.20$). The interaction effect between Body and Condition was instead not significant ($F(2, 233) = 0.22$, $p = 0.92$). That is, data revealed that Body Illusion from both Egocentric and Allocentric conditions influenced size estimation for all body areas. *Figure 4* presents the ANOVA results.

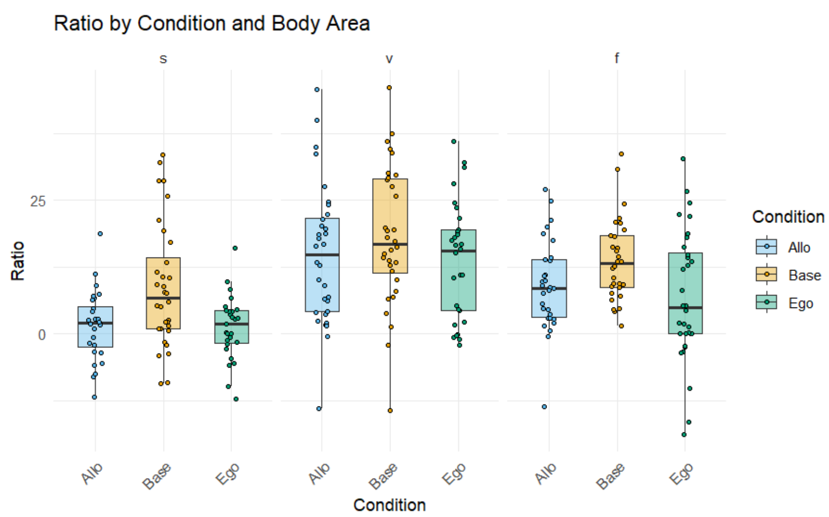

Figure 4 How body size estimation of each body area varied across conditions. The plow presents how Misestimation varied across conditions (Base = baseline, Ego =

Egocentric, Allo = Allocentric) for each body area (f = hips; s = shoulders; v = waist).

Post hoc analysis with Bonferroni correction showed that significant differences emerged between Egocentric and Allocentric conditions as compared to the baseline for shoulders and waist circumference estimation, whereas no significant differences emerged when comparing Egocentric and Allocentric conditions. Only when considering hips estimation, we observed no significant differences between Allocentric and Baseline. *Table 4* reports detailed results.

	Body	Mean diff (SE)	df	t	p	d
Base-Allo	s	5.63 (2.10)	233	2.67	0.02*	0.69
Allo - Ego	s	1.13 (2.19)	233	0.51	1.00	0.14
Base - Ego	s	6.77 (2.13)	233	3.18	0.005*	0.83
Base- Allo	w	3.56 (2.02)	233	2.67	0.02	0.43
Allo - Ego	w	1.48 (2.06)	233	0.71	1.00	0.18
Base - Ego	w	5.03 (2.06)	233	2.44	0.04*	0.62
Base - Allo	h	4.76 (2.08)	233	2.27	0.07	0.58
Allo - Ego	h	2.46 (2.06)	233	1.19	0.70	0.30
Base - Ego	h	7.21(2.06)	233	3.50	0.001*	0.89

Table 4. Misestimation across conditions for each body area: Post-hoc. This table outlines post-hoc comparisons utilizing Bonferroni correction to assess the differences in misestimation between the various conditions (Allo = Allocentric, Base = Baseline, Ego = Egocentric) across body areas (f = hips; s = shoulders; v = waist). Df = degree of freedom, d = Cohen's d, SE = standard error, mean diff = mean difference. Significance level (*).

Discussion

In this study, we investigated whether both 1PP and 3PP body illusions presented in immersive VR alter Body Self- Consciousness and body perception. The study yielded two primary insights. First, embodiment was significantly higher in 1PP as compared to 3PP. Second, both perspectives significantly affected the participants' ability to estimate their body size accurately. That is, it seemed that both egocentric and allocentric information might be used to develop and maintain bodily self-perception. In the forthcoming sections, we will present a thorough discussion of the results.

Embodiment

Data revealed that embodiment strength was higher in 1PP as compared to the 3PP, aligning with the idea that body illusions are inherently tied to an egocentric perspective and that that central processing of bodily multisensory signals operates primarily in egocentric reference frames (Petkova et al., 2011; Petkova & Ehrsson, 2008b).

This advantage for 1PP can be partly due to our habitual experience of viewing our bodies from this reference frame. Indeed, we are used to see ourselves from a 1PP and to see other from a 3PP. This familiarity might lead to a more immediate association of the virtual body with the self when presented from 1PP (Preston & Newport, 2012). Notably, a difference between 1PP and 3PP is supported by neural mechanisms required to encode egocentric and allocentric information. Indeed, 1PP and 3PP information processing rely on distinct brain networks: the first one seems to be been associated with the parietal cortex and striatum - which are closely linked to self-referential processing networks, namely the cognitive process of relating information to the self (Moraresku & Vlcek, 2020; Wang et al., 2020) - whereas the second one seems to involve brain areas as the hippocampus and its neighboring regions (Rinaldi et al., 2020). Then, if egocentric representation is influenced by processing incoming crossmodal information (bottom-up), and allocentric representation relies more on representations stored in memory (top-down; Riva & Gaudio, 2012), they might differently contribute to embodiment processes and Body Self Consciousness.

However, recent studies found similar embodiment levels when presenting virtual bodies from both 1PP and 3PP (e.g., Liou et al, 2024). Such results were explained in light of neuropsychological models highlighting that bodily experience requires the integration of both egocentric and allocentric information (Brizzi, Sansoni, & Riva, 2023; Brizzi, Sansoni, Di Lernia, et al., 2023; Maselli, 2015). How can we deal with this heterogeneity of results?

One possible explanation might rely on temporal dynamics in the processing of bodily stimuli. Typically, Body Illusions are transient and brief experiences, lasting only a few minutes (e.g., 90 seconds; Serino et al., 2016; Keizer et al., 2016). If we link this time window to the familiarity effect previously introducedthe egocentric perspective might need less time to promote embodiment. That is, the allocentric condition might require a longer stimulation duration to reach 1PP like level of embodiment, owing to its relative unfamiliarity in daily life. This hypothesis aligns with findings from Slater and colleagues (2019) and Debarba and colleagues (2017) who found comparable levels of embodiment after 1PP and 3PP bodily illusions after seven minutes of synchronous stimulation. Such observations suggest a nuanced interplay between visual perspective and the temporal dynamics of embodiment, warranting further exploration.

Another possible reason might be that different perspectives influence different aspects of Body Self Consciousness. For instance, the study by Gorisse and colleagues (2017) observed that 1PP elicited a greater sense of ownership and self-location, whereas no differences emerged when considering the sense of agency. Their findings might suggest that different spatial frames might impact different subcomponents of embodiment. Specifically, it might be that an allocentric perspective fosters embodiment based more on sensorimotor information, whereas a first-person perspective influence ownership based moew on visual and spatial information (Gorisse et al., 2017). This implies that different procedures to induce embodiment might work on various components of Body Self Consciousness and embodiment process. To better understand this aspect, different multisensory stimulations might be used to induce embodiment, such as visual stimulation alone, visuo-tactile or visuomotor.

Another possible explanation might be linked to the heterogeneity of paradigms used to induce the illusion (e.g., video recording, immersive virtual reality) in addition to the type of synchrony multisensory stimulation (e.g., visuo-tactile, motor-visual) across studies. As deeply discussed by Liou and colleagues (2024), the experimental setting and the procedures significantly influence the outcome: for instance, it might be that sensorimotor feedback facilitates embodiment in 3PP, so that it is possible to observe a similar level of embodiment from 1PP and 3PP when there is visual and motor synchrony between the real and artificial bodies. Moreover, there might be a difference in reliance on different sensory modalities at the basis of embodiment (Liou et al., 2024).

Body Size Estimation

In line with previous research, we observed that participants tended to overestimate the circumferences of all body parts at the baseline (Mölbert et al., 2017) and reported a reduction of this overestimation tendency after Body Illusion swapping into a slimmer body presented from 1PP (Serino et al., 2019). However, a novel aspect of this study is that similar changes in body size estimation occurred following both the 1PP and 3PP experiences.

Keizer and colleagues (2016) hypothesize that changes in perceptual accuracy after Body Illusions might be merely due to the reliance on the most recent information to estimate own body dimensions. That is, individuals might heavily rely on the most recent visual information when judging the size of their bodies (Petkova & Ehrsson, 2008a; Thaler et al., 2018). If this is the case, we can refers to the Predictive Coding framework (PP; Friston, 2012; Friston & Kiebel, 2009) to explain results. PP suggests the brain constantly generates and updates a model of the world based on incoming sensory information. The brain predicts what it expects to experience based on previous experience and knowledge (priors) and then compares this prediction with the actual sensory input (likelihood). Both priors and likelihood are judged in terms of their reliability (weight or precision). When there's a mismatch between the internal model and the actual sensory information (prediction error), the brain updates its model to better match reality or look for other information to solve the discrepancy (Friston, 2012; Friston & Kiebel, 2009; Hohwy Jakob, 2013, 2018). Then, the observed change in body size estimation might be due to visual information being prioritized over other information - i.e., having more weight/ precision than other sensory information - so that the most recent visual information (i.e., the virtual body) was able to influence real body perception. However, similar to previous research, we also observed a change in shoulder estimation in the egocentric condition, when the artificial body's shoulders were not visible (Keizer et al., 2016). This suggests that deeper mechanisms may be involved.

Embracing the PP framework, changes linked to VR experiences might be due to technology features. Specifically, VR is a technology that presents two main characteristics from a psychological perspective. First is the sense of presence. VR can elicit a psychological state of consciousness known as the "sense of presence." This involves a subjective sensation of being within the virtual environment and a tendency to respond to virtual stimuli as if they were physically real (Sanchez-Vives & Slater, 2005). This sense of presence encompasses both psychological and physical dimensions. Psychological presence, often referred to simply as "presence," involves cognitive and emotional engagement with the environment, leading to a perception of authenticity and immersion. Physical presence refers to the subjective experience of being physically located in a particular place or environment. Second is VR as a cognitive Simulation. VR is a cognitive technology because it can simulate the brain's predictive processes. Just as the brain attempts to predict incoming sensory events (see Predictive Coding; Friston et al., 2010), VR anticipates and adapts sensory output based on user input (Riva et al., 2019). These characteristics make VR an appropriate technology for studying cognitive processes and human behavior.

Notably, studies have shown that real-life and VR exposures are mostly indistinguishable on a psychological and psychophysiological level, while both differ significantly from conventional 2D experiences (Schone et al., 2023). That is, emotional and cognitive processing in VR resembles the corresponding mechanisms deployed in a real-life setting (Schöne et al., 2019; Kisker et al., 2020). Meta-analyses and systematic reviews of the literature have demonstrated that VR is a suitable and effective tool for understanding and manipulating embodiment processes and bodily experience (Matamala-Gomez et al. 2021; Turbyne et al. 2021, Mattelson et al., 2023). Indeed, VR provides a unique opportunity to swap into another body – i.e., embody a body different from one's own – which has been shown to have real profound implications for how individuals relate to their surroundings and perceive their own bodies, both perceptually and affectively (e.g., Serino et al., 2016; Porras-Garcia et al., 2020).

In this context, this means that VR represents an immersive and multisensory modified version of reality that the brain interprets as real: in terms of PP, virtual sensory inputs are substituted for real-world information, and immersion in the simulated world could be so convincing that the brain resolves the prediction error determined by the discrepancy between what is expected from the real environment (real body) and the virtual environment (virtual body) by updating the internal model based on the incoming - virtual - sensory information.

We could hypothesize that this mechanism involves both 1PP and 3PP experiences. Indeed, research suggests that we use two different spatial systems to process information - i.e., egocentric and allocentric (Vogeley & Fink, 2003) – and that body representation requires the integration of information from both spatial frames to create a coherent multisensory representation of the body and the space around it (i.e., Body Matrix; Moseley et al., 2012; Repetto Claudia & Riva Giuseppe, 2023). That is, we can develop our body image by using the information we get by looking directly at our stomach, as well as when we look at ourselves through a mirror (Gallup, 1977). When we look ourselves into a mirror, our brain engages in spatial transformations to correlate the reflected image with our own body, a process that is more complex than recognition (Preston et al., 2015).

In addition, it is noteworthy that in our study spatio-temporal congruence in the visual-tactile stimulation was proposed at a limited distance between the virtual and real bodies. In particular, in our study, the virtual body was positioned to fall realistically within the Peripersonal Space (PPS), approximately 50 cm from the participant's actual body. This meets the minimum criteria for altering the subcomponents of bodily self-consciousness (Preston & Newport, 2012). The critical role of the PPS in embodiment has been underlined by the invisible Rubber Hand Illusion (Guterstam et al., 2013; Rohde et al., 2011). This procedure suggest that the embodiment of a visible artificial body part could be achieved when sensations were localised close to the body, within the individual's PPS boundary. It showed that when an object enters the PPS, it is automatically encoded in relation to the body. (De Vignemont, 2018). In this regard, neuroscience research observed that the primary somatosensory cortex reflects not only direct touch on the body (1PP) but also stimulation within the PPS (Schaefer et al., 2012).

Going more into detail, research showed the existence of a specialized neural system, predominantly located within the fronto-parietal network, responsible for processing multisensory cues associated with the body (Grivaz et al., 2017). This system adeptly integrates tactile sensations with visual or auditory stimuli that occur near the body, effectively mapping out PPS. Crucially, studies showed that maps related to both PPS and body ownership involved largely overlapping fronto-parietal networks (Grivaz et al., 2017)). It has been proposed that the spatial boundaries of the PPS, defined by the multisensory receptive fields of PPS neurons, are subject to modification by synchronous visuo-tactile stimulation and that such modifications have the potential to extend PPS boundaries to encompass virtual body parts or even the whole body. This can induce sense of ownership over virtual elements, thereby influencing Body Self-Consciousness.

However, concerns might arise when considering the discrepancy between embodiment and body size estimation change. Notably, while the level of embodiment was indeed lower in the allocentric perspective, there isn't a definitive threshold defining the minimum level of embodiment required to induce perceptual changes. Therefore, the third-person perspective might achieve a sufficient level of embodiment to induce change. This might also explain why some research found body size estimation changes both after synchronous and asynchronous stimulation in egocentric conditions (e.g., Serino et al., 2016). Another possibility is that embodiment might be not necessary for such change (Galvan Debarba et al., 2017). Further research is indeed needed to better understand the role of embodiment strength in driving changes.

The hypothesis that even minimal (or no) embodiment can promote temporary changes in body image is important given that exposure to images on social media can affect the relationship between self and body (Vandenbosch et al., 2022). . If exposure to 2D images on social media can alter body image and negatively affect emotional aspects (Ando et al., 2021; Slater et al., 2019), immersive experiences may have similar effects. However, the multisensory synchronization may prevent the activation of comparison mechanisms thus enhancing body-self relationship.

Another possible explanation relates to the mirror-like experience per se. From early childhood, we learn how mirrors work – they reflect images in a specific way (reversed left-right but not top-bottom). This understanding becomes an integral part of our cognitive schema, a mental framework that helps us interpret and predict the world around us, including the virtual world.

A Bayesian account of Egocentric and Allocentric Body Illusions

PP framework can efficiently explain Body Illusions. Specifically, body Illusions can be seen as a way of the brain to solve the binding problem through predictive inferential processing (Hohwy, 2013). Different brain regions are involved in this binding process (a top-down attentional mechanism) and bottom-up processes (object recognition based on priors, previous experience, and knowledge; (Hohwy, 2013, 2020)). PP suggests that sensory attributes are linked by the causal inference embodied in the parameters of the current hypothesis, which is maintained through hierarchical processing. When individuals are presented with a Body Illusion, two different hypotheses can explain what is happening: the independence hypothesis, which suggests that they are watching an artificial body being touched but it has nothing to do with the touch they can feel on the hidden body, and the binding hypothesis, which instead suggests that the touch that they can feel being administered to the artificial body is also the touch they can feel (Hohwy, 2013, 2020). Both hypotheses are consistent with the incoming sensory input, except that the spatio-temporal synchrony of the input better fits the binding hypothesis. This is because we have a stronger expectation (prior) that there is a common cause when information co-occurs in time space, and time (Hohwy, 2013).

In other words, during Body Illusions, individuals are presented with a barrage of low-level tactile and visual information. Then, they need to adjust the hypothesis' parameters accordingly and predict how the input will evolve, partly based on prior beliefs about the nature of the body and the statistical regularities in the world. Instead of sticking with the known truth ("that the artificial body is not my real body so touch cannot be felt there"), the system goes with whatever alternative hypothesis about the world that can most efficiently reduce prediction error down through the perceptual inferential processing (Hohwy, 2013).

Notably, the superiority of this hypothesis is supported then both by general priors (i.e., spatio-temporal synchrony implies a common cause) as well as fine-grained priors (i.e., plausible shape and texture of the artificial body; Hohwy, 2013). This perspective is also consistent with the complexity proposal, which suggests that our brains tend to move away from complex explanations in favor of simpler and more effective ones.: That is, the illusory experience is simpler and with fewer levels and parameters as compared to the independence hypothesis (Hohwy, 2013).

We could hypothesize the same mechanism concerns both the 1PP and 3PP experiences. In the first-person perspective, the brain compares the sensory information of the virtual body with the internal body model. The brain experiences a conflict between the pre-existing internal body model and the new sensory information provided by the VR environment. To reduce this predictive error, the brain updates its internal model, resulting in a modified perception of body size. The winning of the binding hypothesis is favored by parameters such as the spatial perspective in which the body is observed (prior: first-person perspective), spatiotemporal synchrony (prior: events occurring synchronously in spatiotemporal terms have a common cause) and the plausibility of the body (prior: skin color, human-like morphology). Similarly, in the third-person perspective, the brain faces the task of updating its internal model in response to the prediction error prompted by the virtual body. Also in this case, the mirror-like perspective adheres to priors such as synchrony and plausibility of the body as well as mirror functioning.

This update manifests behaviorally as a change in perceived body size. Moreover, the variation in the degree of embodiment experienced between 1PP and 3PP can be attributed to the strength and nature of these priors. The 1PP typically aligns more closely with the brain's expectations, leading to a more seamless and automatic embodiment. In contrast, 3PP often presents a greater deviation from these expectations, resulting in a higher degree of surprise and potentially a less automatic process of embodiment.

Limitations

It is noteworthy to note that this study presents some limitations. Firstly, we proposed participants with only synchronous stimulation, since egocentric condition was conceptualized as a control condition. Future research might include also asynchronous stimulation in both 1PP and 3PP conditions. This would also allow to investigate differences between allocentric synchronous and asynchronous stimulation in terms of embodiment strength, as well as to better understand the role of embodiment in drive changes. Secondly, we measured embodiment only from an explicit level with self-report measures. Future research might include behavioral and implicit measures to assess embodiment strength, such as proprioceptive drift, physiological measures, or hurting the fake body. Thirdly, we used a normal-weight body in line with previous research (Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2019), so that the virtual body was thinner than the participants' real one. Future research might propose swapping experience manipulating body dimensions to see the direction of body size estimation change and evaluate its congruency with the virtual body. This might elucidate whether the observed perceptual change is toward the virtual body or if there was an update of the internal model of the participants' body. Lastly, to preliminary test our hypothesis we included healthy participants so that further validation of results is needed when considering clinical samples as patients with a diagnosis of AN.

Conclusions

This study investigated the impact of visual perspective on body experience, focusing on embodiment and body perception. Our findings lighten how a first-person perspective significantly enhances embodiment with a virtual avatar, yet both egocentric and allocentric perspectives profoundly influence the perceptual component of body experience.

Although our findings are preliminary and call for further validation, they contribute meaningful insights into the complexity of bodily experience and possible mechanisms underpinning body-related disorders. Firstly, this research expands the discourse beyond the traditional dominance of the first-person perspective by exploring the factors that foster a sense of embodiment—whether with one's own body or a virtual counterpart. We propose that the nature and duration of multisensory stimulation are critical determinants in this process. Secondly, our study links to existing literature advocating for virtual reality body swapping as a potent intervention to alter body experience and representation in individuals facing body image challenges, including those with Weight and Eating Disorders. Prior applications of first-person body swapping have aimed at modifying body image perceptions in individuals with AN (Serino et al., 2019) as well as obesity (Scarpina et al., 2019). However, our findings advocate for the inclusion of a third-person perspective, supporting the use of mirror-like experiences combined with body swapping to alter bodily perceptual, cognitive, and affective components. This dual-perspective approach could engender a more profound and enduring transformation by engaging both egocentric and allocentric representations of the body.

The potential of integrating an allocentric perspective supports the Allocentric Lock Theory of Eating Disorders. According to this theory, individuals affected by Eating Disorders are locked in a wrong allocentric representation of their body, unable to update it to reflect their current physical state (Riva, 2012; Riva & Dakanalis, 2018; Riva & Gaudio, 2012). This framework stresses of the adoption of a third-person visual perspectives in body-focused interventions. This type of work in addition to VR opportunities might allow to deeply influence body experience on both a perceptual (bottom-up) and cognitive-emotional (top-down) level, thereby offering a more comprehensive treatment strategy.

In conclusion, these findings underscore the importance of a multifaceted approach to body representation and suggest that VR, with its capacity to fluidly navigate between egocentric and allocentric perspectives, holds significant promise for developing more effective treatments for body image disorders. This research paves the way for future explorations into the therapeutic potential of virtual reality, advocating for interventions that harness the full spectrum of spatial perspectives to foster a healthier body experience and self-perception.

3.4 Conclusions

This chapter introduces the third protagonist of this project: Virtual Reality Technology. After an overview of what VR is from a psychological perspective and how it works, the chapter presents how immersive multisensory experiences can be used as transformative experiences able to deeply change cognitive and emotional processes. This discussion clarifies why VR is the most suitable tool for working on an intimate experience, such as that of the body.

Building on the existing literature, I proposed Full Body Illusions in virtual reality (VR) as a potential immersive intervention to alter subjective body experience. To explore this, I conducted two studies. The first study demonstrated that males and females differ in their body experiences and susceptibility to the Full Body Illusion, highlighting the importance of adopting a gender-specific approach. The second study revealed that the spatial frame from which the Full Body Illusion is presented significantly influences the effectiveness of the illusion in transforming bodily experience.

These two studies were needed to have a rationale and guidelines to drive the development of the final Full Body Illusion software, the main "technical outcome" of this thesis project. However, a deeper analysis of existing VR approaches used to assess, understand, and treat ED was still needed.

4. Virtual Reality for Eating Disorders

In the previous chapter, we saw how Virtual Reality can transform the way we experience ourselves, including our bodies, and the world around us. This chapter will focus instead on how this evidence can be translated into a clinical application context in the field of eating disorders. The first part will present a scoping review aimed at systematizing scientific evidence on the use of virtual reality for the assessment, understanding, and treatment of eating disorders. In the second part, a new intervention protocol developed during the PhD course will be presented. Because of the novelty of the software, a previous usability and user experience study was conducted. Only after this step, a single-subject experimental design was conducted to test the protocol's preliminary feasibility and acceptance in a real-world clinical setting.

4.1 Harnessing Immersive Virtual Reality: A Comprehensive Scoping Review of Its Applications in Assessing, Understanding, and Treating Eating Disorders [5]

Introduction

Eating disorders (EDs) are complex psychopathological conditions characterized by abnormal eating habits and a distorted body image (BI), significantly affecting individuals' physical health and psychosocial well-being. EDs include a broad spectrum of conditions, of which Anorexia Nervosa (AN), Bulimia Nervosa (BN) and Binge Eating Disorder (BED) are the primary types. AN is classified into two primary subtypes: the restrictive subtype, where individuals achieve extreme body weight through dieting, fasting, or excessive exercise; and the purging subtype, characterized by an unhealthy low body weight with episodes of binge eating followed by compensatory behaviors such as vomiting or the use of laxatives to prevent weight gain. BN is distinguished by recurrent episodes of binge eating accompanied by compensatory behaviors to counteract the effects of overeating and weight gain. In contrast, BED involves repeated episodes of binge eating without subsequent compensatory actions (American Psychiatric Association, 2013).

In Western countries, a substantial proportion of young women and men, up to 17.9%, meet the diagnostic criteria for an ED in early adulthood (Silén & Keski-Rahkonen, 2022), and the number of diagnoses is dramatically increasing after Covid-19 (McLean et al., 2022). What underscores these conditions as a mental health emergency is the increasing prevalence combined with the limited effectiveness of available prevention, assessment, and treatment procedures. This is partially linked to multifaceted factors that contributes to EDs etiology and maintenance.

[5] This study has been published: Di Natale, A. F., Pizzoli, S. F. M., Brizzi, G., Di Lernia, D., Frisone, F., Gaggioli, A., Rabarbari, E., Oasi, O., Repetto, C., Rossi, C., Scerrati, E., Villani, D., & Riva, G. (2024). Harnessing Immersive Virtual Reality: A Comprehensive Scoping Review of its Applications in Assessing, Understanding, and Treating Eating Disorders. Current psychiatry reports, 26(9), 470–486. https://doi.org/10.1007/s11920-024-01523-2

EDs manifest primarily across two dimensions: behavioral and experiential. The behavioral domain encompasses the actions undertaken by individuals to exert control over their bodies, including, food elimination, food restriction, and episodes of binge eating. These behaviors are the visible manifestations of the disorder, observable and quantifiable. However, the complexity of EDs also reaches the experiential domain, namely the internal, subjective experiences of individuals with EDs. Specifically, the experiential domain includes the emotional, perceptual, and cognitive aspects that shape individuals' relationships with food and their bodies, which in turn influence overall daily functioning.

On one side, EDs are characterized by profound food-related dysfunctional emotional reactions (Esposito et al., 2018). The fear of gaining weight, the anxiety or disgust triggered by certain foods in certain situations, and the guilt following eating are emblematic of the disordered relationship with food that characterizes EDs. This complex emotional experience significantly impacts the individual’s ability to maintain a healthy eating behavior, often leading to avoidance, restriction, compensatory or uncontrolled behaviors that further exacerbate the disorder.

On the other side, a critical and pervasive issue is BI distortion (Brizzi, Sansoni, Di Lernia, et al., 2023; Dakanalis, Gaudio, et al., 2016), where individuals inaccurately perceive their bodies as larger or more flawed than reality and deeply link their self-esteem and self-worth to distorted BI. This distortion is deeply linked to a significant difficulty in developing a stable sense of self, exacerbated by a lack of coherent, first-person experience of their body (Mancini & Esposito, 2021). Individuals with EDs often struggle to feel a direct, personal connection to their bodily sensations and emotions. Instead, they adopt an external, object-centered perspective (self-objectified) influenced by societal ideals and past observations (Calogero, 2012).

Intriguingly, two separate longitudinal studies conducted over four years, each involving upwards of 2000 participants (Dakanalis et al., 2017; Dakanalis, Pla-Sanjuanelo, et al., 2016) revealed that self-objectification held a significantly higher predictive value for both the remission and emergence of EDs when compared to other widely acknowledged factors - body dissatisfaction, thin-ideal internalization, negative affectivity and lower self-esteem - that demonstrated significant less predictive power. This suggests a potentially essential role for self-objectification in the progression and mitigation of EDs, meriting further investigation within the field.

Recently, the Allocentric Lock Hypothesis (ALH) proposed that EDs may arise from difficulties in multisensory body integration (Riva & Dakanalis, 2018). This integration process involves combining internal bodily signals (e.g. hunger, proprioception) with external sensory information (e.g. vision, touch) and autobiographical memories to form a coherent representation of one's physical self (Repetto & Riva, 2023).

According to predictive coding theories, the brain continuously generates and updates an internal model of the body and surroundings, allowing it to predict and integrate diverse sensory inputs through embodied simulations (Talsma, 2015). The ALH proposes that in EDs, there is a disruption in these predictive mechanisms underlying multisensory integration (Riva & Dakanalis, 2018). As a result, individuals with EDs become locked into an observer-based (allocentric) embodied simulation of their body (Riva, 2012; Riva & Gaudio, 2018). Negative experiences like teasing, objectification through social media exposure, or distorted autobiographical memories originally shape the allocentric perspective. This outdated model remains rigid, failing to update accurately despite contradictory information from current sensory inputs about the individual's actual bodily state. This persistent allocentric representation can cause ongoing BI disturbances, leading to persistent dissatisfaction and shame. These experiences trigger anxiety and drive maladaptive behaviors aimed at controlling perceived bodily flaws based on memory rather than true corporeal reality.

In this context, a key advantage of Immersive Virtual Reality (IVR) for EDs is that it can simulate virtual bodies and the worlds around them that dynamically adjust to the user's actions, providing predicted multisensory feedback just as the brain generates and updates internal body models to anticipate sensory inputs (Riva et al., 2019). This is particularly supported by advanced IVR technologies, such as head-mounted displays (HMDs), that enable real-time interaction with the virtual world through motion tracking, hand controllers, and sensory feedback devices. This alignment makes IVR an unprecedented "playground" to directly apply principles of predictive coding.

Through carefully constructed virtual environments, it is possible a controlled delivery of challenging multimodal experiences (e.g., exposure to high-calorie food) that induce modest prediction errors in a safe, immersive manner (Cerasa et al., 2024). For example, IVR can recreate triggering situations, such as mealtimes, in personalized environments, placing patients in a range of contexts from kitchens to restaurants, whether alone or with others, and presenting various types of food (de Carvalho et al., 2017). These environments have the potential to elicit patients’ authentic emotional reactions that allow clinicians to understand deeper the patient’s emotional difficulties and to work with them on managing the emotional responses.

Moreover, IVR allows the embodiment in bodies different from the actual one (e.g., full body illusions) providing disconfirming multisensory feedback, that create opportunities to update the internal body models of the user iteratively (Mottelson et al., 2023). For example, by embodying virtual avatars that closely mirrors or subtly adjusts their physical form, users can experience a different perspective on their body size, shape, or appearance (Riva et al., 2021). This "re-training" of the predictive mechanisms can foster more accurate modeling of reality with reduced predictive biases that contribute to eating disorder psychopathology (Matamala-Gomez et al., 2021).

Initial review works have focused on outlining and summarizing the application of IVR in EDs (Ciążyńska & Maciaszek, 2022; Clus et al., 2018; de Carvalho et al., 2017), and preliminary studies suggest its efficacy in addressing core EDs symptoms (Riva et al., 2019). These data suggest that IVR could be a supportive tool for clinical practice, as it can offer an alternative or an addition to available assessment and intervention approaches.

Rationale

This scoping review aims to explore the current use of IVR technology across various aspects of eating disorders (EDs). This work moves beyond previous theoretical works, that either provided a general description of the techniques (Ciążyńska & Maciaszek, 2022), or focused on specific techniques (Riva et al., 2021), specific EDs (de Carvalho et al., 2017) or specific outcomes (Ferrer-García & Gutiérrez-Maldonado, 2012), aiming at providing a more updated and comprehensive representation of the field (Clus et al., 2018).

Specifically, it offers a detailed analysis of novel IVR methods in EDs assessment, understanding and treatment, evaluating their effectiveness across various disorders. Furthermore, it not only evaluates the effectiveness of IVR in key aspects of EDs, including body image distortion and food-related anxiety, but also discusses its integration with established treatments.

Methods

Protocol

The protocol of this scoping review was crafted following the Preferred Reporting Items for Scoping Reviews (PRISMA-ScR). By adopting this methodology, we aimed to provide an extensive analysis of the developments in IVR for EDs over the past five years, focusing on the range still not covered by other theoretical works (Ciążyńska & Maciaszek, 2022; Clus et al., 2018; de Carvalho et al., 2017).

Eligibility Criteria

Data extraction was performed on March 30th, 2024. Peer-reviewed journal papers were included if they were published from January 1st, 2019, up to the extraction date, written in English, involved human participants, and described a measure for ED treatment or assessment using IVR. Both experimental and quasi-experimental studies were selected, including randomized controlled trials and pre-post design studies. Papers were excluded if they did not fit into the conceptual framework of the study or if they did not present empirical data (e.g., background articles). Papers focusing on non-immersive virtual reality were also excluded to maintain the focus on immersive VR experiences specifically.

Information Sources

To identify potentially relevant documents, the following bibliographic databases were searched: Scopus, Web of Science, PsychInfo, Pubmed. The search strategies were drafted by A.F.D.N. and further refined through team discussion. The final search results were exported directly into Rayyan, and duplicates were removed.

Search Strategy

The following string was used for the search: ("virtual reality" OR vr) AND ("eating disorder*" OR bulimia OR "binge eating" OR anorexia) and adapted for each database. Notably, the term "immersive" was intentionally omitted in favor of the broader term "VR" to avoid prematurely excluding relevant studies. This approach acknowledges that some research may refer to VR in a way that implicitly includes IVR, despite not combining the term “immersive” and “virtual reality” one after the other. The aim was to encompass a wider range of studies, subsequently refining the selection to focus on immersive experiences as needed, based on the context provided within individual papers. The final string for each database can be found in “Supplementary Materials”.

Selection of Sources of Evidence

We performed a two-step screening of all the references generated by the search strategy. In step 1, two authors (A.F.D.N. and S.F.M.P.) independently screened the titles and abstracts to exclude any irrelevant references that did not meet eligibility criteria. Conflicts were resolved through discussion. In step 2, two authors (A.F.D.N., S.F.M.P.) independently screened the full texts of the references selected in Step 1 against the eligibility criteria. To minimize bias during the selection process, the screening was blind, using the option “blind status on" in Rayyan. Once all authors have completed the selection process, the blinding status was turned off, and any disagreement was resolved through consensus.

Data Charting

The team developed a data-charting form to decide on the variables for extraction. Two authors (A.F.D.N., S.F.M.P.) independently gathered the data, then discussed their findings with the rest of the team, refining the charting form through an iterative process to ensure comprehensive data collection and analysis.

Results

A total of 423 papers were found. Two-hundred and nine were removed as duplicates and 147 were removed after screening Step 1 (titles and abstracts). A total of 67 were sought for retrieval and 3 were not found. As a result, a total of 64 full texts were screened for eligibility. After full-text screening, a total of 20 articles met the inclusion criteria and were included in our scoping review. The flowchart of the paper selection is shown in *Figure 1*. Sixteen papers included participants with AN, 2 studies included patients affected by BED and only 1 study considered individuals with solely BN and 1 with BN and BED. *Table 1* summarizes the sociodemographic information of the population of the included studies.

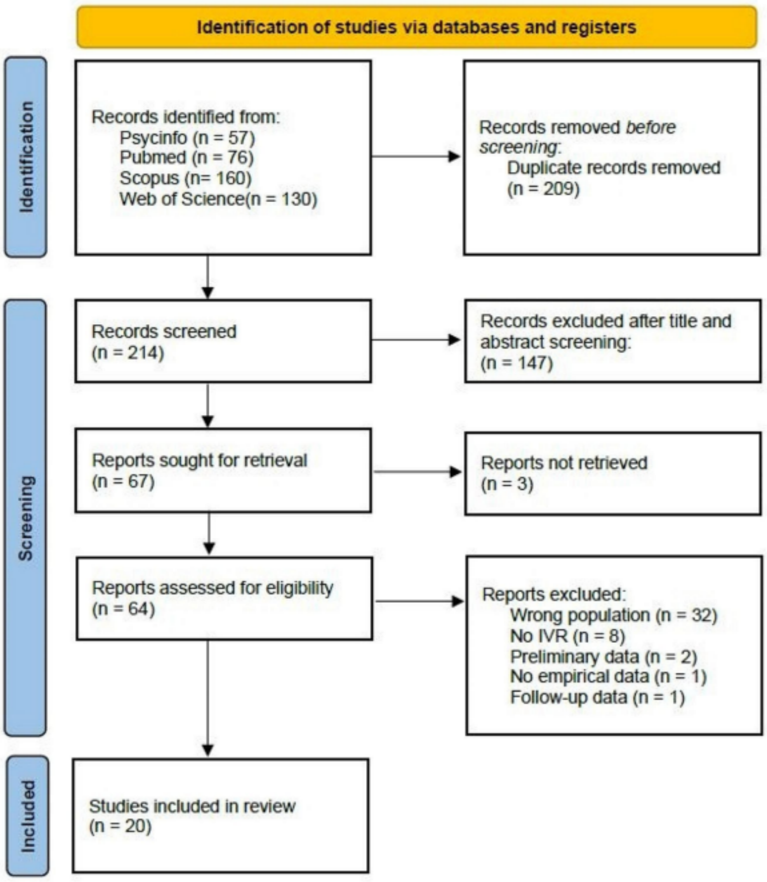

Figure 1 PRISMA flowchart.

Study	IG	IG sex	IG age	CG	CG sex	CG age	N_tot
Ascione et al. (2023)	AN	23 F	15.30 ± 1.29	n.a.	n.a.	n.a.	23
Behrens et al., (2023) - study 2	AN	20 F	30.1 ± 11.9	n.a.	n.a.	n.a.	20
Bektas et al., 2023	AN	66 F, 4 M	25.7 ± 7	n.a.	n.a.	n.a.	70
Di Lernia et al., 2023	AN	15 F	18.93 ± 3.97	HC	15 F	22 ± 0.59	30
Ferrer-Garcia et al., 2021	AN	11 F, 2 M	n.s.	n.a.	n.a.	n.a.	13
Fisher et al., 2020	AN	31	13.9 ±4.25	n.a.	n.a.	n.a.	31
Malighetti et al., 2020	AN	7 F	17±1.87	n.a.	n.a.	n.a.	7
Malighetti et al., 2021	BED	1 F	54	n.a.	n.a.	n.a.	1
Matamala-Gomez et al., 2021	AN	5 F	17 ±1.8	n.a.	n.a.	n.a.	5
Max et al., 2023	BED	31 F, 7 M	36.26 ± 13.37	n.a.	n.a.	n.a.	31
Nameth et al., 2021	BED + BN	11 F, 1 M	40.90 ± 15.7	n.a.	n.a.	n.a.	11
Natali et al., 2024	AN	140 F, 2 M, 3 other	21.75 ± 6.68	n.a.	n.a.	n.a.	145
Porras-Garcia et al., 2020 (a)	AN	1 F	14	n.a.	n.a.	n.a.	1
Porras-Garcia et al., 2020 (b)	AN	30 F	17.73	HC	43 F	21.12	73
Porras-Garcia et al., 2020 (c)	AN	1F	15	n.a.	n.a.	n.a.	1
Porras-Garcia et al., 2021	AN	14 F, 2 M	18.25 ± 1.30	AN	19 F, 2 M	19.21 ± 1.78	35
Provenzano et al., 2020	AN	20 F	23.30	HC	20 F	23.85	40
Sansoni et al., 2024	BN	12 F	29.25 ± 7.75	BN	12 F	28.83 ± 6.48	24
Serino et al., 2019	AN	1 F	30	n.a.		n.a.	1
Schroeder et al., 2024	AN	60 F	19.1 ± 4.88	HC	29 F	20.0 ± 3.87	89

Table 1. Sociodemographic information. The table presents sociodemographics information related to the included studies regarding diagnosis, sex, age mean values, and standard deviation when applicable. IG = intervention group, CG = control group, n.a. = not available.

Overall, the included articles comprise a total sample of 661 participants, (479 with AN, 75 with BN, or BED, and 107 healthy controls), aged 14 to 65. The female gender was the most represented (638 females, 10 males, 3 non-binary or others). Most of the studies were conducted in Europe (Spain, Italy, Germany, and French), two were carried out in the United States, and one in the United Kingdom.

To systematize results and better understand the impact of new IVR approaches in EDs treatment, we pooled the results according to three mutually exclusive categories: 1) studies where IVR is used as a diagnostic or assessment tool to identify patients and/or assess their symptoms (assessment), 2) Studies where IVR is used to better analyze certain aspects or processes which characterize people with EDS that might shape IVR treatment efficacy for EDs (understanding), and 3) studies aimed at testing the efficacy of IVR treatment on ED symptoms (treatment). Although some papers could fall into multiple categories, such as understanding and treatment (Serino et al., 2019) or assessment and treatment (Provenzano et al., 2019), we have placed each of them in the most representative category, based on the main aim of the study. An overview of the included studies is available in *Table 2* and an overview of the IVR technology and procedure used is detailed in *Table 3*.

First author	Aims and scopes	Study design	Main findings
	Assessment		
Bektas et al., 2023	To explore the correlations between food-specific disgust, eating disorder psychopathology, and food interaction in anorexia nervosa patients through different virtual kitchen scenarios using VR.	cross-sectional	Significant positive correlations were found between food-specific disgust and eating disorder symptom severity. The study highlights the potential clinical utility of addressing food-specific disgust in anorexia nervosa treatment.
Fisher et al., 2020	To assess body image disorder (BID) symptoms in anorexia nervosa (AN) using virtual reality (VR) with standardized 3D avatars compared to traditional paper-based figure rating scales (FRS). The study hypothesized that VR would improve body image perception and evaluation among adolescents with AN due to the enhanced visual perception and immersive conditions provided by VR technology.	retrospective, cross-sectional	Adolescents with AN overestimated their own body size regardless of the assessment tool used (VR or paper-based FRS). BPI and body dissatisfaction did not significantly differ between the two methods. VR-based evaluation was correlated with psychometric parameters related to BID and body dissatisfaction. Head-tracking data revealed a longer engagement with avatars representing malnutrition and underweight states, indicating a preference for thinner body images among participants.
Matamala-Gomez et al., 2021	To test the usability and UX of the VR-based protocol for patients with AN, specifically how a virtual body-swapping illusion can influence their perception of their own body.	pre-test and post-test design without a control group	The study found high levels of embodiment (ownership, agency, and self-location) when patients were embodied in a virtual body that resembled their real perceived body size. User experience, measured through embodiment scores, think-aloud technique, and patient

			interviews, indicated that patients with AN could benefit from using VR as a technological solution for assessing and modulating body image distortions
Provenzano et al., 2020	To characterize and mitigate body image distortion in AN by employing virtual reality to assess body overestimation and dissatisfaction, examining the effectiveness of embodied virtual avatars in altering these perceptions.	pre-test and post-test design	Patients with AN exhibited higher body dissatisfaction without overestimating their body size. The study underscored the cognitive-emotional component of body image distortion as more severely altered in AN, noting that embodiment through virtual reality did not significantly ameliorate these distortions.

Understanding

Di Lernia et al., 2023	To objective of the study was to the influence of interoceptive metacognition and predictive Bayesian models on embodiment and body perception distortions in patients with AN compared to healthy controls.	cross-sectional	Patients with AN demonstrated a disconnect between interoceptive perception and metacognitive evaluation of these perceptions, showing a pattern where higher levels of interoceptive metacognitive beliefs were associated with greater embodiment and body perception distortions. This pattern, however, was partially recovered following the clinical rehabilitation program.
Ferrer-Garcia et al., 2021	To assess the effectiveness of VR-BE incorporating body related attentional bias, in addition to TAU, for reducing FGW, BIDs, and other ED symptoms in patients with AN.	RCT	Post-intervention, the experimental group showed significantly reduced FGW and BIDs compared to the control group, suggesting VR-BE's efficacy in addressing core AN fears and disturbances. Body-related Attentional Bias before therapy predicted less favourable clinical outcomes, such as a smaller reduction in FGW, BID, and a smaller increase in body appreciation after treatment.
Max et al., 2023	To investigate cognitive processes underlying BED through embodied interaction with food in VR, examining the relationship between behavioral biases in manual interaction with food and BED psychopathology, eating behavior, impulsivity, and food craving.	RCT	The study identified a faster recognition and approach behavior towards food, followed by a slower collection of food compared to office tools. This pattern suggests an initial impulsive reaction to food stimuli, followed by a more cautious or aversive motivational process in handling food. No significant changes in behavioral patterns were observed after a clinical intervention aimed at reducing BED symptoms, and no direct relationships between behavioral biases and sample characteristics were detected.
Schroeder et al., 2024	To explore the behavioral patterns associated with food avoidance in individuals diagnosed with AN-restrictive type. The goal was to employ a novel VR stopping task to investigate the trajectories of food avoidance behavior and to understand if food avoidance stem from either automatic, habitual responses or heightened inhibitory control abilities.	pre-test/post-test with a control group	The paper explores food avoidance in patients with AN-restrictive type using a VR stopping task, finding evidence of persistent food avoidance and heightened inhibitory control in these patients.

Treatment

Ascione et al.., 2023	The study aimed to assess the efficacy of a single session of a new body-related ABMT that combines VR with eye tracking in patients with AN. The goals were to reduce body-related AB by balancing attention between weight and non-weight-related body areas and to reduce BD levels.	pre-test/post-test without a control group	A significant reduction in both the total fixation time on weight-related body parts and BD levels post-intervention, suggesting the potential clinical utility of ABMT in treating AN.
Behrens et al., 2023 (study 2)	To evaluate the potential of virtual reality (VR) exposure to healthy weight bodies as an adjunct treatment for anorexia nervosa (AN), focusing on its effects on fear of weight gain among patients with AN.	pre-test and post-test without a control group	VR exposure to healthy weight bodies was found to evoke high arousal in patients with AN and demonstrated a trend toward improving fear of weight gain after four sessions of exposure.
Malighetti et al., 2020	To explore the effectiveness of VR in unlocking the allocentric memory of the body in patients with AN by combining autobiographical recall and body-swapping techniques to affect body size distortion and related negative memories.	pre-test and post-test design without a control group	Participants showed reduced negative emotions and body shame, increased body satisfaction, and more accurate body perception post-intervention, suggesting the potential of VR as a tool for assessment and treatment of body perception in AN.
Malighetti et al., 2021	To evaluate the effectiveness of a novel ER-focused VR immersive intervention in reducing	case study	Post-treatment assessments indicated a decreasing trend in emotional eating, emotion

	EE and improving emotion regulation among individuals with a history of binge eating disorder.		dysregulation, binge episodes, depression, and anxiety, alongside an increasing trend in self-esteem and confidence in eating and performing eating-related activities.
Nameth et al., 2021	To assess the translation of VR-CET from controlled research settings to a real-world clinical setting, focusing on its feasibility, acceptability, and preliminary signals of effectiveness for patients with BED or BN who have experienced at least one binge episode per week.	pre-test and post-test design without a control group	The study found significant reductions in OBEs and high acceptability among both patients and therapists. The adoption of VR-CET in clinical settings appears feasible and acceptable, with preliminary evidence suggesting its effectiveness in reducing binge eating symptoms.
Natali et al., 2024	To investigate the feasibility of utilizing positive mood induction or social support to augment the impact of virtual food exposure on food-related anxiety in patients with AN.	RCT	Findings reveal decreased anxiety levels in the positive mood condition compared to the baseline condition, shedding light on potential strategies to mitigate food-related distress in this population
Porras-Garcia et al., 2020a	To assess the efficacy of VR Body Exposure Therapy in reducing FGW, BID, body-related anxiety, and improving BMI in a patient with AN.	case study	The intervention led to significant improvements in FGW, body-related anxiety, drive for thinness, and BID immediately after treatment, with a slight increase in BMI. Some improvements decreased at the 3-month follow-up.
Porras-Garcia et al., 2020b	To assess the VR-based body exposure's utility in eliciting FGW, body anxiety, and body-related attentional bias among patients with AN.	cross-sectional	Patients with AN experienced higher FGW, body anxiety, and attentional bias towards weight-related body areas than healthy controls. Interestingly, patients with AN showed lower level of FBI compared to healthy participants, suggesting a potential disconnect or discomfort with embodying a virtual body closely resembling their actual physique.
Porras-Garcia et al., 2020c	To provide preliminary evidence of VR-BET's usefulness in treating AN by reducing FGW, body-related anxiety, and dissatisfaction, and by achieving a healthy BMI.	case study	Significant reductions in FGW, drive for thinness, body-related anxiety, and dissatisfaction post-intervention, with BMI increasing to healthy levels. These improvements were largely maintained at a 5-month follow-up, except for FGW.
Porras-Garcia et al., 2021	To evaluate the efficacy of virtual reality-based body exposure therapy (AN-VR-BE) combined with treatment as usual (TAU) for reducing fear of gaining weight (FGW), body image disturbances (BIDs), and other ED symptoms in patients with AN.	RCT	The study found that AN-VR-BE combined with TAU was more effective than TAU alone in reducing FGW, body distortion, and body dissatisfaction among patients with AN. Improvements were significant for body distortion and body dissatisfaction, with trends toward improvement in FGW and other ED measures. These effects were maintained or became more pronounced at the three-month follow-up.
Sansoni et al., 2024	To compare the effectiveness of a VR-CBT intervention to an Inpatient Program (IP) for female patients diagnosed with BN	RCT	The study found that the VR-CBT intervention resulted in a consistently stable BMI trajectory over time, contrasting with the control group's BMI fluctuations. Additionally, VR-CBT demonstrated effectiveness in alleviating preoccupation with weight, fear of weight gain, and occurrences of binge eating and purging behaviors. Conversely, the IP group experienced a notable BMI increase post-treatment, followed by a decline between 9 and 12 months after discharge.
Serino et al., 2019	To assess the potential of VR-based body swapping illusion in treating body-size distortion in AN by altering the patient's body representation through multisensory bodily integration.	case study	The VR full body illusion was successful in monitoring and partially modifying the patient's distorted body representation. It highlighted the importance of multisensory integration in the treatment of AN, suggesting the VR-based approach could serve as both an assessment and therapeutic tool.

Table 2 Overall information of included studies.

Study	VR technique	Technology	Procedure of VR-based intervention	Control group
Ascione et al., 2023	VR-ABMT	HTC Vive Pro Eye head-mounted display with built-in Tobii eye tracker; VR environment developed on Unity 3D software.	Participants, embodied in a virtual avatar matching their physical characteristics, completed the ABMT in a VR setting. This involved directing attention to geometric figures appearing on various body parts of the avatar to balance attention across weight and non-weight-related body areas.	n.a.
Behrens et al., 2023	VR-BE	Valve Index headset and controllers, VIVE trackers, Lenovo Legion Y740 laptop	Participants underwent four 30-min VR exposure sessions to a body of higher weight, aiming to elicit and manage fear of weight gain. The VR environment featured a u-shaped changing cabin with two virtual mirrors showing the avatar from front, side, and first-person perspectives.	n.a.
Bektas et al., 2023	VR-FE	Oculus Quest 2 headsets with Unity3D game engine and Oculus Integration SDK.	Participants were exposed to one of three VR kitchen scenarios (kitchen only, kitchen plus virtual pet, and kitchen plus avatar), where they interacted with virtual foods. This setup was used to measure food-specific trait and state disgust, eye gazes towards, and touching of virtual foods, before and after VR exposure.	n.a.
Di Lernia et al., 2023	VR-BS	Oculus Rift DK2, connected to a portable computer for the virtual reality illusion. The illusion was facilitated by synchronous visuotactile stimulation.	Participants experienced a VR full-body illusion in both synchronous (experimental) and asynchronous (control) conditions to assess the effect on body perception. The procedure included body size estimation tasks and embodiment questionnaires, performed at two time points: upon hospital admission and after a 12-week rehabilitation program.	Healthy controls underwent the same VR intervention in a single experimental session, allowing for comparative analysis with patients with AN.
Ferrer-Garcia et al., 2021a	VR-BE	The study utilized HTC-VIVE head-mounted displays, VR controllers, and body trackers for full-body tracking, alongside a FOVE VR headset with eye-tracking for certain assessments.	The experimental group underwent AN-VR-BE, involving immersion in a VR environment where patients were exposed to a virtual body matching their real body size and then gradually introduced to a healthy BMI increase across sessions.	The control group received the standard treatment without the VR-based body exposure sessions.
Ferrer-Garcia et al., 2021b	VR-BE	VR system including HTC-VIVE head-mounted display (HMD), VR controllers, body trackers, and a FOVE VR-HMD with eye-tracking technology. Powerful VR-ready computers with high-end CPU processors and graphic cards were used to run 3D immersive environments.	Participants in the experimental group received five sessions of AN-VR-BE, involving exposure to a virtual body matching their real-size silhouette and BMI. Small BMI increases were applied over successive sessions until reaching a healthy BMI target. The intervention aimed to reduce FGW by allowing patients to confront their body image fears in a controlled, virtual environment. Procedures included visuomotor and visuo-tactile stimulation to elicit the Full Body Illusion (FBI) of owning the virtual body.	Control group received treatment as usual (TAU) only.
Fisher et al., 2020		Oculus Rift headset for VR exploration; VR software developed by C2CARE under the UNITY 3D framework; head-tracking technology for implicit measurement of explicit choices.	Participants evaluated their perceived and desired body figures using both paper-based FRS and VR-based avatar rating scale. In VR, participants engaged with ten 3D standardized female avatars arranged in a circle for a 15-minute session, during which they were asked to choose avatars that best represented their current and desired body forms. The head-tracking software calculated the time spent looking at each avatar (Fixation Time Percentage - FTP).	Comparison made with paper-based FRS.
Malighetti et al., 2020	VR-BS	VR intervention included a head-mounted display connected to a laptop and a motion tracker (Microsoft Kinect sensor), immersing participants in a virtual environment and embodying them in a virtual avatar.	The intervention consisted of four sessions with VR embodiment from both egocentric and allocentric perspectives. The BMI of the avatar was progressively increased to normal weight across sessions. Participants recalled negative and positive life events to associate emotions with body sizes and estimated their real and ideal BMI using VR body size estimation tasks.	n.a.

Malighetti et al., 2021		The intervention was delivered using a stand-alone head-mounted display (HMD), specifically the Oculus Go.	The treatment comprised an initial assessment session, followed by two sessions focusing on emotion regulation and four sessions on emotional rescripting. Techniques included mindfulness-based strategies for exploring landscapes in VR to identify emotional states, immersive metaphorical journeys, and anchoring positive emotions to real-life experiences.	n.a.
Matamala-Gomez et al., 2021	VR-BS	Virtual Reality (VR) with a head-mounted display (Oculus Rift), connected to a laptop and a Kinect Sensor for motion tracking.	The VR-based intervention involved embodying participants in a virtual avatar from both first-person and third-person perspectives, across four sessions. The technique aimed to create a body swap illusion, allowing participants to experience ownership, agency, and self-location in a virtual body that mirrors their perceived real body size. This intervention focused on modifying participants' long-term memory of their body through visuomotor synchronization and autobiographical recall within the VR environment.	n.a.
Max et al., 2023	VR-FE	Oculus Rift CV1 head-mounted display with Leap Motion sensor for real-time hand tracking, allowing participants to interact with virtual stimuli through actual hand movements.	Participants completed practice trials followed by the main task, where they had to recognize and collect one of two simultaneously presented objects (food vs. office tools), with the task designed to measure both the speed of recognition/approach and the collection of food objects compared to office tools.	n.a.
Nameth et al., 2021	VR-CET	Oculus Rift head-mounted displays (HMD), Oculus sensors, and Oculus controllers were used to provide immersive VR experiences simulating real-life triggering eating-related situations.	The intervention involved up to eight one-hour sessions, starting with an assessment phase followed by an intervention phase where patients were exposed to virtual environments and food cues designed to provoke cravings and urges to eat without allowing actual binge eating.	n.a.
Natali et al., 2024	VR-FE	Oculus Integration SDK for Unity was installed on Oculus Quest 2 headsets to visualize the VR kitchen environment. Participants experienced full immersion in a room-scale environment, facilitated by two Oculus Touch controllers for interaction with user interface menus and scene objects.	The study examines the potential of two interventions—positive mood induction and social support—to enhance the effectiveness of virtual food exposure in alleviating food-related anxiety. Participants were assigned to one of three conditions: virtual food exposure alone (baseline condition), virtual food exposure combined with positive mood induction (positive mood condition), or virtual food exposure combined with social support (social support condition). In the social support condition, an avatar provided participants with supportive and motivational dialogue aimed at empowering them to confront the voice of their eating disorder.	n.a.
Porras-Garcia et al., 2020a	VR-BE	VR head-mounted display (HTC-VIVE) with full body motion tracking using additional body trackers.	The patient underwent five VR exposure sessions, starting with an avatar matching the patient's current BMI. The BMI of the avatar was gradually increased in each session to simulate weight gain towards a healthy BMI. The intervention aimed to reduce FGW, body-related anxiety, and BID by allowing the patient to experience a full-body illusion (FBI) of a healthier body.	n.a.
Porras-Garcia et al., 2020b	VR-BE	HTC-VIVE head-mounted display with full-body motion tracking and FOVE-Eye Tracking for eye movement detection	Participants owned a virtual body resembling their silhouette and BMI. The FBI over the virtual body was induced through visuo-motor and visuo-tactile stimulation. Subsequently, FBI, FGW, body anxiety, and body-related attentional bias towards weight-related and non-weight-related body areas were assessed.	Healthy college women divided into those with low and high body dissatisfaction.
Porras-Garcia et al., 2020c	VR-BE	HTC-VIVE HMD with body trackers and FOVE Eye Tracking for gaze detection and registration. Virtual avatars created with Unity 3D and Blender 2.78.	Five sessions of VR body exposure therapy were conducted, starting with the patient's current BMI and progressively increasing the BMI of the avatar across sessions. The therapy aimed to systematically expose the patient to her virtual silhouette in a mirror within the VR	n.a.

			environment, with body parts that produced anxiety being illuminated and focused upon	
Provenzano et al., 2020	VR-BE	Virtual reality environments created with 3D modeling software, presenting participants with personalized avatars to embody their perceived body size, and avatars representing a verisimilar loss and gain of their original weight.	Participants were exposed to personalized avatars through visuo-tactile stimulation, aiming to induce embodiment and assess changes in body image distortion. The study evaluated embodiment, body dissatisfaction, and emotional response to different-sized avatars.	The healthy control group was subjected to the same VR intervention procedure to compare body image distortion, embodiment, and emotional responses between patients with AN and individuals without eating disorders. This comparison aimed to elucidate the specific effects of VR body exposure therapy on the cognitive-emotional components of body image distortion in AN.
Sansoni et al., 2024		During VR-CBT sessions, participants wore a head-mounted display through which scenarios were presented. Utilizing the NeuroVR software, participants engaged with fourteen virtual critical environments.	Participants attended five weekly CBT-group sessions and underwent ten biweekly one-hour VR sessions utilizing NeuroVR software, featuring diverse virtual environments.	The group received five-week treatment periods, during which two licensed psychotherapists conducted CBT sessions.
Serino et al., 2019	VR-BS	The protocol utilized a head-mounted display (HMD Oculus Rift DK2) connected to a portable computer, with a Razer Hydra motion-tracking device for inducing multisensory stimulation.	The patient underwent three sessions of the VR-based body swapping illusion, incorporating synchronous and asynchronous visuotactile stimulation to induce ownership over a virtual body. The intervention was designed to assess and potentially alter the patient's body representation disturbances.	n.a.
Schroeder et al., 2024		A mobile VR task was developed for the stand-alone Meta Quest 2 head-mounted display by the research team. The Meta Quest 2 controller was utilized within the virtual environment, depicted as a white right hand, with its position and movement continuously updated at the refresh rate.	The methodology involved investigating behavioral trajectories of food avoidance using a novel kinematic task in VR to record spatial displacement in stop-and go-trials to virtual food and control objects. Inhibitory control abilities were assessed through stopping performance, and habitual avoidance of virtual food was measured across both go-and stop-trials.	The healthy control group was subjected to the same VR intervention procedure

Table 3 The table presents the intervention studies' main characteristics.

Assessment

All studies included in this category explored how IVR can be employed to assess specific characteristics of AN. Four studies, among those identified, fell into this category. Specifically, three studies used body-swapping procedure and avatars to assess perceptual and affective BI disturbance (Fisher et al., 2020; Matamala-Gomez et al., 2021; Provenzano et al., 2019), while one study used virtual food exposure (VR-FE) to evaluate emotional reactions to food-related stimuli (Bektas et al., 2023).

Fisher and colleagues (Fisher et al., 2020) assessed BI (i.e., body distortions and body dissatisfaction) in AN patients with avatars or paper-based rating scales. The authors asked patients to select the figure (3D avatar vs. 2D image) that better fitted their real and ideal body shape, finding that the virtual avatar that patients selected corresponded closely to the silhouette they chose on a paper-based rating scale, thus yielding comparable self-rating results.

Provenzano and colleagues (Provenzano et al., 2019) used IVR to assess and measure the perceptual and cognitive-emotional components of BI disturbance in patients with AN. Participants' perceptions of their body size and shape were assessed by creating personalized avatars that vary in size. This allowed for a detailed assessment of how patients perceived their body size (real body) versus how it appeared (ideal body), which is crucial for understanding the perceptual components of BI distortion in patients with AN. Although primarily designed as an assessment tool, the study also observed the influence of inducing a body ownership illusion on body dissatisfaction and perceptual distortions among patients with AN. Specifically, the authors observed that patients expressed more negative emotions after being embodied in the fattest avatar, especially in patients with more severe symptoms. This finding suggests that IVR can not only assess BI disturbances but also potentially influence them, indicating a dual role for IVR in both evaluating and addressing BI issues in the therapeutic setting.

Similarly, Matamala-Gomez and colleagues (Matamala-Gomez et al., 2021) explored the use of IVR to modulate BI disturbances through a pilot study focusing on user experience. In their study, patients with AN were embodied in virtual avatars reflecting their perceived body size, and high levels of embodiment were reported. The results emphasized that immersive experiences with a high degree of body ownership can significantly affect how patients perceive their bodies, highlighting IVR's potential to assess BI distortions in therapeutic settings.

As concerns VR-FE, Bektas and colleagues (Bektas et al., 2023) used IVR to measure and assess food disgust in AN patients. The authors presented patients with a virtual kitchen, with or without other avatars. Results revealed a correlation between food disgust and patients' symptoms severity, regardless of the presence of avatars in the virtual scenario, showing the clinical potential of IVR for in-depth exploration of food disgust in patients with AN.

Understanding

Four studies focused on examining cognitive and emotional processes and variables relevant to the treatment of EDs in IVR. Two studies assessed cognitive processes related to BI in samples of individuals with AN (Di Lernia et al., 2023; Ferrer-Garcia et al., 2021), while two explored the impact of interacting with foods during VR-FE in BED (Max et al., 2023) or food avoidance in AN patients (Schroeder et al., 2024). Ferrer-Garcia and colleagues (Ferrer-Garcia et al., 2021) investigated body-selective visual attention bias and how it influenced clinical outcomes in patients with AN undergoing VR body exposure therapy (VR-BE). They observed that higher pre-intervention body-related attentional bias predicted less favorable clinical outcomes. Di Lernia and colleagues (Di Lernia et al., 2023) used VR-induced body illusions to deepen the link between interoception and body distortions in patients with AN. Participants with AN exhibited greater interoceptive metacognition compared to healthy participants. The authors concluded that the presence of a strong interoceptive metacognition might impair the possibility of revising bodily distorted expectations with real-time multisensory bottom-up bodily information during IVR treatment. Max and colleagues (Max et al., 2023) studied the presence of dysfunctional interaction patterns in the interaction with virtual foods in BED , revealing pathology-specific patterns in manual interaction with food (i.e., slower picking up of food items compared to non-food items), even though no significant link between interactions and behaviors or BED features emerged. Finally, (Schroeder et al., 2024) Schroeder and colleagues studied the phenomenon of food avoidance among individuals diagnosed with AN-restrictive type, compared with healthy controls, by employing a IVR stopping task. Results showed that AN patients had both persistent food avoidance tendencies and increased inhibitory control. Indeed, individuals with AN-R consistently displayed patterns of avoiding food, alongside an enhanced ability to exert inhibitory control over their eating behaviors compared to healthy participants.

Treatment

Twelve of the included studies aimed to investigate the effectiveness of VR in treating EDs. They used VR-BE or body swapping (VR-BS) (Behrens et al., 2023; Malighetti et al., 2020; Porras-Garcia, Ferrer-Garcia, et al., 2020; Porras-Garcia, Ferrer-García, et al., 2020; Porras-Garcia, Serrano-Troncoso, et al., 2020; Serino et al., 2019), food exposure (Nameth et al., 2021; Natali et al., 2024), attentional bias training (Ascione et al., 2023), or CBT combined with IVR (Sansoni et al., 2024) or psychological rescripting approaches combined with VR-BS to modify emotions and cognition (Malighetti et al., 2021).

Four studies utilized body exposure approaches with patients with AN. In a single case study on a patient with AN, Porras-Garcia and others (Porras-Garcia, Ferrer-García, et al., 2020; Porras-Garcia, Serrano-Troncoso, et al., 2020) observed that seeing one's body from an external (observer) perspective diminished negative beliefs associated with the "self" and enhance body acceptance. They also noted that VR-BE therapy facilitated an increase in BMI reaching healthy levels and reduced fear of gaining weight (FGW); moreover decrease in body-related anxiety, drive for thinness, and BI disturbances were maintained after 5 months. A subsequent RCT with the same approach (Porras-Garcia et al., 2021) revealed that patients with AN in the VR-BE group exhibited significant reductions in FGW and BI disturbances compared to the control. The exposure to healthy-weight virtual bodies was confirmed to elicit body concerns and treat and diminish FGW in the study by Behrens and colleagues (Behrens et al., 2023), suggesting that VR-BE could be an effective technique in AN treatment. Three studies focused on VR-BS approach in AN. VR-BS sessions, integrated into a multidisciplinary AN treatment, influenced a patient's body perception and multisensory body integration in Serino and colleagues (Serino et al., 2019), while the combination of autobiographical recall techniques and VR-BS was pilot-tested by Malighetti and colleagues (Malighetti et al., 2020), showing reductions in negative emotions and body shame, improvements in body satisfaction, and accuracy of body perception after VR sessions. Furthermore, the identification with a virtual avatar matching one's BMI proved to be a useful intervention tool, as it resulted in a reduction of fear of weight gain, body anxiety, and attentional bias towards weight-related body parts in patients with AN compared to healthy controls, according to Porras-Garcia and colleagues (Porras-Garcia, Ferrer-Garcia, et al., 2020).

Concerning VR-FE studies, a good feasibility and acceptability in treating BED with IVR cue exposure therapy in clinical settings emerged, with promising preliminary results in reducing binge episodes in the short-term and loss of benefits at follow-up (Nameth et al., 2021). While concerning AN patients, Natali and colleagues (Natali et al., 2024) (REF) investigated whether positive mood induction or social support can amplify the effect of VR-FE on food-related anxiety. Results showed that participants in the positive mood condition experienced lower levels of anxiety compared to baseline. Specifically, they reported reduced virtual food-related anxiety after exposure, with a medium effect size.

Concerning eye-movements and attentional aspects, two studies proved the effectiveness of IVR-based attention modification training with eye-tracking to reduce body-related attention bias and levels of body dissatisfaction in adolescents with AN (Ascione et al., 2023).

Finally, the positive effect of combining traditional psychological treatments with IVR for BN and BED patients emerged in two papers. Specifically, CBT treatments and IVR for BN patients resulted in a more consistent BMI over time compared to the standard treatment, where BMI fluctuated significantly, and reduced preoccupation with weight, fear of weight gain, and instances of binge eating and purging (Sansoni et al., 2024), while combining VR-BS with the reshaping of emotional experience in immersive environments led to an improvement in emotion regulation and binge episodes (Malighetti et al., 2021). These findings suggest that these interventions may enhance therapeutic outcomes and contribute to overall patient well-being.

Discussion

The present scoping review aimed to investigate the use of IVR in addressing the complex nature of EDs. IVR tools resulted useful to target particularly the emotional, perceptual and cognitive aspects characterizing the experiential domain of EDs symptoms. Within the papers included in the review, three categories of IVR utilization were identified (assessment, understanding, and treatment).

Concerning IVR as an assessment tool, studies revealed that immersive experience can efficiently assess both perceptual and cognitive-emotional BI components (Bektas et al., 2023; Fisher et al., 2020; Matamala-Gomez et al., 2020; Provenzano et al., 2019). This aligns with previous research (Di Lernia et al., 2023; Keizer et al., 2016), suggesting that IVR can provide ecological, reliable, and engaging assessment tools (Brizzi, Riva, et al., 2024). The latter aspect is critical in disorders such as AN, in which building therapeutic alliances and having genuine responses is often complicated (Brizzi, Boltri, et al., 2024). Thus, technology offers advantages for both the clinician (i.e., accurate measurements less subject to bias) and the patient (i.e., active participation, engagement). Furthermore, following the trend of personalized medicine, IVR allows the development of tools tailored to patients' needs, such as exposure to customized bodies (Provenzano et al., 2019) or specific foods (Gutiérrez-Maldonado et al., 2016).

As regards the understanding of the complex processes and features that characterize the psychopathology of EDs, the multisensory capabilities of IVR have emerged as a promising tool for enhancing our understanding of both inner and outer body perceptions (Brizzi, Sansoni, & Riva, 2023). In particular, the present scoping review confirmed the potential of eye-tracking integrated IVR tools in understanding attentional biases in EDs, which already emerged in a previous systematic review (Clus et al., 2018; Riva et al., 2021).

The use of IVR as a treatment tool aligns with previous systematic reviews (Butler & Heimberg, 2020; Ciążyńska & Maciaszek, 2022; Clus et al., 2018). IVR has indeed demonstrated considerable promise in modifying the maladaptive behaviors characteristic of EDs. The studies included in this review consistently highlight IVR's efficacy in creating realistic, controlled environments that facilitate BI retraining, exposure therapy, and cognitive restructuring within a clinical setting. IVR environments can indeed trigger genuine physiological and psychological responses like those experienced in real-world situations, providing a powerful platform for confronting fears and practicing coping strategies (Gutiérrez-Maldonado et al., 2016). Going a step further, we tried to understand why IVR might be so impactful by thinking about IVR features.

First, by experiencing VR-BS and VR-BE with avatars that represent either their actual or healthier BMI, patients are exposed to new perspectives on their BI. This exposure is crucial as it helps recalibrate the brain's internal models of the body by providing real-time, accurate body-related sensory feedback, encouraging the brain to update these internal predictions, often reliant on distorted body internal representation (Brizzi, Sansoni, Di Lernia, et al., 2023). In particular, IVR allows users to 'change' their bodies in unexpected ways, leading to discrepancies between expected and actual sensory feedback (prediction errors). These prediction errors can prompt significant updates in the brain's internal body model, which may result in a more accurate body perception and healthier body interactions. This process can be further supported and enhanced by integrating autobiographical rescripting techniques, which help reshape personal experiences and improve emotion regulation in patients (Malighetti et al., 2020).

Second, the use of IVR in food exposure therapy has been particularly effective. By simulating environments that trigger disordered eating behaviors, such as settings that involve food interaction, IVR allows patients to navigate their anxieties in a safe and controlled manner. This method has been beneficial for patients with both AN and BED helping them to manage their fear of eating and reduce binge-eating episodes, respectively. Considering the efficacy of food exposure in IVR and the foundational role of prediction error in the treatment of EDs, as demonstrated in studies involving body illusions, future research might explore integrating food exposure with the deliberate creation of prediction errors. For example, combining food exposure with the predictive coding framework could involve altering expected sensory characteristics of foods within VR environments. This approach has the potential to induce unexpected discrepancies between anticipated and actual sensory feedback.

Considering both body-focused approaches (VR-BS and VR-BE) and food exposure (VR-FE), IVR is distinguished as a deeply experiential and embodied technology. It enables direct modifications of perceptions, emotions, beliefs, and memories, bypassing the need for patients to consciously recall these elements or rely on metacognitive skills, which are often impaired in individuals with EDs.

In conclusion, this scoping review highlights the potential of IVR as a complementary tool in clinical practice in addressing the experiential domain that characterizes EDs. In this respect, it is crucial to emphasize that IVR should be viewed as an adjunctive resource rather than a standalone treatment. The primary benefit of IVR lies in its ability to offer a multisensory, embodied, and cognitive experience. This rich, immersive experience can significantly influence the brain's predictive mechanisms related to body perception and emotional responses to key stimuli. However, it should be used judiciously and in conjunction with established therapeutic interventions to ensure a holistic and effective assessment and treatment approach for those suffering from EDs.

Limitations

It is important to interpret the reported results considering some limitations. Firstly, there are few randomized controlled trials among the included studies. Additionally, many studies have small sample sizes, limiting statistical power and potentially introducing bias. Furthermore, the lack of standardized treatment protocols or consistent follow-up assessments across studies impacts the possibility to conclude on interventions efficacy. Moreover, male participants are underrepresented in these studies, which may influence the applicability of the findings to this population. Further research with larger and more diverse samples, as well as the implementation of standardized protocols, is needed to enhance the reliability and validity of IVR applications to EDs.

Conclusions

In summary, the IVR's ability to simulate embodied experiences that align with the brain's predictive coding mechanisms provides a powerful avenue for delivering immersive, experiential interventions that can help recalibrate distorted body representations and affective predictive models implicated in eating disorders. This innovative approach holds significant potential for more effective and engaging treatments, particularly through their ability to immerse patients in experiences that directly address and integrate the experiential domain into comprehensive treatment plans. By offering innovative ways to confront and alter distorted BI and food-related negative reactions, IVR technology holds the potential to significantly impact the landscape of ED treatment, making it a valuable tool in the quest for more effective therapeutic interventions.

4.2 Conclusions

This chapter provides a comprehensive overview of how VR has been utilized to assess, treat, and enhance our understanding of ED. Given the limited number of studies in this domain, a scoping review was conducted to map the breadth of existing research and identify key trends and gaps. The review encompassed all ED pathologies, offering a holistic perspective on the methods, tools, and procedures. This broad approach was chosen to ensure a deep and inclusive understanding of the field, enabling the identification of strengths to build upon and areas in need of improvement.

The insights gained from this review were crucial in forming a clear foundation for the development of my own VR protocol. By systematically analysing the existing literature, I aimed to pinpoint the potential of VR applications in ED while recognizing their limitations. This chapter serves as a stepping stone toward advancing the field, laying the groundwork for innovative interventions tailored to enhance the assessment and treatment of eating disorders through immersive and multisensory experiences.

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5. Developing an Intervention for Altered Body Experience

Once the possible existing approaches to the treatment of eating disorders based on VR techniques and methods were identified, the next step was to develop an intervention protocol focusing on the relationship with one's body and the perceptual experience of the body, to work on different levels of the person: perceptual, emotional and cognitive. After the protocol was drafted, virtual reality software was developed to be made open access (https://drive.google.com/drive/folders/1icaDksADA2Z6VWZ2rxkSnF_-dDR1C7rc?usp=drive_link)

5.1 Bridging Experimental and Clinical Settings: Usability and User Experience of Virtual Reality Body Swapping for Body-Focused Interventions [6]

Introduction

In recent years, there have been many attempts to develop new approaches to promote psychological well-being and treat mental disorders using technological advances, especially in the realm of Virtual Reality (VR). VR is an embedded, cognitive, and multisensory technology that works similarly to the human brain: it creates and maintains a model of the user's body and the surrounding environment (embedded), and adapts the output (multisensory) based on the user's input (cognitive; Malighetti et al., 2022; Riva et al., 2017). Due to these specific characteristics, VR has been increasingly used in different areas of psychology to better understand the human mind. Among them, one area that has particularly benefited from this technology is that of bodily experience.

[6] This article has been presented at the *Mindcare – 11th Pervasive Technologies for Mental Health* conference (2024). Brizzi, G., Signorelli, A., & Riva, G. (In Press) Bridging Experimental and Clinical Settings: Usability and User Experience of Virtual Reality Body Swapping for Body-Focused Interventions. Pervasive Computing Paradigms for Mental Health

Bodily experience is a complex process requiring the integration of information from different sensory modalities (e.g., visual, tactile, sensorimotor) and spatial frames (i.e., first and third-person perspectives) into a single and coherent percept (Brizzi et al., 2023a). That is, how we experience our bodies derives from a Multisensory Integration process (Beizzi et al., 2023a; Brizzi et al., 2023b).

Because of its properties, VR emerged as a valid tool to study such a complex phenomenon, thanks to paradigms such as Body Illusions (Matamala-Gomez et al., 2020). In Full-Body Illusions (FBI), individuals experience an entire virtual body as their own due to the spatiotemporal synchronization between the real and the artificial bodies (Petkova & Ehrsson, 2008); that is, for instance, the synchronization between individuals' movements and those of the avatar makes them perceive the virtual body as their own, thus producing embodiment over the artificial body. Essentially, the multisensory correspondence between what a person feels, performs, and sees in the physical and virtual environment fosters a sense of ownership, agency, and self-location toward the artificial body, significantly altering Body Self-Consciousness (Matamala-Gomez et al., 2019).

Notably, further research revealed that embodiment can occur even when the virtual body significantly differs from the physical form, as demonstrated by the Body Swapping (BS) illusion (Serino, Polli & Riva, 2019). During BS, individuals experience embodiment over a completely different body as compared to the real one. Several research observed that individuals could embody a taller or a thinner body as compared to their one (Serino, Polli & Riva, 2019; Malighetti et al., 2020) and that this influenced body representation and how they interact with the surrounding environment (Dollinger et al., 2022). Then, Body illusion in VR offers a unique opportunity to better understand the mechanisms underlying body experience, revealing how it can be easily manipulated.

Body-focused Interventions in Virtual Reality

VR offers the opportunity to immerse oneself in an alternative reality and experience scenarios that are otherwise only achievable via imagination. Given this possibility, the use of avatars has attracted attention in the treatment and assessment of body-related disturbances (Dollinger et al., 2022; Horne et al., 2020; Turbyne et al., 2021). Specifically, this gave rise to new possibilities in the field of disorders characterized by body-self disturbances, such as Anorexia Nervosa (AN). Patients affected by AN indeed reliably report being dissatisfied with their bodies and show a limited ability to correctly perceive their bodies in terms of size and shape (Gutiérrez-Maldonado et al., 2010). Remarkably, this body-self alteration seems to play a key role in the onset and maintenance of AN symptomatology, so it became a key aspect to work on to improve current assessment, prevention, and therapeutical interventions (Brizzi et al., 2023b).

Body Swapping in Virtual Reality (VR-BS) emerged as a promising tool to correct this altered body-self relationship (Porras-Garcia et al., 2020a,b; Porras-Garcia et al., 2021). Initial findings indicate that allowing patients with AN to experience being in a different body through a first-person (egocentric) perspective reduces inaccuracies in their perception of their own body's size (Keizer et al., 2016; Serino et al., 2016). More recent procedures for body-self interventions aim instead for enhanced mirror confrontation (Dollinger et al., 2022). They surpass real mirror confrontation by modifying the mirror image or the shown avatars into different body shapes. In this regard, research observed that experiencing a normal-weight body from a third-person (allocentric) perspective - akin to viewing oneself in a mirror - has been shown to positively influence symptoms such as the fear of gaining weight in patients affected by AN (Porras-Garcia et al., 2020a,b; Porras-Garcia et al., 2021).

Current literature endorses the application of VR-BS for addressing body-self relationship issues, highlighting VR's potential as a significant enhancement in mental health care.

Despite its promise, the practical deployment of VR-BS beyond research environments remains limited. This limitation is partly due to the complexity of VR technology, which involves sophisticated hardware and software that are not widely accessible and typically demand specialized knowledge to operate.

Before introducing a VR system into clinical practice, testing the usability and user experience (UX; Bitkina, KIm & Park, 2020) of the system itself is needed. Usability focuses on how easily a product can be used to achieve its intended purpose, while UX encompasses the user's subjective responses to using the product, such as satisfaction, engagement, and enjoyment (Papakostas et al., 2021). This evaluation is essential to ensure the system operates smoothly without negatively affecting the intervention's success or causing user discomfort (e.g., cybersickness; Verkuyl, Romaniuk & Mastrilli, 2018). It's also vital to confirm that the system is intuitive and enjoyable for users, including both the healthcare professionals administering it and the patients experiencing it. Despite the limited research on user experience and usability of VR-BS systems, we argue that their integration into clinical practice necessitates user-friendly interfaces for healthcare professionals and comfort for patients as a fundamental prerequisite.

In this study, we developed and assessed a VR-BS system's usability and user experience from the perspectives of both the administrator and the participant using qualitative and quantitative methods. We expected an overall good usability level and positive user experience from both conditions; though, we expect to gain useful insights to improve the system so that it will have the necessary qualities for being clinically relevant and easy to use by non-technical users. The final goal is to propose an open-source tool that balances technical and clinical requirements.

Methods

Participants

A total of 20 female participants participated in the study (mean age = 25.35, sd = 3.759). None of them disclosed having a current or previous diagnosis of neurological or eating disorders. Out of these, 12 participants had no prior experience with Virtual Reality technology.

Procedure

The study procedure is divided into four phases. *Figure 1* shows a graphic representation of the procedure.

- Phase 1. Participants were briefly introduced to the means and aims of the research and, afterward, they completed a questionnaire gathering socio-demographic information and the Cybersickness Scale Questionnaire to assess symptoms and discomfort before the virtual experience.
- Phase 2: Subject condition. Participants engaged in the Virtual Reality Body Swapping (VR-BS) experience. They began by standing in front of a Kinect motion-tracking camera and donning a VR headset. The experimenter then calibrated the system to align the participant's real body with their virtual avatar. To promote embodiment, the experimenter applied tactile stimulation to the participant's abdominal area using a controller, which was coherently replicated on the avatar's abdomen for 90 seconds (Serino, Pedroli & Riva, 2019). Following the visuo-tactile synchronous stimulation - from a 1st person perspective - participants assessed their level of embodiment using a Visual Analogue Scale (VAS; Porras-Garcia et al., 2020a). They then observed their virtual body in a mirror within the VR environment - from a 3rd person perspective - which tracked them in real-time with their movements. Throughout this experience, participants verbalized their thoughts about

the system, including opinions, advice, and questions (Think Aloud Method; Eccles & Arsal, 2017). After completing the VR-BS experience, participants filled out questionnaires to evaluate their sense of presence within the virtual environment (Presence Questionnaire; Witmer & Singer, 1998), their overall user experience (User Experience Questionnaire; Laugwitz, Held & Schrepp, 2008), and any symptoms of cybersickness experienced during the session (Cybersickness Scale Questionnaire; Kourtesis et al., 2023).

- Phase 3: Experimenter Condition. In this phase, the roles were reversed to assess the system's usability from the experimenter's viewpoint. Initially, participants were introduced to the functionalities of the controller used during the VR-BS experience. Subsequently, they assumed the role traditionally held by the experimenter, while the actual experimenter acted out the role of a participant. This role reversal was designed to evaluate the system's usability more comprehensively by having participants replicate the actions performed by the experimenter in Phase 1 (e.g., calibrating the avatar and administering tactile stimulation to the abdominal area, inserting the mirror). The participant can see what happens in the virtual environment by looking at the computer. Task success was documented using a Task Analysis grid (Annet, 2003), which helped in identifying any operational challenges or areas for improvement. Again, participants were encouraged to verbalize doubts, concerns, or suggestions they had regarding the system (employing the Think Aloud Method). This feedback was crucial for understanding the system's usability from a new user's perspective, particularly one with responsibilities akin to those of an experimenter. After completing the role-reversal tasks, participants were asked to fill out the System Usability Scale questionnaire (Laugwitz, Held & Schrepp, 2008). This tool was specifically chosen for this phase to evaluate the system's usability, considering that the participants' role in this condition was more active and involved compared to their relatively passive role in the "participant condition." The consistent presentation order of Phases 2 and this experimenter condition ensured that all participants had a similar experience and basis for their evaluations.

- Phase 4: Debriefing. Lastly, there was a debriefing in which participants asked questions and expressed their considerations, opinions, and a personal evaluation of the experience. The total duration of the experiment was approximately 45 minutes.

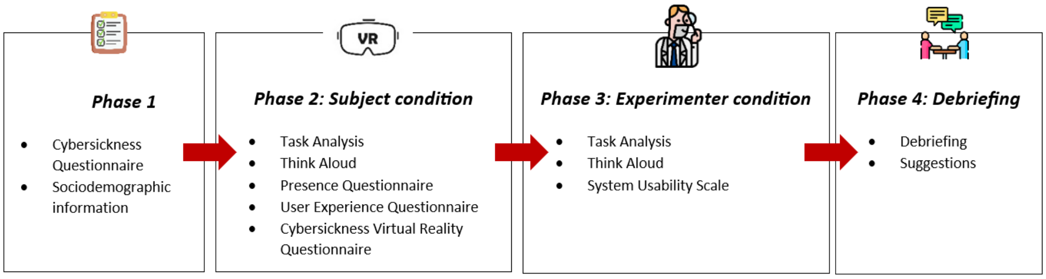


Figure 1 Procedure. The figure shows the experimental design.

Body Swapping in Virtual Reality (VR-BS)

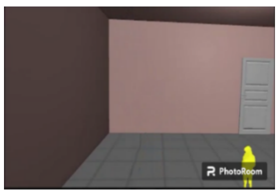
We developed a Virtual Reality Body Swapping (VR-BS) experience that allows participants to view a normal-weight- avatar (waist-to-height ratio equal to 0.4606) from both a first-person (egocentric) and a third-person (allocentric, mirror-like) perspective, building upon the findings of previous research (Porras-Garcia et al., 2020a,b; Porras-Garcia et al., 2021). The avatar was crafted using the MakeHuman software (www.makehumancommunity.org), incorporating body measurements from earlier studies (Keizer et al., 2016; Serino, Pedroli & Riva, 2019). To minimize potential anchoring effects, the avatar is situated in a neutral room, created with Unity 3D software (www.unity3d.com). The application is compatible with the Oculus Quest 2 headset, requiring a connection between the headset and a computer. During the experience, one controller is provided to the participant and another to the experimenter. An initial scene facilitates embodiment by aligning the experimenter's controller with a virtual ball, enabling the experimenter to touch the avatar's and participant's abdominal areas synchronously (Embodiment). The experimenter can add or remove the ball from the scene. Subsequently, participants can become accustomed to the motion tracking system and observe the synchronization between their movements and those of the avatar, facilitated by the Azure Kinect (Familiarization). The experimenter can then administer a Visual Analogue Scale to assess the degree of embodiment (as detailed in research by Porras-Garcia et al., 2020a,b; Porras-Garcia et al., 2021; Embodiment Questionnaire). Additionally, the experimenter can introduce or withdraw a mirror to switch between viewing the avatar from a first-person perspective (without the mirror) or a third-person perspective (with the mirror). In the mirror-like scenario, participants can see the avatar from the neck down to avoid the uncanny valley effect (i.e., when a computer-generated figure that bears a near-identical resemblance to a human being evokes a sense of unease or revulsion in the viewer; Wang, Lilienfeld & Rochat, 2015) and enhance self-projection. *Figure 2* illustrates the system's key features.

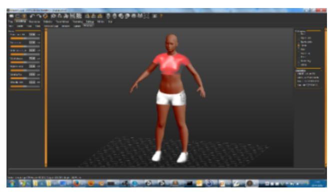
Software and Hardware Features

Hardware
Hardware needed: Oculus Quest 2, Azure Kinect, USB link, Gaming portable computer.

Neutral Room
A neutral environment was developed in Unity. There was no furniture to avoid anchoring or reference biases, in line with previous research (e.g., Di Lernia et al., 2023).

Avatar Parameters
The avatar was developed to resemble a normal-weight body. This body has been used to alter body representation in clinical and non-clinical populations (Keizer et al., 2016, Di Lernia et al., 2023).





Embodiment
The experimenter touches the user's body with the controller on the abdominal area. The user sees a virtual ball touching the avatar's abdominal area (i.e., synchronous visuo-tactile stimulation).

Familiarization
The avatar movements are synchronized with the user's movements. The user is invited to move and familiarize with the setting. The body is seen from a first-person perspective.

Embodiment Questionnaire
Visual Analogue Scale to check the embodiment level. The item specifically asks "Answer reporting how much do you agree with this statement from 0 (null) to 100 (strongly): How much do you perceive the virtual body as your own body?"

First-person perspective
The avatar movements are synchronized with the user's movements (visuo-motor synchrony). The user sees the body when looking down, toward the own belly ("pure" egocentric condition).

Third-person perspective
The avatar movements are synchronized with the user's movements (visuo-motor synchrony). The user sees the virtual body in the mirror. The experimenter can choose to present the virtual body from a first-person perspective too (real-like experience) or to hide the body from a first-person perspective ("pure" allocentric condition).

Switch
The experimenter can switch from first and third-person perspectives (mirror/ no mirror).
The experimenter can select whether the body from the first-person perspective should be shown in the third-person condition.

Figure 2 System main features design and implementation. Embodiment refers to the classical visuo-tactile stimulation to promote a sense of embodiment over the virtual body (for more, see Serino et al., 2016); Familiarization refers to a first approach with the motion tracking system; Embodiment Questionnaire refers to the Visual Analogue Scale to measure embodiment strength (Porras-Garcia et al., 2020); First- and Third-person perspective refers to the experience with and without the mirror (based on Porras-Garcia et al., 2020).

Usability Measures

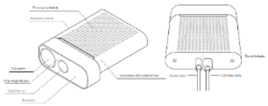
- System Usability Scale (SUS; Laugwitz, Held & Schrepp, 2008): The SUS is a "quick and easy to use" questionnaire to assess interfaces and system usability. It consists of 10 items to which the subject must respond according to a Likert scale ranging from 1 (strongly agree) to 5 (strongly disagree). It has proven to be a valuable, robust, reliable evaluation tool for evaluating a wide range of technologies. The final score ranges from 0 (lack of usability) to 100 (optimal usability). The scores were interpreted according to the 7-point adjective rating scale consisting of the following levels: 'best imaginable', 'excellent', 'good', 'OK', 'poor', 'dreadful', and 'worst imaginable'. Specifically, scores higher than 68 indexed a good usability level.

- Presence Questionnaire (PQ; Witmer & Singer, 1998): The PQ measures the sense of presence. It consists of 24 items to be answered by the subject on a Likert scale from 1 (null) to 7 (completely). The questionnaire analyses various aspects of the sense of presence: specifically, the level of realism, the possibility of acting, interface quality, the possibility of examining, self-assessment of performance, sounds, and tactile feedback.
- Cybersickness Scale Questionnaire – Virtual Reality (CSQ-VR; Kourtesis et al., 2023): The CSQ-VR measures symptoms and burdens related to immersive VR experiences and the use of the VR headset. It consists of a 7-point Likert scale (1 = absent to 7 = very much) comprising 6 questions for the assessment of the three core symptoms typically related to cybersickness (i.e., nausea, vestibular, and oculomotor symptoms).
- Task Analysis (Annet, 2003): Task Analysis is an observational method that involves the analysis of the activities, tasks, and subtasks that users must perform to achieve one or more objectives when interacting with a system. It allows the identification of critical and strong points of the human-system interaction. Key steps of the interaction between the user and the system were identified (*Figure 3*) and the experimenter reported whether the user was able to perform the task or not, or whether encountered difficulties.

Task participants had to complete

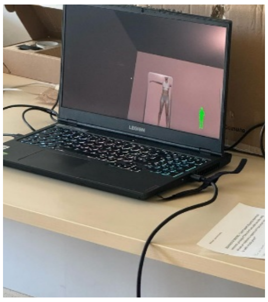
Connect the Kinect

Connect the Azure Kinect to the computer for the motion tracking system.



Launch the app

Launch the VR application on the computer.

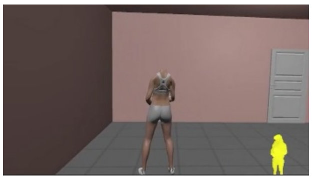


Stimulation

Use the controller the control the virtual ball and apply the visuo-tactile stimulation over the abdominal area of the virtual and real body.

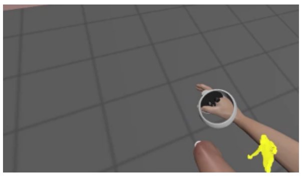
Enter the avatar

Alignment between the virtual and real bodies; the user has to enter the virtual body.



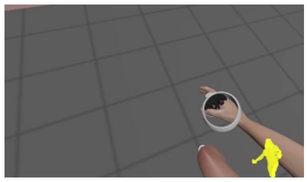
Calibration

The Kinect tracks the movements of the user. The user has in his or her hand only one controller.



First-person perspective

The user can see the virtual body from a first-person perspective (i.e., the user sees the virtual body when looking at his or her belly).



Insert/ Remove the Mirror

Insert the mirror; the Kinect tracks the movement of the user and the user can see the reflection in the mirror in front of him or her.

Questionnaire

Insert the Visual Analogue Scale to assess embodiment strength.

Insert / Remove the ball

Insert the ball for the embodiment induction; the controller of the experimenter controls the virtual ball. Remove the ball after the stimulation.

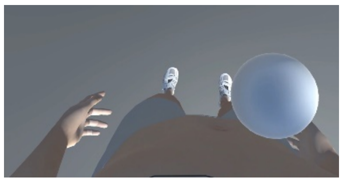


Figure 3 Task Analysis core steps. Participants were instructed to mimic the core procedures commonly employed in the application of body swapping within a clinical context (Di Lernia et al., 2023; Porras-Garcia et al., 2020).

User Experience Measures

- User Experience Questionnaire (UEQ; Laugwitz, Held & Schrepp, 2008): the User Experience Questionnaire is a standardized questionnaire used to evaluate the user experience of interactive products such as software or online tools. The UEQ contains 6 scales with 26 items covering a comprehensive impression of the user experience. The scales cover both classical aspects of usability (efficiency, perspicuity, reliability) and aspects of user experience (originality, stimulation, and attractiveness). The UEQ was designed with opposing adjectives as items for each domain, to be answered by the subject on a Likert scale from 1 to 7.
- Think-Aloud Method (Eccles & Arsal, 2017): The think-aloud method is a qualitative method used to assess usability when a new technology is developed. Users are asked to report their opinions regarding the technology and criticism while interacting with the device/software. The experimenter was asked to take notes or to record the participants' observations, which could include what they were looking at, thinking about, doing, and feeling. All the verbalizations were transcribed into a reporting grid and analyzed with thematic analysis to develop the formal usability report.

Analysis and Results

Experimenter Condition

System Usability Scale

The participant's scores for each question were added together and then multiplied by 2.5 to convert the original scores of 0-40 to 0-100. The total SUS score of the proposed system was 70.25 (sd = 6.3815), thus indicating good usability. *Figure 4* shows the SUS scoring interpretation.

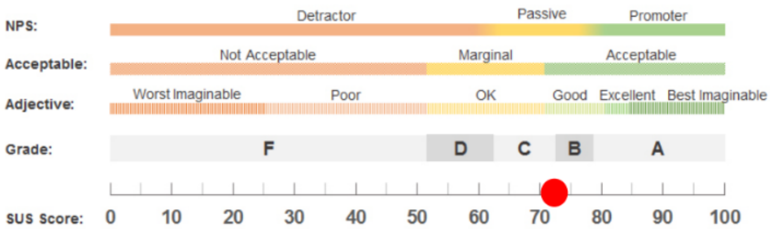


Figure 4 SUS scoring interpretation. Grid to interpret SUS total score. The red dot represents the mean score obtained by the proposed system (image from https://measuringu.com/interpret sus-score/).

Task Analysis

During the interaction with the system, the experimenter reported whether the participant was able to complete the task. The percentage of task success was then calculated for each subtask to identify critical points (*Figure 5*). Task completion was categorized based on previous usability studies (i.e., Successfully completed =1, Partial, =0.5, Unsuccessful = 0; Annet, 2003). The analysis revealed difficulties in the alignment and calibration tasks. Participants found it demanding to align the virtual and real bodies and specify the Kinect to track the users' movement. Notably, such difficulty was higher for participants without previous experience with VR. However, complications decreased the second time calibration was performed. The reasons underlined observed difficulties were then clarified by think-aloud reports. All the other tasks instead were correctly performed by all participants.

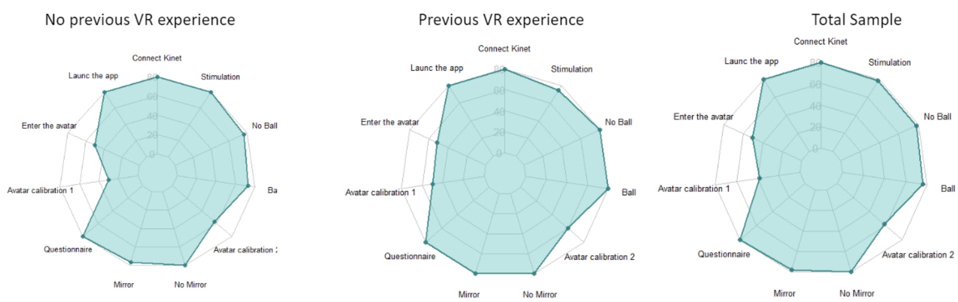


Figure 5 Task Analysis Results. The graph shows the results of the task analysis in terms of the success rate, both concerning the previous Virtual Reality experience as well as the sample. Labels: launch the application, connect Kinect, abdominal stimulation, insert the ball, remove the ball, calibrate the avatar two times, insert the mirror, remove the mirror, questionnaire, and enter the subject in the avatar's body.

Think Aloud

The thematic analysis of participant reports indicated that most of the users initially experienced anxiety about potentially damaging the system, expressing specific concerns about breaking the controller or computer. This apprehension decreased as they grew more accustomed to the system and gained confidence in their ability to execute the necessary tasks. The challenges identified through task analysis concerning the alignment and calibration tasks primarily stemmed from difficulties in memorizing the commands and buttons. A common mistake was the inadvertent pressing of the trigger button instead of the intended lateral one, with some participants resorting to pressing the trigger or other buttons randomly when they did not remember what to do.

Some of the participants' comments were: "I automatically click on random buttons", "I feel a little bit scared", "I think trying the experience as a subject before is essential to understand what to expect", "I guess that trying the system two or three times will be sufficient to be more confident", "I am scared that something will go wrong and I do not know how to fix it", "How to align the body?", "I click on random buttons when I do not remember what to do", and "I automatically click on the trigger button".

In response to these issues, participants recommended system improvements. One suggestion was to reassign specific functions, such as alignment and calibration, to different buttons to avoid confusion. Additionally, there were proposals for providing users with a checklist or guidelines to facilitate easier navigation through the system's functions.

Participant Condition

User Experience Questionnaire

UEQ scores revealed notable variations across different scales of users' perceptions. For the scale of Attractiveness, the mean score was 1.883 (sd= 0.401, CI [1.707; 2.059]), indicating a high level of attractiveness. In the domain of Perspicuity, the mean was 0.550 (sd = 0.536, CI [0.315; 0.785]), suggesting variability in clarity or understandability. Efficiency was scored with a mean of 0.925 (sd = 0.414, CI [0.743; 1.107]) reflecting an average efficiency perception. Similarly, Dependability had a mean score of 0.925 (sd = 0.460, CI [0.724; 1.126]) indicating participants' relative confidence in the system's reliability. Stimulation and Novelty showed mean scores of 2.213 (sd = 0.552, CI [1.971;2.454] and sd = 0.482, CI [2.001; 2.424] respectively), indicating above-average levels. *Figure 6* shows UEQ results.

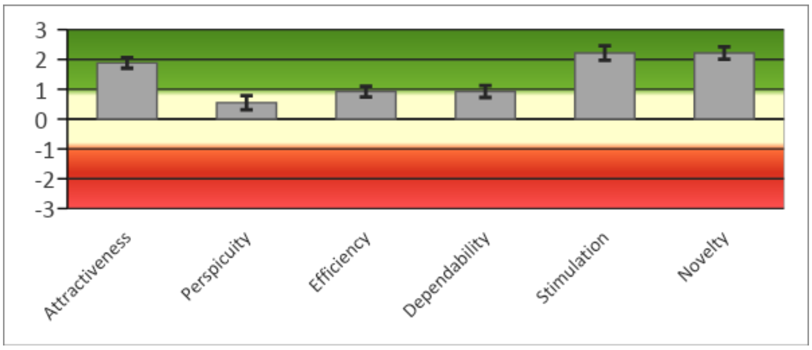


Figure 6 User experience after VR exposure. The figure shows UEQ scores for each subscale. The colors (green, yellow, and red) indicate above, within, and below average thresholds. The bar chart shows the means and standard deviations obtained in the six different qualities of the VR system.

Presence Questionnaire

Sense of presence within the virtual environment was overall highly rated. The "Possibility to Act" was rated with a mean value of 24.0 (sd = 2.11), indicating a strong sense of agency experienced by participants. In terms of "Quality of Interface," participants reported a mean value of 19.7 (sd = 0.856), reflecting a high degree of satisfaction with the interface. The "Possibility to Examine" achieved a mean value of 13.4 (sd = 2.26), suggesting that participants felt the ability to explore and interact with the environment in a meaningful way. The "Self-evaluation of Performance" garnered a mean value of 10.1 (sd = 1.52), pointing good level of perceived effectiveness in navigating and manipulating the virtual environment. The "Haptic" feedback dimension had a mean value of 4.6 (sd = 1.64). Remarkably, the "Realism" factor scored the highest mean value of 42.3 (SD = 3.29), significantly enhancing the overall sense of presence for users. Collectively, these dimensions contributed to a total mean value of 71.8 (SD = 3.29), encapsulating the participants' overall sense of presence within the virtual environment.

Cybersickness Virtual Reality Questionnaire

None of the participants reported symptoms before and after the virtual reality experience. CSQ-VR mean score was 0 both before and after the virtual reality experience.

Think Aloud

The thematic analysis of participant reports revealed participants' perceptions of a high-quality, immersive, and engaging experience. They underscored the role of movement synchronization in fostering a sense of ownership over the virtual body, with many reporting moments where they felt completely absorbed by the virtual environment, to the extent of momentarily forgetting their real bodies. The experience of seeing their reflection in a virtual mirror was highlighted as particularly impactful, creating a profound sense of connection with the virtual avatar.

Participant comments included: "The graphics and synchronicity exceeded my expectations.", "The virtual environment was simple yet realistic enough to make me forget about the real world at some point.", "I found myself automatically moving at the beginning just to verify the body was indeed mine.", "The synchronization was impressive: super-fluid and realistic, responding accurately in all directions."

Participants also voiced some criticisms. For example, they expressed a desire for more interactive elements, such as the ability to engage with other virtual people or objects and to move freely around the room. One of them reported preferring the experimenter to be present in the virtual environment too, to avoid the experimenter's voice being outside the virtual environment. Two participants noted occasional calibration issues, resulting in slight latency between their movements and those of the avatar, and instances where the virtual ball malfunctioned.

Discussion

Virtual Reality (VR) stands at the forefront of technological advancements, offering a gateway into alternate realities that were once confined to the boundaries of the imagination. As an immersive, cognitive, and multisensory platform, VR has the unparalleled capability to forge deeply engaging experiences that are instrumental in exploring and understanding the intricacies of the human mind (Riva et al., 2017). Such capabilities are particularly transformative in clinical settings, where VR's potential to alter bodily perceptions holds promising implications for conditions associated with distorted body-self relationships (Horne et al., 2020; Turbyne et al., 2021).

Among the most groundbreaking applications of VR is the Body Swapping (BS-VR) illusion, which empowers individuals to inhabit an alternate body, thereby altering their physical self-perception. This approach offers a novel method for patients to reconceptualize their bodies, providing a potential therapeutic avenue for conditions like Anorexia Nervosa (AN; Matamala-Gomez et al., 2019).

In this study, we introduced a BS-VR system that enables swapping into another body from both first-person (egocentric) and third-person (allocentric) perspectives, building upon the foundation laid by previous research (Porras-Garcia et al., 2021, 2020). We specifically evaluated the user experience and usability of the proposed system. This focus diverges from prior research by encompassing the perspectives of both the recipients of the VR experience and the administrators, thereby offering a comprehensive understanding of the system's practicality in clinical and therapeutic settings.

Results from the experimenter and subject conditions will be discussed in the next sections with related Virtual Reality design advice.

Experimenter Condition

In the experimenter condition participants assumed the role of the experimenter and administered the VR experience firsthand. Most of the participants initially expressed apprehension about using the system, fearing they might damage it. This emotional obstacle and fear of technology (juutinen, Huovinen & Yalaho, 2011) might account for resistance to Virtual Reality applications in clinical settings. However, this concern diminished as they became more familiar with the system, reinforcing the importance of practice in building confidence and self-competence (Schank, Berman & Macpherson, 2013). These data suggest that familiarization and training phases are critical for the adoption of technological devices and should be taken carefully into account when proposing new systems (Kalonde & Mousa, 2016) .This was confirmed also by task analysis. Indeed, participants with previous experience performed slightly better than those without previous experience with VR. That is, technical and specific experience in the VR-BS influenced the system's successful implementation. Notably, participants with previous experience did not present a high level of knowledge (e.g., they reported having tried VR in previous experiments) meaning that little expertise might be sufficient to appropriately use the system. In line with this consideration, the task analysis revealed that participants were more adept at performing alignment and calibration tasks independently on their second attempt.

Moreover, participants expressed the need for initial hands-on experience with the system to fully grasp what to expect and how to navigate the experience. They appreciated the subject's experience before having to play the role of the experimenter because this allowed them to understand if they were doing right and if everything was working as intended. In this regard, participants appreciated the possibility of seeing what the subject sees in the headset by computer, possibly because this enhanced their feeling of control over the technological device (Deng et al., 2010). Then, good usability results might be linked to the condition presentation order.

Future studies might also consider reversing and counterbalancing the conditions to better investigate usability. That is, half of the participants might start trying the system as a subject while the others have written instructions. This might reveal additional insights in terms of design optimization.

Going more into detail, task analysis uncovered specific challenges related to the calibration and alignment of the physical body with the virtual avatar. Participants struggled with manually aligning the virtual and physical bodies and correctly setting up the motion-tracking system. Qualitative feedback revealed difficulties in remembering specific commands or inadvertently pressing the trigger button in terms of design and programming, this suggests that critical commands should not be assigned to the trigger button to prevent unintentional modifications of the experience. Moreover, it suggests the potential benefits of automating tasks to minimize the cognitive load of remembering multiple commands.

Despite initial concerns, the System Usability Scale indicated that the system was generally considered user-friendly. Then, different from previous systems (Matamala-Gomez et al., 2020), our system was rated as easy to use by both users with and without previous experience with Virtual Reality technology.

Based on results and previous research (Matamala-Gomez et al., 2020; Dollinger et al., 2020), some VR design suggestions were extracted (*Table 1*).

Familiarization and Training	• Implement comprehensive training sessions to familiarize with the VR system before actual use. This helps in overcoming initial apprehensions and builds confidence and self-competence. • Provide hands-on experience as part of the training to help users grasp the system's functionality and navigation, enhancing their preparedness for the actual application. • Incorporate features that allow administrators to see what the subject sees through the headset on a computer to increase the feeling of control over the device.
Systema design and Calibration	• Simplify the alignment and calibration process between the physical and virtual bodies. • Consider automation of tasks to reduce the cognitive load on users. • Avoid assigning critical commands to buttons that can be easily triggered unintentionally. Explore alternative interaction methods to prevent accidental modifications of the experience.
Support and Documentation	• Provide clear and comprehensive documentation and support materials, including troubleshooting guides, to assist users in overcoming challenges related to system use and calibration.

Table 1 Virtual Reality design suggestions.

Participant Condition

In the subject condition, participants were introduced to the virtual reality experience by the experimenter. A key finding is that the system, despite involving movement with a motion tracking system, did not cause discomfort or cybersickness, regardless of whether participants had previous virtual reality experiences or were first-time users (Matamala-Gomez et al., 2020). This outcome was consistent with the VR exposure limited duration, aligning with the typical duration of a VR intervention protocol (e.g., Porras-Garcia et al., 2020a). While some preliminary studies have explored the user experience of body swapping in a clinical sample of patients with anorexia, they did not account for this variable (Kalonde & Mousa, 2016). However, discomfort related to the equipment might play a crucial role in the adoption of this technique in clinical practice, especially for vulnerable individuals (Dollinger et al., 2022).

In terms of UX, there was a positive evaluation of the experience in both the questionnaire and the participant reports. All scales on the questionnaire were rated average or above average according to standard parameters. Notably, the scales for attractiveness (overall impression of the system), novelty (impression that the product design and idea are creative and original), and stimulation (impression that using the product is interesting and fun) scored above average. From the qualitative data, we observed that most participants were pleasantly surprised by the graphic quality, level of immersion, and accurate movement tracking. For instance, participants reported, "I got a much higher quality than I expected: that was impressive," and "It was my first time with this type of experience, and I did not expect it would be so engaging and immersive."

For the remaining scales—Perspicuity (ease of learning how to use the product), Efficiency (impression that tasks can be completed without unnecessary effort), and Dependability (feeling in control of the product interaction)—the results were lower but still within the average range. The qualitative data helped identify possible reasons for this. For example, many participants expressed fear of breaking something or damaging the system, while others felt intimidated by their first virtual reality experience and were unsure what to expect. Additionally, some participants did not understand the purpose of the ball procedure. Overall, however, the experience was positive and engaging for all participants. This finding is particularly significant considering the clinical application in conditions characterized by a lack of therapeutic alliance, reduced compliance, and strong resistance (Ellrodt et al., 1995), with ego-syntonic symptoms such as Anorexia Nervosa (Gregersten, mandy & Serpell, 2017): finding procedures that can break down the barrier between therapist/clinician and patient is even more crucial in these cases.

As for the sense of presence, the questionnaire showed high levels of immersion and presence in the virtual environment, confirmed by qualitative data. For example, some participants noted, "The part with the mirror especially was impressive: I thought that I was looking at myself," "I have tried the previous version without the motion synchronization, and the feeling of owning the artificial body wasn't as strong. I understand what immersive means now: it was like I was in another time and space." This is particularly important as presence might significantly contribute to the efficacy of VR interventions (Ferri et al., 2019).

These comments clarify that movement was a critical component in promoting a sense of presence and embodiment. This aligns with the sensorimotor theory of perceptual experience, suggesting a critical role of bodily interaction with the environment in shaping perception (Silverman, 2014; Ferri et al., 2012) and the sensorimotor foundation of Bodily Self-Consciousness (Ionta, Gassert & Blanke, 2011). In terms of design, static procedures like those used by (Serino, Polli & Riva, 2019; Keizer et al., 2016) might be therefore sub-optimal, and dynamic experiences should be preferred.

Based on results and previous research (Matamala-Gomez et al., 2020; Dollinger et al., 2020), some VR design suggestions were extracted (*Table 2*).

Minimize Discomfort and Cybersickness	• Limit the duration of VR interventions with the typical length of VR exposure: shorter sessions (around 20-30 minutes) can help maintain user comfort and engagement without inducing fatigue and cybersickness.

Emphasize Quality and Immersion	• Invest in high-quality graphics and accurate motion tracking systems to enhance the sense of presence (physical and psychological presence/ immersion).
Simplify Learning and Interaction	• Design interfaces that facilitate easy learning and efficient task completion. • Addressing fears of damaging the system and clarifying the purpose of specific procedures (like the ball procedure) can improve perspicuity, efficiency, and dependability.
Maximize Presence and Embodiment	• Leverage dynamic experiences that promote a strong sense of presence and embodiment, as movement and sensorimotor interaction are key to these sensations. • Prefer dynamic experiences, as they are more effective than static procedures in promoting bodily self-consciousness and a sense of presence.

Table 2 Virtual Reality design suggestions.

In the present study, we did not investigate user-experimenter interaction. However, this might be an important factor in determining the overall user experience. Future research might better focus on more specific aspects of the VR-BS experience such as tactile stimulation. In particular, the intensity and direction of tactile feedback could have a significant impact on users' sense of embodiment and the overall effectiveness of the intervention. This is especially true for sensitive areas such as the abdomen, which can cause discomfort for some participants and potentially detract from the experience. Consequently, further research could explore the implementation of targeted tactile stimuli – e.g., affective touch (Della Longa et al., 2021) – to evaluate its impact on the user experience and the embodiment induction.

Limitations

The current study, while insightful, encounters several limitations that warrant discussion. First and foremost, the relatively modest sample size poses a constraint. Despite aligning with recommended norms for usability and user experience research as suggested by Hwang and Salvendy (2010), the sample size may still limit the generalizability of our findings. Nonetheless, the data's consistency lends credence to our conclusions, suggesting a minimal likelihood of uncovering new critical factors with a larger cohort. Our system's development and evaluation were meticulously designed with a focus on ethical considerations, particularly given its intended future application in clinical settings. This formative evaluation with healthy participants lays the groundwork for subsequent studies involving potential patients, as part of a broader feasibility study aimed at clinical implementation (Dollinger et al., 2022).

Looking ahead, future research should aim to include a broader spectrum of participants, encompassing both clinical populations and healthcare professionals. This expansion is critical for validating our findings within therapeutic contexts. Moreover, the feedback regarding system limitations, especially the challenges related to calibration and alignment tasks, underscores the need for enhancements. Automating these processes could significantly improve user-system interaction, echoing the principles of iterative design where user feedback drives system refinement (Jonassen, 2008).

The necessity for effective communication between therapists and users, which may intermittently disrupt the sense of presence, raises important questions regarding the overall impact of presence in body image interventions. This consideration is equally pertinent to augmented reality applications (Wolf et al.,2022).

Finally, due to the aim of this study, we only implemented one body, but the next development requires the introduction of different body sizes and shapes to cover a spectrum from underweight to overweight, in line with previous protocols (e.g. Porras-Garcia et al., 2020).

Conclusions

This study introduces a pioneering open-source virtual reality (VR) software, designed to facilitate the body-swapping illusion protocol for a wide range of applications, from assessment to therapeutic interventions across non-clinical, sub-clinical, and clinical populations (Serino et al., 2019). Specifically, it addresses the needs of individuals experiencing altered body perceptions, such as those suffering from Anorexia Nervosa (AN). Our findings reveal the feasibility of employing an affordable VR setup—comprising a head-mounted display, a laptop, and a webcam—to immerse users in a virtual environment where they can embody a virtual avatar different from their physical one. A distinctive feature of the proposed VR system is its support for both egocentric (first-person) and allocentric (third-person, mirror-like) perspectives, enriching the user's engagement with and exploration of bodily experiences.

Contrary to prior research, our application has been well accepted in terms of usability and user experience by both participants and administrators. With minor modifications, this system emerges as a well-balanced tool that satisfies both technical and experimental demands, ensuring accessibility for users and practitioners outside the technical domain.

We contend that such analytical approaches are crucial for crafting effective tools aimed at exploiting Multisensory and Embodied VR technology to promote Transformative Experiences (METE), namely immersive experiences that significantly impact an individual's perception, cognition, and emotional state, fostering a profound personal and psychological transformation. This work not only bridges the gap between experimental and clinical domains but also harnesses technological advances to improve prevention and intervention strategies. Ultimately, this study highlights the potential of VR technologies to create powerful, accessible, and user-friendly platforms for addressing complex psychological conditions, paving the way for innovative therapeutic solutions.

5.2. Therapeutic Immersion: A Single-Subject Study on Virtual Reality Multisensory Experiences for Mitigating Body Disturbance in Anorexia Nervosa [7]

Introduction

Anorexia nervosa (AN) is an Eating Disorder (ED) characterized by reduced food intake, extremely low body weight, fear of gaining weight, and Body Image Disturbance (BID). BID reflects an altered perceptual, cognitive, and affective body experience (Brizzi & Riva, 2024). Notably, BID plays a critical role in AN development, maintenance, and relapse (Brizzi & Riva, 2024). Because of the limited effectiveness of available AN treatment, previous authors pointed out the need to include BID-focused protocols in AN interventions (e.g., Cognitive Dissonance Mirror Exposure; CD–ME; Luethcke et al., 2011). In this regard, Virtual Reality (VR) has been increasingly used to allow patients to enter (embody) a different body compared to their real one. Such procedures include Body Swapping (BS; Serino et al., 2019) and VR–Mirror Exposure (VR–ME; Porras-Garcia et al., 2021). Keizer et al. (2016) and Serino et al. (2019) observed that swapping into a normal-weight body reduced body size overestimation in AN patients, suggesting that embodiment in an artificial body with different dimensions from an egocentric frame altered body perception congruently with the artificial body (Serino et al., 2019; Keizer et al., 2016). Porras-Garcia et al. (2021) used VR–ME to gradually expose patients affected by AN to a virtual normal-weight body from an allocentric spatial frame (i.e., mirror-like perspective), observing a reduction in patients' fear of gaining weight and body-related anxiety after this exposure. Alleva et al. (2015) suggested a new way to address BID focusing on body functionality (i.e., the body's sensory, creative, and social abilities). Following this suggestion, Warren and Murray (2022) proposed an ME variant called Functionality-Focused Mirror Exposure

[7] This study has been published: Brizzi, G., Boltri, M., Guglielmini, R., Castenuovo, G., Mendolicchio, L., & Riva, G. (2025) Therapeutic immersion: a single-subject study on virtual reality multisensory experiences for mitigating body disturbance in anorexia nervosa. *Eat Weight Disord* **30**, 32 (2025). https://doi.org/10.1007/s40519-025-01740-5

(FME). Here, individuals are asked to reflect on what their bodies allow them to do in everyday life while looking at themselves in the mirror. However, no study has integrated this concept into VR approaches. By merging functionality-focused principles with VR-based interventions, this study aims to offer an innovative method to address BID, leveraging the strengths of different techniques. As suggested by Kazdin (2019), the single-case methodology represents a first step in developing evidence-based practices and can be used to investigate a treatment's preliminary effectiveness. Here, we present a case study investigating the feasibility, acceptability, and preliminary efficacy of a new BID intervention in a patient affected by AN. We call it "VR-Functional Mirror Exposure" (VR-FME), and it was designed to include a combination of CD–ME and FME in VR. This design might allow the evaluation of the intervention's feasibility and acceptability from the patient's and clinician's point of view, promoting valuable insights to inform subsequent Randomized Control Trials.

Case Formulation

The patient was a 24-year-old woman. She started restricting her food intake in 2014, reporting that her family encouraged her to control her body weight and diet. Food restriction led to significant weight loss and a first hospitalization in 2015 with a diagnosis of restrictive AN. In 2016, she entered a center specializing in ED. In the following years, the patient reported a fair psycho-physical well-being. Restricted eating, purging episodes, and motor hyperactivity reemerged in 2023, coinciding with the transfer to another city for studying. She sought admission in 2024 to the IRCCS (Istituto di Ricovero e Cura a Carattere Scientifco) Istituto Auxologico Italiano, with a BMI=15.7 and a diagnosis of Restrictive AN. The hospital program includes a 4-week stay. During the hospitalization, a series of activities are offered (see Table S in Online Resources for the description of standard intervention activities). The patient was introduced to an innovative protocol using VR experiences to address BID alongside the standard approach.

Methods

Procedure

The protocol consisted of 2 weekly sessions for a total of 6 meetings. A pre-assessment before the first session, a post assessment after the last session, and a follow-up 1 week after the end of the intervention were conducted. In the preassessment, ED symptomatology and body disturbance were assessed. The patient was also asked about her expectations and attitudes toward VR. VR sessions started with the induction of a full-body illusion (i.e., visuomotor and visuotactile stimulation for 90 s). Then, based on the session, CD–ME or FME exercises were proposed in VR. The same body model (BMI=18.5) was presented throughout the sessions. Finally, the patient was immersed in a relaxing virtual scenario. In the post-assessment, pre-assessment measures were administered. Finally, thoughts about the experience were collected. In the follow-up, questionnaires were e-mailed to the patient (*Figure 1*). An in-depth explanation of the procedure—including a session-by-session description and the script used in the different sessions—is available in Online Resources.

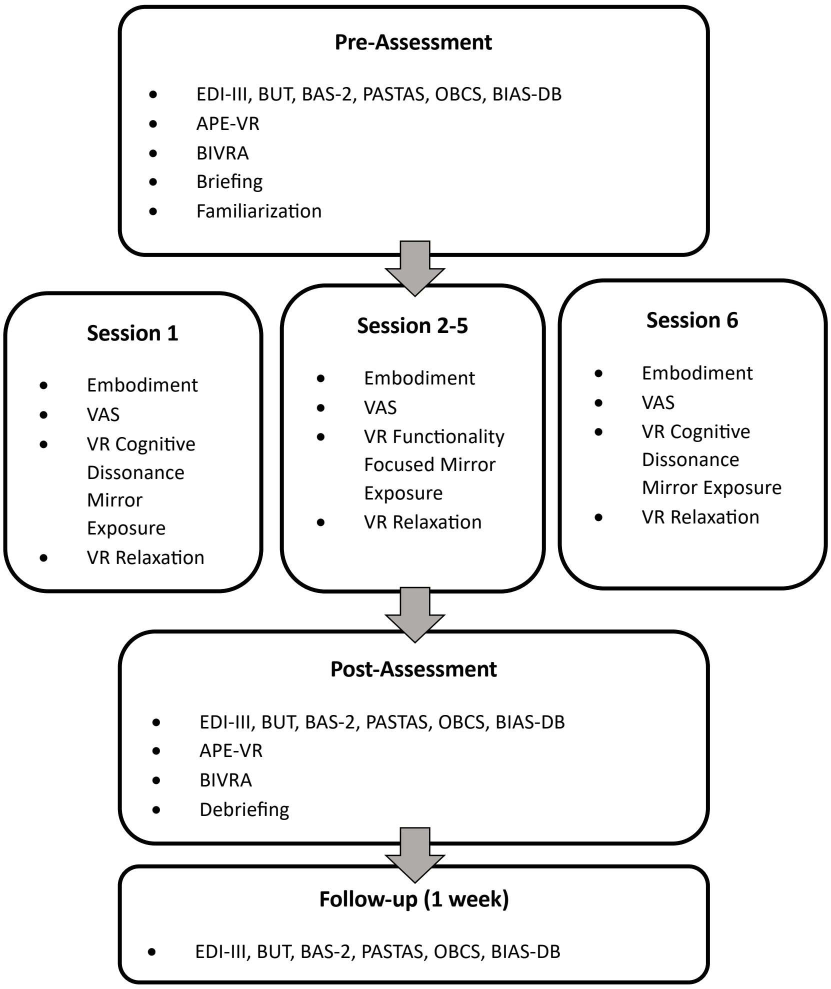
Measures

The Eating Disorder Inventory-III (EDI-III) and Body Mass Index (BMI) were used to assess symptomatology. For the body–self relationship, the Body Uneasiness Test (BUT), Body Appreciation Scale-2 (BAS-2), Physical Appearance State and Trait Anxiety Scale (PASTAS), and Objectified Body Consciousness Scale (OBCS) were included. Body perception was evaluated using the Figure Rating Scale (BIAS–BD), the Body Image Virtual Reality Assessment (BIVRA), and Affordance Estimation Procedures in Virtual Reality (APE–VR). Finally, a Visual Analog Scale (VAS) assessed embodiment during VR sessions. See Online resources for additional information about assessment measures and scoring.

Virtual Reality Intervention

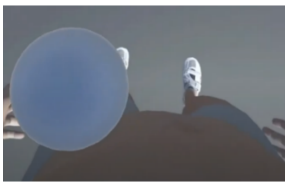
Cognitive dissonance mirror exposure (CD–ME) was proposed in the first and last sessions. The exposure started with the patient standing in front of the virtual mirror. She was encouraged to describe out loud different body parts of the virtual body using positive or neutral words (e.g., the body's physical, emotional, and social qualities). For an individual with high body distress, complimenting oneself in the mirror creates cognitive dissonance. Notably, VR allows the application of this technique to a normal-weight body, unlike real-world procedures. During the last 5 min of the session, the patient was immersed in a relaxing natural VR environment. The session lasted around 60 min. Functional mirror exposure procedure (VR–FME) was used in the central sessions. VR–FME was based on [6, 7], adapting the script to focus on critical body areas (i.e., the facial scan was removed to give more space to body areas, such as the hips and abdomen). The script encouraged the patient to verbalize some activities/experiences her body allowed her to do in the past and present and will allow her to do in the future. Outloud verbalization partially ensured she was paying attention to the task. She was also instructed not to avoid uncomfortable feelings or thoughts but to refocus gently on the instructions. The underlying idea was to prompt a different way to look at the body, away from physical appearance, and create a connection between a healthy body and positive memories. The last 5 min of the session were dedicated to relaxation. Each session lasted approximately 60 min. Online Resources provide detailed information about the VR procedures and the entire protocol structure, techniques, and/or tools.

a) Procedure



b) Virtual Reality Experience Steps

Embodiment
Embodiment induction through visuo-tactile and visuo-motor synchronous stimulation.



VAS
VAS to assess embodiment strength. “Indicate on a scale from 0 (not at all) to 100 (totally) how much you agree with the following statement: ‘I perceived the virtual body as if it were my own’

Script
The clinician follows a pre-defined script to guide the patient through the normal-weight body examination, based on the specific session (cognitive dissonance or functionality-focused mirror exposure).

Relaxation
10 min of immersive relaxing video at the end of the session.

Figure. 1 Procedure and Virtual Experience. a Represents the study procedure. Eating Disorder Inventory–3 (EDI-III), the Body Uneasiness Test (BUT), the Body Appreciation Scale-2 (BAS-2), the Objectified Body Consciousness Scale (OBCS), the Figure Rating Scale (BIAS– BD), the Aperture Task in Virtual Reality (APE-VR) and the Figure Rating Scale in Virtual Reality (BIVRA); Visual Analogue Scale (VAS),

Virtual Reality (VR). Because of technical constraints, VR tasks were not proposed in the follow-up, and the BMI was not asked of the participant, following clinicians' suggestion. Online Resource contains a full description of the measures used, including psychometric information and details of scoring; b shows the VR experience core steps. The body model was developed using MakeHuman Software based on Brizzi & Riva (2024) and resembles a normal-weight body (BMI=18.5).

Results

Quantitative Results

EDI-III scores suggested a reduction across various eating disorder symptoms and related psychological factors. However, some subscales remained unchanged or showed minimal variation (*Table 1*). In general, the intervention seemed to influence more psychological features related to the disorder rather than ED-specific symptoms. In the pre-assessment, the patient's BMI was 15.7. In the first session, it was 15.3, whereas after the intervention, BMI was 15.8. Questionnaires assessing the body–self relationship showed improvements after the intervention (Table 2). The patient showed an overall reduction in body uneasiness, whereas fear of gaining weight and body image concerns did not. The number of areas causing distress decreased, although the distress intensity increased. In addition, the patient showed a higher body appreciation and reduced physical anxiety and self-objectification after the intervention. Finally, the patient showed greater accuracy in the "real" body identification task in the post-assessment as compared to the pre-assessment. Notably, while no significant differences were found in the BIAS–BD, changes in ideal body shape were observed in BIVRA. It followed an overall improvement in body satisfaction. APE–VR indicated changes in the sensorimotor representation of the body.

Eating Disorder Inventory – III			
	Pre	*Post*	*Follow-up*
Drive for Thinness	28	28	28
Bulimia	2	1	3
Body Dissatisfaction	40	40	40
Low Self Esteem	23	28	24
Personal Alienation	20	10	14
Interpersonal Insecurity	5	1	0
Interpersonal Alienation	6	7	8
Interoceptive Deficits	10	4	4

Emotional Dysregulation	7	3	4
Perfectionism	20	20	20
Asceticism	17	16	12
Maturity Fears	32	30	32
Inadequacy Composite	43	28	38
Interpersonal Problems Composite	11	8	8
Affective Problems Composite	17	7	8
Overcontrol Composite	37	36	32
General Psychological Maladjustment Composite	140	109	118

Table 1 EDI-III subscales scores in pre-, post-, and follow-up assessment points

Table 2 presents scores in the questionnaires assessing body–self relationship in the pre-, post-, and follow-up assessment points. Scores in the Body Uneasiness Test (BUT) were divided for subscales on the left side, and scores in the Body Appreciation Scale (BAS-2), Physical Appearance State and Trait Anxiety Scale (PASTAS), and Objectified Body Consciousness Scale (OBCS) were on the right side.

Body self-relationship questionnaires			
	Pre	*Post*	*Follow-up*
BUT			
Global Severity Index	4.5	4.26	4.00
Weight Phobia	5.00	5.00	5.00
Body Image Concerns	4.44	4.44	4.44
Avoidance Behaviors	4.17	3.33	1.83
Image Control	4.17	4.17	4.00
Depersonalization	4.60	4.00	4.17
Positive Total Symptoms	18.00	15.00	16.00
Positive Symptom Distress Index	4.17	5.00	4.81
TOT A (whole body)	26.88	25.20	23.44
TOT B (specific body areas)	22.17	20.00	20.81
BAS-2			
	13	15	14
PASTAS			
	40	32	36
OBCS			
	128	132	126

Table 2 Body self-relationship questionnaires.

Table 3 shows scores in BIAS–BD, BIVRA, and APE_VR tasks in the pre-, post-, and follow-up assessment points. The VR task was reported as the mean value of responses to each trial. In the pre-assessment, BIVRA real selection corresponds to an avatar with a BMI=19.5, whereas in the post-assessment, the real selection corresponds to an avatar with a BMI=18.5. Ideal body selection in BIVRA showed that the ideal body shape in the pre-assessment corresponds to an avatar with a BMI of 18.5 and an avatar with a BMI of 19.5 in the post-assessment. More detailed information about the measures and scoring is available in Online Resources.

Body perception and internalized self-concept			
	Pre	*Post*	*Follow-up*
BIAS-BD			
Real	140	105	100
Ideal	60	60	60
Dissatisfaction	80	45	40
BIVRA			
Real	2.00	1.20	
Ideal	1.50	1.00	
Dissatisfaction	1.20	0.20	
APE-VR			
	1.65	1.22	

Table 3 Body perception and internalized self-concept

Embodiment strength ranged from 100 (max) to 88.43 (min) across the sessions, suggesting high embodiment.

Free Feedback

Cognitive dissonance. In Session 1, the participant reacted with dissatisfaction to the virtual body's appearance, focusing on perceived flaws. She noted a positive aspect in the virtual figure's height, but overall, the negative focus dominated. By Session 6, the participant began to acknowledge the virtual body's positive aspects, such as a normal neck, a fat stomach, and strong legs and arms, viewing them as beneficial for swimming and walking. This marked a transition from focusing solely on aesthetics to appreciating the body's capabilities.

Virtual reality expectations and user experience. Before the intervention, the participant, concerned about body distortion, hoped it would help address this issue. Although new to

VR, she was eager for the experience. After the sessions, she found the experience enjoyable and felt comfortable with the technology and experimenters. However, she was unsure of its impact on body image. She had expected more noticeable changes and suggested the intervention would be more impactful if the virtual body matched her current body. Despite this, she expressed a willingness to use VR in the future.

Discussion

The current case study supports using VR–FME—a combination of CD–ME and FME in VR—to address BID in AN. Results revealed positive changes in altered body–self relationship, internalized self-concept, and improvements in psychological functioning.

Anorexia Nervosa Symptomatology

While EDI-III psychological functional subscales showed improvements, ED risk scales remained stable—consistent with minimal BMI variation—differing from previous research (Porras-Garcia et al., 2021). However, the latter considered patients with lower symptom severity than this study. Therefore, understanding for whom and when the VR–FME might be more useful is needed. In addition, differences might be linked to the fact that we followed (Keizer et al., 2016) and proposed a standard body instead of increasing the body BMI across sessions (i.e., starting from the patient's BMI to arrive at a normal-weight body in the last session; Porras-Garcia et al., 2021). Furthermore, here we focused on body functionality (Brooks et al., 2023): we did not directly target weight-related anxiety or body satisfaction (Porras-Garcia et al., 2021). VR–FME is intended to achieve two goals: correcting the distorted body representation and offering a new way to relate to the body, suggesting this might impact different body–self components. Indeed, the VR experience can produce a sensory "surprise" and change the internal body model (Brizzi & Riva, 2024) and can restore a functional body–self relationship by linking a normal-weight body to positive autobiographical memories (Malighetti et al., 2020).

Body Self Relationship

The patient showed improvements in BUT, differently from Malighetti et al. (2020). However, because the number of dissatisfying areas decreased but the total stress score did not, it could be that the intervention impacted medium/low critical body area judgments, while most critical areas remained distressing. It could also be that the level of uneasiness is accentuated when measured immediately after an emotionally demanding procedure such as body exposure. The decrease between pre-assessment and follow-up confirms this hypothesis. Another possibility is that to affect most critical areas, prolonged exposures are needed. Following the personalized medicine approach, an initial assessment could lead to tailored exposure time and script, which could be adjusted based on the patient's responses. Notably, we observed a reduction in self-objectification in the follow-up. While a rise in post-assessment was observed, this may reflect the experience's emotional impact. This aligns with Alleva et al. (2015), who suggested that changes in body perception can be slow but lasting. Like Serino et al. (2019) and Malighetti et al. (2020), we observed that embodying and viewing a normal-weight body through mirror exposure reduced body-related anxiety. This reduction likely stems from both the exposure itself and the script’s focus on encouraging a more compassionate, positive view of the body. These findings support the idea that a body-functionality approach can improve the body–self relationship, expanding the body concept. Our results also differ from previous studies using writing tasks (Walker & Murray, 2022), possibly indicating that verbalizing may act as a catalyst for a functional-oriented body perception.

Internalized Self-Concept

A reduction in body dissatisfaction was observed, as measured through avatar or silhouette selection and the aperture task. In line with results by Serino et al. (2019) and Keizer et al. (2016), the participant reduced body size overestimation after the intervention, demonstrating improved recognition of a body resembling her actual dimensions. This could be because embodying a different body might disrupt the brain's internal model, aligning with predictive coding theory (Brizzi & Riva, 2024). Notably, no change was noted in the ideal body estimation through silhouette selection, possibly due to response bias from presentation order. Indeed, the BIVRA variation underscores the limitations of traditional paper-and-pencil tasks.

Free Feedback

In the first session, the patient failed to report positive aspects of the virtual body. In the last session, she automatically focused on body functionality. This suggests that the work has promoted a different way of approaching the body. This further supports VR's ability to drive transformative experiences. Notably, overall feedback about the experience was positive. Starting from the patient's feedback, future research might consider proposing body functionality exercises while changing the BMI of the virtual body at each session (i.e., starting from the current patients' BMI to arrive at a normal weight body in the last session).

Strengths and limits

This study presents some limitations. First, we cannot strongly conclude that the changes were due to VR exposure per se. A larger sample size and RCTs are needed to understand the specific VR effects better. Second, we considered only one follow-up assessment, but future research should consider different assessment points to detect changes over a longer period. Third, the BMI of the virtual body did not match the BMI of the patient, and we did not use a personalized body model, based on (Behrens et al., 2023).

What is already known on this subject and what this study adds

VR body exposure showed promise in treating BID by allowing individuals to embody a different body from their own. However, while VR is a powerful tool, it is not inherently a treatment: specific tasks during exposure are necessary to enhance its potential therapeutic power.

This study offers preliminary evidence supporting the integration of VR–FME for BID in AN. Additional research is needed to better understand the clinical changes induced by this protocol on a larger sample size and in an RCT.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s40519-025-01740-5

5.3 Conclusions

This chapter focused on the use of virtual reality to address the altered body experience typically observed in patients with anorexia nervosa. It presented the first concrete outcome of my PhD project: a software designed to deliver the body-swapping/full-body illusion experience in virtual reality. Unlike previous systems described in the literature, I prioritized evaluating the usability and user experience of the tool I developed, as I believe these two factors are critical in determining whether a technological tool will be effectively adopted in clinical settings. Addressing these aspects helps bridge the gap between research and clinical practice.

The study demonstrated that the system was easy to use for both the individual undergoing the experience and the person administering it. The second outcome of my PhD project was the development of an intervention protocol. Conducting a pilot study with a patient diagnosed with anorexia nervosa, I confirmed the feasibility and acceptance of the tool, as well as its preliminary effects on the patient's body experience.

Although these are preliminary steps toward a full validation study of the protocol and tool, the results from these two studies are encouraging and provide a solid foundation for further work in this direction.

6. Conclusions

This doctoral research is based on the idea that we can apply the Predictive Coding framework to understand how we experience our bodies. It begins with the theoretical framework, according to which subjective body experience relies on a probabilistic multisensory integration process grounded in the combination of both high-level information (e.g., memories, knowledge, prior experience, beliefs) and low-level information from the different sensory domains (e.g., visual, tactile, somatosensory). The challenge of this thesis was to apply this framework to understand conditions characterized by disrupted body experience, with a specific focus on Anorexia Nervosa.

The first two chapters of the thesis presented the two main protagonists of this research project: the Body Matrix and Anorexia Nervosa pathology. A Machine Learning study highlighted the link between these two main actors, revealing the importance of body-focused interventions to improve current therapeutic approaches for Anorexia Nervosa and reach clinically relevant outcomes. However, before starting to think about the design of any body-related intervention, it was necessary to identify which cognitive processes to target: we need to alter how patients experience their bodies, but on which mechanisms should we work? The core theoretical proposal of this thesis is that altered subjective body experience, like the one typically observed in patients affected by Anorexia and Bulimia Nervosa, might result from an impaired predictive processing of multisensory information. A systematic review of the literature analyzing multisensory integration across different sensory modalities in these conditions supported this perspective.

Once a possible target mechanism has been individualized, understanding the most suitable tool to work on this complex cognitive mechanism was necessary: what type of experience and manipulation can we use to alter the multisensory predictive processing at the basis of bodily experience? The third chapter presented Virtual Reality as a possible apparatus for studying the multisensory body experience process for three main reasons. First, it is a multisensory, simulative, embodied, and cognitive technology. Second, it elicits a strong sense of "presence" within the virtual environment. Third, the previous characteristics make it an optimal medium for fostering transformative experiences also in the context of a complex object like the own body. More specifically, the link between Virtual Reality technology and body experience was exemplified by Body Swapping and Full Body Illusion experiences, which emerged as possible multisensory and immersive experiences able to alter subjective body experience.

Two experimental studies were conducted to investigate how VR Full Body Illusion alters the Body Matrix, developing ad hoc virtual experiences. In the first research, I investigated whether males and females responded differently to VR Full Body Illusion, observing that gender-specific approaches are needed to observe these alterations. In the second study, I evaluated the contribution of the reference frame – namely, first- and third-person perspectives – in which the body illusion is presented on the observed Body Matrix change. Results revealed that both spatial frames contributed differently to Body Matrix changes after the illusion is experienced, suggesting the need to work on both levels to elicit perceptual and affective changes. These two studies contributed to defining technical characteristics to better design a possible body-focused intervention.

The fourth chapter presented a revision of existing VR approaches for assessing, treating and understanding EDs. This review was conducted to understand the state of the art of this research field. This was essential for the final step of this thesis: design and test a new intervention to study and alter dysfunctional bodily predictions, which I called "VR-Functionality-Focused Mirror Exposure (VR-FME)". This protocol was designed to integrate VR advantages with work at different levels of human functioning: from a bottom-up (perceptual) and a top-down (cognitions and beliefs) level. Indeed, the main strength of this protocol was the integration of full-body illusions in virtual reality with an evidence-based technique (e.g., relaxation, cognitive dissonance, exposure procedures). A preliminary usability and user experience analysis was conducted before a single-subject experimental design. These two studies confirmed the feasibility and acceptance, as well as preliminary efficacy, of both the VR software and the intervention in a real-world clinical setting. This preliminary testing was useful to individualize interventions' strengths (i.e., engagement, compliance) and weaknesses (i.e., the need for a personalized body model and the need to diversify the activities across sections).

Notably, these studies have allowed me to think more about who might benefit from this protocol and when it should be incorporated into a rehabilitation program. For instance, if we consider the Transtheoretical Model of Change (Prochaska & Velicer, 1997), we might hypothesize that this intervention might be more effective when the patient is at the contemplation and determination levels. I had the opportunity to optimize my Body Swapping VR software and to discuss with clinicians about questions and doubts, arriving at a final version of the tool and the protocol. I put in the new VR tool for Body Illusion as an open-source software[8], embracing the principles of open science framework. Fostering collaboration, transparency, and accessibility is essential for advancing research and ensuring that scientific innovations benefit the broader community.

I am now dedicating myself to deepening the study of the improved VR-intervention with a larger sample size, conducting a pilot Randomized Controlled Trial (registration DOI:

[8] Link to Body Swapping VR Software:
https://drive.google.com/file/d/1aYu9XCXJ1nfYmdoXRrV8y6Ju9qhR5zX3/view?usp=drive_link
Link to Body Image Assessment VR Software:
https://drive.google.com/file/d/1IMT5P4OT1sSIsak3f3wSOnrwtpyMO6S6/view?usp=drive_link

https://doi.org/10.17605/OSF.IO/MJ4V6) in collaboration with ABA – Bulimia and Anorexia Association (Fatebenefratelli Hospital).

One important limitation of this project is that it focuses on the external body, both in terms of exteroceptive sensory domains and the allocentric spatial frame of reference. Then, I did not specifically focus on the inner body. The inclusion of inner body stimulation during the immersive experience (e.g., the visual representation of inner body signals such as heartbeat or respiratory rate) might boost the body illusion effects in terms of improving body-self connection, body awareness, and overall, Body Matrix update. For instance, it might be possible to integrate into the VR-FME protocol also inner body (interoceptive) stimulation alongside external perceptual manipulations. In line with this preliminary idea, I am now conducting studies to understand the role of interoception in embodiment processes and its effect on the Body Matrix linked to Full Body Illusion experiences.

Another possible future implementation might be related to a better predictive process manipulation. The REBUS (Relaxed Beliefs Under Psychedelics) model proposed by Carhart- Harris and Friston (2019), hallucinatory experiences—whether pharmacologically induced or virtually simulated—can temporarily reduce the precision of entrenched top-down priors, thereby enhancing the influence of bottom-up sensory information in shaping perception. In this context, simulated visual hallucinations could be employed to weaken rigid body-related beliefs—such as the persistent conviction of being overweight often reported by individuals affected by Anorexia Nervosa—and increase the salience of raw sensory signals, such as those induced by body illusion paradigms. In other words, hallucinatory-like visual stimulation may create a more malleable perceptual state, facilitating the plastic reconfiguration of the Body Matrix when combined with immersive embodiment experiences like body swapping. Building on this perspective, I propose a novel paradigm—the Body Matrix Tuning (BMT)—designed to temporarily relax rigid body-related priors and promote adaptive embodiment through the sequential use of simulated hallucinations and body illusion techniques. This approach leverages the perceptual flexibility induced by hallucinatory-like visual stimulation to "reload" the brain's internal body model, making it more receptive to bottom-up updates provided by immersive body-swapping scenarios. The BMR thus aims to create a state of enhanced neurocognitive plasticity, offering a promising tool for both experimental research and therapeutic interventions targeting maladaptive body representations. All these ideas align with the Embodied Medicine proposal (Riva et al., 2017), which emphasizes the use of advanced technologies to target the bodily self through multisensory stimulation, aiming to restore or enhance health and well-being by acting directly on the embodied experience of the individual.

I started working on body perception during my master's thesis project (Brizzi et al., 2024). I had the opportunity to continue into this complex and continuously evolving field of research during my PhD journey. This allowed me to make available a VR tool for body image assessment and a VR software for body-focused intervention. Then, the challenge concretely is to further validate – and improve - these tools and integrate these techniques into real-world clinical practice to help people struggling with their bodies.

To conclude, the theoretical and experimental work presented in this thesis has led to one central insight: our perception of the body aligns with our expectations and is shaped by contextual influences. Reformulating Descartes' famous proposition, we might say, *Sum quod cogito*—I am what I think.

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Appendix

List of publications from the beginning of my PhD.

2025

- **Brizzi, G**, Pupillo, C, Sajno, E, Boltri, M, Brusa, F, Scarpina, F, Mendolicchio, L, & Riva G. Predicting anorexia nervosa treatment efficacy: an explainable machine learning approach. J Eat Disord. 2025 Jun 2;13(1):97. doi: 10.1186/s40337-025-01265-3. PMID: 40457487; PMCID: PMC12131494.
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- **Brizzi,G**, Sansoni, M, Chittaro, L, Malighetti, C, Mancuso, V, Villani, D, & Riva, G (2025) Exploring Self-Discrepancies Through Customizable 3D Avatars Using MySelf Desktop Tool. Annual Review of Cybertherapy and Telemedicine- 146

2024

- **Brizzi, G.**, Pupillo, C., Rastelli, C., Greco, A., Bernardelli, L., Di Natale, A. F., Pizzoli, S. M. F., Sajno, E., Frisone, F., Ubaldi, A., Di Lernia, D. & Riva, G. (2024). Exploring the Relaxing Effects of Hallucinatory Simulated Experiences in Virtual Reality: A Pilot Study. Annual Review of Cybertherapy and Telemedicine, 22(A), 81-85.
- **Brizzi G.**, & Riva, G. (2024). Playing With Spatial Frames: Altering the Body Matrix Through Multisensory Egocentric and Allocentric Body Illusions. *Human Behavior and Emerging Technologies*. https://doi.org/10.1155/2024/7316063

- **Brizzi, G.**, Frisone, F., Rossi, C., & Riva, G. (2024). Gender differences in bodily experience: Insights from virtual reality body illusion. *Acta Psychologica*, *249*, 104386.
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- Sajno, E., Rossi, A., De Gaspari, S., Sansoni, M., **Brizzi, G.**, and Riva, G. (2023) XAI in Affective Computing: a Preliminary Study. Annual Cyberpsychology, Cybertherapy and Social Networking Conference
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- Sansoni, M, **Brizzi, G.**, Vila, A., Guillen Sanz, H., Strocchia, F., De Gaspari, S., Sajino, E., and Riva, G. (2023) Looking Through Your Eyes: Using Immersive Virtual Reality to Promote Well-Being among Cancer Survivors and Their Partners. Annual Cyberpsychology, Cybertherapy and Social Networking Conference
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- Frisone F, **Brizzi G,** Riva G. VR-MEM: Harnessing Virtual Reality for Autobiographical Memory Enhancement in High School Settings. Cyberpsychol Behav Soc Netw. 2023 Nov 16. doi: 10.1089/cyber.2023.29300.ceu. Epub ahead of print. PMID: 37972046.

Supplementary Materials

Predicting Anorexia Nervosa treatment efficacy: an Explainable Machine Learning Approach

Table 5. List of abbreviations of predictive variables and their explanation.

	Abbreviation	Full Name	Meaning
	BIA - Bioelectrical impedance analysis		
1	BIA-ECW	Extracellular water	The ECW index refers to the proportion of water outside the cells. It's calculated as a ratio or percentage of extracellular to the Total Body Water
2	BIA - BCM	Body Cell Mass	The BCM index is the total mass of all the body cells responsible for consuming oxygen and metabolizing substrates. It includes muscle tissue, organs, and other cellular components actively involved in metabolic processes.
3	BIA-PA	Phase Angle	The PA index reflects the relationship between resistance (R) and reactance (Xc) in body tissues. It is calculated using the arctangent function of the ratio of reactance to resistance.
	EDI3 - Eating Disorder Inventory 3		
4	EDI3-DT	Drive for thinness	The EDI3_DT measures an excessive concern with dieting, preoccupation with weight, and fear of weight gain.
5	EDI3-B	Bulimia	The EDI3-B assesses the tendency to engage in binge eating and purging episodes.
6	EDI3- BD	Body Dissatisfactio n	The EDI3-BD evaluates dissatisfaction with body shape and size, particularly concerns about specific body areas.
7	EDI3-EDRC	Eating Disorder Risk Composite	The EDI3-EDRC is calculated as the sum of DT, B, and BD subscale scores.
8	EDI3-LSE	Low Self-Esteem	The EDI3-LSE assesses feelings of inadequacy and a lack of self-worth.

9	EDI3-PA	Personal Alienation	The EDI3-PA measures feelings of isolation, emptiness, and lack of fulfillment in life.
10	EDI3-II	Interpersonal Insecurity	The EDI3-II evaluates discomfort in social situations and fear of rejection or disapproval from others.
11	EDI3-IA	Interpersonal Alienation	The EDI3-IA assesses feelings of detachment and lack of connection with others.
12	EDI3-ID	Interoceptive Deficits	The EDI3-ID measures difficulties in recognizing and accurately identifying internal emotional states and bodily sensations.
13	EDI3-ED	Emotional Dysregulation	The EDI3-ED evaluates problems with managing and regulating emotions.
14	EDI3-P	Perfectionism	The EDI3-P assesses the extent to which an individual has high personal standards and a need for flawless performance.
15	EDI3-A	Asceticism	The EDI3-A measures a tendency towards self-denial, excessive self-discipline, and a belief that self-sacrifice is virtuous.
16	EDI3-MF	Maturity Fear	The EDI3-MF assesses fear of adult responsibilities and a preference for a more childlike role.
17	EDI3-IC	Inadequacy Composite	The EDI3-IC is calculated as the sum of LSE and PA subscale scores.
18	EDI3-IPC	Interpersonal Problems Composite	The EDI3-IPC is calculated as the sum of II and IA subscale scores.
19	EDI3-APC	Affective Problem Composite	The EDI3-APC is calculated as the sum of ID and ED subscale scores.
20	EDI3-OC	Obsession Composite	The EDI3-OC is calculated as the sum of A and P.
21	EDI3-GPMC	General Psychological Disadaptation Composite	The EDI3-GPMC is calculated as the sum of LSE, PA. II, IA, ID, ED, P, and A.
22	EDI3-IN	Response Incoherence	The EDI3-IN assesses the consistency of responses across the inventory.
23	EDI3-IF	Infrequency	The EDI3-IF assesses the frequency of atypical or rare responses, helping to identify unusual or inconsistent

			patterns in how individuals respond to the questionnaire items.
24	EDI3-NI	Negative Impression	The EDI3-NI assesses respondents' tendency to present themselves in an overly negative or pathological manner.
	SCL90 - Symptom Check List-90		
25	SCL-90-Somatization		tHE SCL-90-Somatization subscale assesses distress arising from perceptions of bodily dysfunction. It includes items related to cardiovascular, gastrointestinal, respiratory, and other systems.
26	SCL-90-Obsession/Compulsivity		The SCL-90-Obsession/Compulsivity subscale measures thoughts, impulses, and actions experienced as unremitting and irresistible but are unwanted.
27	SCL-90-Interpersonal Sensitivity		The SCL-90-Interpersonal Sensitivity subscale reflects feelings of personal inadequacy and inferiority compared to others, including discomfort in interpersonal interactions.
28	SCL-90-Depression		The SCL-90- Depression subscale covers a range of depressive symptoms, including mood and affect, as well as cognitive and somatic aspects.
29	SCL-90-Anxiety		The SCL-90- Anxiety subscale captures symptoms associated with general anxiety, such as nervousness, tension, and panic attacks.
30	SCL-90-Hostility		The SCL-90-Hostility subscale measures thoughts, feelings, and actions characteristic of anger and aggression, including irritability and rage.
31	SCL-90-Phobic Anxiety		The SCL-90-Phobic Anxiety subscale reflects persistent fears of specific situations or objects, as well as agoraphobia and other situational fears.
32	SCL-90-Psychoticism		The SCL-90-Psychoticism subscale measures a broad spectrum of psychotic symptoms, from mild interpersonal alienation to more severe symptoms like hallucinations and thought disorder.
33	SCL-90-Paranoid Ideation		The SCL-90-Paranoid Ideation subscale assesses paranoid thoughts, including suspiciousness, hostility, and fear of loss of autonomy.

34	SCL-90-SCL Global Index		The SCL-90-SCL Global Index subscale provides an overall measure of psychological distress. It is calculated by averaging the scores of all 90 items.
	BUT - Body Uneasiness Test		
35	BUT-GSI (scale A)	Global Severity Index	The BUT-GSI (scale A) is the sum of WP, BIC, A, CSM, and D subscale scores
36	BUT-WP (scale A)	Weight Phobia	The BUT-WP (scale A) measures the fear of being or becoming fat/gaining weight.
37	BUT-BIC (scale A)	Body Image Concerns	The BUT-BIC (scale A) assesses worries related to physical appearance.
38	BUT-A (scale A)	Avoidance Behavior	The BUT-A (scale A) assesses body image-related avoidance behavior.
39	BUT-CSM (scale A)	Compulsive Self-Monitoring	The BUT-CSM (scale A) assesses compulsive checking of physical appearance.
40	BUT-D (scale A)	Depersonalization	The BUT-D (scale A) measures the detachment and estrangement feelings toward the body.
41	BUT-PST (scale B)	Positive Symptom Total	The BUT-PST (scale B) represents the number of body areas that create distress (i.e., body areas with a score greater than 0)
42	BUT-PSDI (scale B)	Positive Symptom Distress Index	The BUT-PSDI (scale B) is calculated as the sum of scores assigned to each body area.
	PGWBI - Psychological General Well-Being Index questionnaire		
43	PGWBI-Anxiety		The PGWBI-Anxiety subscale measures feelings of tension, worry, and nervousness.
44	PGWBI-Depression		The PGWBI-Depression subscale measures feelings of sadness, hopelessness, and lack of interest in daily activities.
45	PGWBI-Positivity and Wellbeing		The PGWBI-Positivity and Wellbeing subscale evaluates positive emotions, satisfaction with life, and overall happiness.

46	PGWBI-Self-Control		The -PGWBI-Self-Control subscale reflects perceptions of one's ability to cope with stress and control one's emotions.
47	PGWBI-General Health		The PGWBI-General Health subsale assesses perceptions of overall physical health and well-being.
48	PGWBI-Total Score		The PGWBI-Total Score subscale is calculated as the sum of the ratings assigned to each item within each dimension.
	FMPS - Frost Multidimensional Perfectionism Scale		
49	FMPS-Concerns Over Mistakes		The FMPS-Concerns Over Mistakes subscale measures the extent to which individuals are preoccupied with making mistakes, as well as the fear of criticism and negative evaluations.
50	FMPS-Organization		The FMPS-Organization subscale assesses uncertainty about the correctness of one's actions and the tendency to seek reassurance from others.
51	FMPS-Personal Standard		The FMPS-Personal Standard subscale reflects the setting of high personal standards and the motivation to achieve them.
52	FMPS-ParentaL Exp. and Parental Criticism	Parental Expectation and Criticism	The FMPS-ParentaL Exp. and Parental Criticism subscale measures perceptions of high parental expectations and criticism and perceived levels of parental criticism and disapproval, particularly related to performance and achievement.

Table 6. Sample descriptives in variables of interest. The table presents descriptives of predictor variables at admission.

Descriptives questionnaires

	Mean (SD)	Minimum	Maximum
BIA-ECW	15.50 (8.34)	8.60	57.00
BIA-BCM	14.6 (4.73)	1.60	32.10
BIA-PA	4.34 (1.17)	1.30	7.80
BIA-ECWr	14.46 (3.88)	10.40	26.90
BIA-BCMr	15.38 (5.77)	1.90	38.90

BIA-PAr	4.35 (1.07)	1.50	6.30
EDI3-DT	22.29 (7.45)	0	28
EDI3-B	5.62 (7.83)	0	32
EDI3-BD	28.15 (7.24)	15	40
EDI3-EDRC	56.06 (16.48)	20	96
EDI3-LSE	15.93 (5.84)	1	24
EDI3-PA	15.23 (6.56)	2	28
EDI3-II	13.52 (6.82)	0	26
EDI3-IA	12.84 (5.83)	1	28
EDI3-ID	21.27 (8.50)	2	36
EDI3-ED	10.88 (7.20)	0	37
EDI3-P	11.76 (5.10)	0	24
EDI3-A	14.36 (5.78)	4	28
EDI3-MF	17.30 (7.34)	0	32
EDI3-IC	31.16 (11.84)	5	52
EDI3-IPC	26.37 (11.65)	3	51
EDI3-APC	32.02 (13.69)	2	63
EDI3-OC	26.12 (9.29)	5	51
EDI3-GPMC	133.00 (40.04)	46	237
EDI3-IN	12.37 (5.85)	0	27
EDI3-IF	1.77 (1.97)	0	10
EDI3-NI	26.93 (14.24)	1	82
SCL-90-Somatization	1.70 (0.96)	0	3.92
SCL-90-Obsession-Compulsivity	2.12 (0.86)	0.20	3.90
SCL-90-Interpersonal Sensitivity	2.14 (0.92)	0.22	3.89
SCL-90-Depression	2.44 (0.86)	0	3.92
SCL-90-Anxiety	2.08 (0.91)	0	3.70
SCL-90-Hostility	1.20 (0.91)	0	3.67
SCL-90-Phobic Anxiety	1.09 (0.85)	0	3.00
SCL-90-Psychoticism	1.29 (0.66)	0	3.00

SCL-90-Paranoid Ideation	1.85 (0.83)	0	3.67
SCL-90-SCL Global Index	2.23 (3.53)	0.13	31.19
BUT-GSI	3.05 (1.03)	0.44	4.79
BUT-WP	3.54 (1.09)	0.25	5.00
BUT-BIC	3.44 (1.17)	0.22	5.00
BUT-A	2.32 (1.14)	0	4.67
BUT-CSM	2.84 (1.32)	0	5.00
BUT-D	2.77 (1.42)	0	6.40
BUT-PST	21.25 (9.65)	2	37
BUT-PSDI	3.10 (0.72)	1.46	5.00
PGWBI-Anxiety	9.44 (5.31)	0	24
PGWBI-Depression	6.77 (4.25)	0	14
PGWBI-Positivity and Wellbeing	4.97 (3.31)	0	15
PGWBI-Self-Control	6.55 (3.28)	0	15
PGWBI-General Health	7.88 (3-09)	0	14
PGWBI-Vitality	7.41 (4.36)	0	19
PGWBI-Total Score	43.236 (18-73)	5	87
FMPS-Concern Over Mistakes	50.55 (11-42)	22	70
FMPS-Organization	24.56 (5.38)	7	30
FMPS-Personal Standard	24.65 (6-11)	7	35
FMPS-Parental Exp and Parental Criticism	19.72 (8.29)	8	40

Table 7. Evaluation metrics of the Dummy Classifier. The table shows the results for both binary classes.

Dummy classifier

	Class 0 (negative)	Class 1 (positive)
Accuracy	0.73	
AUC-ROC	0.50	
Precision	0.00	0.73
Recall	0.00	1.00
Specificity	/	0.00
F1-Score	0.00	0.84

Linear Discriminant Analysis (LDA)

	Class 0 (negative)	Class 1 (positive)
Accuracy	0.32	
AUC-ROC	/	
Precision	0.09	0.55
Recall	0.17	0.38
Specificity	/	/
F1-Score	0.12	0.44

Table 8. Multidisciplinary inpatient intensive rehabilitation treatment structure.

Activity	Frequency	Duration	Notes
Individual psychological consultation	1/week	45 minutes	Specialized psychologists provide support for psychological distress, and eating pathology
In-group psychotherapy	2/week	1 hour	Specialized psychologists provide support on a group basis working on the disease, trauma, psychological distress, and eating pathology
Dance Movement Therapy	1/week	1 hour	A specialized psychologist provides an intervention based on *Dance Movement Therapy* to improve body image perception
Body image therapy	2/week	30 minutes	Specialized physiotherapists provide interventions to work on body image distortion
Physiotherapy	5/week	30 minutes	Specialized physiotherapists provide tailored physiotherapy treatments
Low intensity physical activities	3/week	30 minutes	Specialized physiotherapists provide gentle gymnastic sessions

Nutritional counselling - individual	1/week	30/45 minutes	Patients received a personalized dietary therapy with progressive caloric intake adjustments throughout her hospitalization. This approach was aimed at addressing the patient's restrictive eating patterns and facilitating gradual weight gain or arresting further weight loss. The program included regular individualized dietary monitoring and consultations with a dietitian, as well as the use of nutritional supplements (e.g., Meritene cream and Endodien), which were tailored to meet her specific caloric and nutritional needs. The dietary strategy also involved educational courses on nutrition for patients with eating disorders, to promote a better understanding of the relationship between nutrition, weight gain, and overall well-being.
Nutritional counseling - group	1/week	1 hour	Group intervention provided by specialized dietician relative to healthy eating, general nutrition, and core food groups
Assisted meals	breakfast, snack, lunch, snack, dinner, snack	30 minutes to 1 hour	Participants eating all together supervised by a dietician

Therapeutic Immersion: A Single-Subject Study on Virtual Reality Multisensory Experiences for Mitigating Body Disturbance in Anorexia Nervosa

2. Methods

2.1 Protocol

6 sessions + 1 pre-assessment, 1 post-assessment and 1 follow-up (after 1 week) **Twice per week, 60 minutes for each session**		
Pre-Assessment measures*/ ****	Technology familiarization and procedure presentation.	• Questionnaires administration • Presentation of the procedure/ technology
Session 1	Stice and Presnell (2007) incorporated cognitive dissonance in mirror exposure sessions in an eating disorders prevention program. In their CD ME, participants described positive aspects of their physical, emotional, intellectual, and social qualities while looking at their image in a mirror. For an individual with body dissatisfaction, the act of complementing his or herself while looking in the mirror should induce cognitive dissonance.	• Embodiment procedure from first-person perspective (visuo-tactile stimulation for 90 seconds; Serino et al., 2016) – the body model has a BMI equal to 18.5 • Embodiment measures through a VAS (Porras-Garcia et al., 2021) • Cognitive Dissonance Mirror Exposure (CD ME; Luethcke et al., 2011): The body exposure task began by asking the patients to describe the body parts of their virtual body (starting from the head, shoulders, arms, hands, chest, stomach, waist, hips, thighs, lower legs, and then the feet). The clinician invited to participants describe positive aspects of their physical, emotional, intellectual, and social qualities while looking in the mirror. • Relaxation: the last 5 minutes of the session were dedicated to helping the patients reduce their anxiety or any other sort of discomfort that they might experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).
Session 2	The Functionality-Focused Mirror Exposure Procedure (FME) procedure is based on the empirically supported body-functionality-focused body image intervention Expand Your Horizon (Alleva et al., 2015), which involves writing prompts about body functionality. Additionally, the current FME procedure expanded on	• Embodiment procedure from first-person perspective (visuo-tactile) • Embodiment measures through a VAS • Functionality-Focused Mirror Exposure Procedure (FME; Walker & Murray, 2022) – below the script of the experience** • Relaxation: the last 5 minutes of the session were dedicated to helping the

	the FME script described in Brooks and Walker (2017) to increase the FME's duration and was based on an empirically supported mindfulness-based ME script. Similar to other ME procedures, the FME leads participants to describe body parts, focusing on specific body parts and what they enable the individual to do and experience, with prompts that include physical and creative skills, physical, mental, and emotional capacities, interactions with nature (e.g., viewing beautiful scenery), and interpersonal relationships (e.g., speaking with a friend, hugging a family member or a pet). Patients were instructed to focus on facets of functionality for which they were grateful. They were also instructed not to avoid uncomfortable feelings or thoughts, but to gently refocus on the FME instructions.	patients reduce their anxiety or any other sort of discomfort that they might experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).
Session 3	This session continues and repeats the work started in the previous one.	• Embodiment procedure from first-person perspective (visuo-tactile) • Embodiment measures through a VAS • Functionality-Focused Mirror Exposure Procedure (FME) – 13 minutes ** • Relaxation: the last 5 minutes of the session were dedicated to helping the patients reduce their anxiety or any other sort of discomfort that they might experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).
Session 4	This session continues and repeats the work started in the previous one.	• Embodiment procedure from first-person perspective (visuo-tactile stimulation for 90 seconds) • Embodiment measures through a VAS • Functionality-Focused Mirror Exposure Procedure (FME) – 13 minutes ** • Relaxation: the last 5 minutes of the session were dedicated to helping the patients reduce their anxiety or any other sort of discomfort that they might

		experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).
Session 5	This session continues and repeats the work started in the previous one.	● Embodiment procedure from first-person perspective (visuo-tactile) ● Embodiment measures through a VAS ● Functionality-Focused Mirror Exposure Procedure (FME) – 13 minutes ** ● Relaxation: the last 5 minutes of the session were dedicated to helping the patients reduce their anxiety or any other sort of discomfort that they might experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).
Session 6	This session is equal to the first one to reinforce the work done in the previous meetings.	● Embodiment procedure from first-person perspective (visuo-tactiles; Serino et al., 2016) ● Embodiment measures through a VAS (Porras-Garcia et al., 2021) ● Cognitive Dissonance Mirror Exposure (CD ME; Luethcke et al., 2011): The body exposure task began by asking the patients to describe the body parts of their virtual body (starting from the head, shoulders, arms, hands, chest, stomach, waist, hips, thighs, lower legs, and then the feet). The clinician invited to participants describe positive aspects of their physical, emotional, intellectual, and social qualities while looking in the mirror. ● Relaxation: the last 5 minutes of the session were dedicated to helping the patients reduce their anxiety or any other sort of discomfort that they might experience during the body exposure task. The patients were immersed in relaxing VR environments (i.e., waterfalls, forests, or beaches).

Post-Assessment measures (1st follow up)* / **		• Questionnaires administration • Debriefing
Post-Assessment measures (2nd follow up)*		• Questionnaires administration

2.2 *Pre-Assessment, Post-Assessment, and Three Months Follow-Up Measures

Anorexia Nervosa Symptomatology

- *Eating Disorder Inventory -III (EDI-III; Clausen et al., 2011)* – The EDI-III is a self-report measure to assess psychological characteristics or features that have been demonstrated to be clinically significant in patients affected by Eating Disorders. It consists of 91 items organized into 12 primary scales: three eating disorder-specific scales (Drive for Thinness—DT; Bulimia—B; Body Dissatisfaction—BD) and nine general psychological scales (Low Self-Esteem—LSE; Personal Alienation—PA; Interpersonal Insecurity—II; Interpersonal Alienation—IA; Interoceptive Deficits—ID; Emotional Dysregulation—ED; Perfectionism—P; Asceticism—A; Maturity Fears—MF) that are highly relevant to, but not specific to, Eating Disorders. Each item on the EDI-III is rated on a 6-point response scale ranging from Always (1) to Never (6), with higher scores indicating more severe symptoms or psychological distress. The reliability coefficients of the scales range from 0.83 and 0.90, and test–retest reliability coefficients for the various composite scales are between 0.84 and 0.87. The Italian version of EDI-3 has demonstrated very good test–retest reliability, cross-informant agreement, and good discriminating validity (Cinelli et al., 2020).
- *Body Mass Index (BMI)* - The change in body weight was evaluated each week by weighing the patient and calculating her BMI.

Body -Self Relationship

- *The Body Uneasiness Test (BUT; Cuzzolaro et al., 2006)* – The BUT is a self-report questionnaire to measure body-related uneasiness. It consists of two main factors. The BUT-A consists of four subscales and a global severity index (GSI): Weight Phobia (WP—fear of being or becoming fat), Body Image Concerns (BIC—worries related to physical appearance), Avoidance (A—body image-related avoidance behavior), Compulsive Self-Monitoring (CSM—compulsive checking of physical appearance), and Depersonalization (D—detachment and estrangement feelings toward the body). Here respondents have to rate how much the 34 sentences represent them ranging from 0 (Never) to 5 (Always). BUT-B instead looks at specific worries about body parts or functions and consists of two subscales: the Positive Symptom Total (PST – the number of body areas that cause distress and discomfort) and Positive Symptom Distress Index (PSDI – the average rating of those items constituting PST). Here respondents have to rate how much they hate 37 different body areas from 0 (Never) to 5 (Always). Then, whereas BUT-A focuses on the whole body, BUT-B assesses uneasiness related to specific body areas. Higher scores in BUT-A and BUT-B index higher body-related concerns and distress. The Italian version of the instrument shows good reliability coefficients and a factorial structure congruent with the operative definition of the construct (Cinelli et al., 2020).
- *Body Appreciation Scale-2 (BAS-2; Tylka & Wood-Barcalow, 2015)* – The BAS-2 is a self-report measure of body appreciation, acceptance, favorable opinions, and respect. It consists of 10 items to which respondents respond by rating from 1 (Never) to 5 (Always) the extent to which the statements describe their body-self relationship. Higher scores indicate a greater appreciation of one's own body. The measure has been validated in Italian and shows good psychometric properties (Casale et al., 2021).

- *Physical Appearance State and Trait Anxiety Scale – PASTAS (Thompson, 1999)* - The complete version of PASTAS comprises two self-report scales measuring weight-related and non-weight-related anxiety. In this study, the Trait-Weight Scale (W) was used in line with previous research (Porras-Garcia et al., 2020). It requires respondents to the level of anxiety related to different 16 body features and areas from 0 (Not at All) to 4 (Exceptionally So). Higher scores correspond to higher body appearance anxiety. In previous research, the scale was used in Italian samples (e.g., Malighetti et al., 2020).
- *Objectified Body Consciousness Scale (OBCS; McKinley & Hyde, 1996)* – The OBCS is a self-report questionnaire assessing Objectified Body Consciousness. It is a 24-item questionnaire on a 7-point Likert scale (from 1 = strongly disagree to 7 = strongly agree) to evaluate the three main components of OBC: body surveillance, body shame, and control beliefs. Examples of items are "I rarely think about how I look", "I would be ashamed for people to know what I really weigh", and "I can weigh what I'm supposed to when I try hard enough". Greater scores index a higher objectification level. We used this questionnaire since it has been validated in the Italian language, showing good psychometric properties and the same three-factor structures as the original English version (Dakanalis et al., 2017).

Body Perception

- *Figure Rating Scale (BIAS-BD; Garner et al., 2008)* - The BIAS-BD is a depictive body-image assessment tool comprising 17 gender-specific contour-line drawings based on known anthropometric bodily dimensions. The drawings' body weights range from 60% below the established average to 140% over it. A 5% shift in body weight was represented by differences in figural drawings. Respondents are asked to select the figure that matches their current and ideal body shape and size.

- *Body Image Virtual Reality Assessment (BIVRA; Brizzi et al., 2024)* – BIVRA is an immersive virtual reality body image rating scale consisting of 7 body stimuli ranging from underweight (1) to overweight (7). Respondents are at the center of a virtual room, and they are surrounded by virtual bodies (Figure 2). Here, similarly to BIAS-BD, they must select the stimulus that best matches their current and ideal body shape. Unlike BIAS-BD, the system presents the ideal/real choice task five times, manipulating the aesthetic features of the body models (i.e., eye and hair color) while holding body parameters constant. This allows for assessing body percentual accuracy (i.e., the ability to select the virtual body with a BMI close to the real one) and body dissatisfaction (i.e., the difference between the ideal and real virtual body) as standard figure rating scales while avoiding explicit measures biases. BIVRA's ability to assess body perception and body satisfaction has been demonstrated in previous research (Brizzi & Romano, 2022).
- *Affordance Estimation Procedures in Virtual Reality (APE-VR)* – The Aperture Task (Irvine et al., 2019) is a metric task designed to assess body schema, namely the sensorimotor representation of one's body that is used to plan or guide actions. It requires participants to adjust the aperture of a door-like aperture to determine the minimal aperture they need to pass through without rotating their shoulders or hips. The APE-VR was proposed in a virtual environment where respondents had to adjust the opening of a virtual door four times, starting with the door fully closed or open. The virtual version has been previously observed to correlate with real door aperture estimation (Brizzi & Romano, 2022; *Figure 2*).

BIVRA	**APE_VR**
Participants are immersed in a virtual room where they are surrounded by 7 different body models varying in BMI. The task requires selecting the virtual body that better matches the ideal and current body size and	Participants are immersed in a virtual room in front of a door. The task requires adjusting the sliding door to determine the minimal aperture they need to pass through without rotating their shoulders. The task is proposed

shape five times respectively. The order of body presentation is randomized across trials. In each trial, aesthetic features of the body - but the body parameters - are manipulated.

four times: two times starting with a closed door, and two times starting with a completely open door.

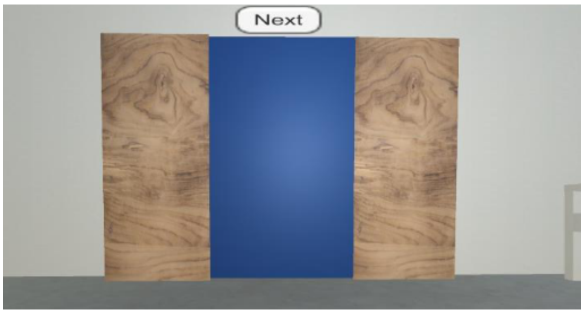

Figure 2. Scene from BIVRA System (Brizzi et al.,2024) and APE_VR (Brizzi & Romano, 2022).

- *Embodiment Strength* - Body illusion strength was assessed after 90 seconds of synchronous multisensory stimulation (Serino et al., 2019) at the beginning of the protocol. We used visuo-tactile synchronous stimulation where the patient sees a virtual ball touching the virtual body's abdominal area while the experimenter applies the same stimulation on her physical body with the controller. Embodiment was assessed using a visual analog scale (VAS) from 0 to 100 proposed directly inside the virtual environment (Porras-Garcia et al., 2020). The question *was Indicate on a scale from 0 (not at all) to 100 (totally) how much you agree with the following statement: "I perceived the virtual body as if it were my own"*.

Virtual Reality Setup

The patient wore the VR headset (Oculus Quest 2) and had to handle one of the controllers while the other controller was managed by the experimenter. The motion tracking system was developed using Azure Microsoft Kinect to synchronize the patient's and the artificial body's movements (https://azure.microsoft.com/it-it/products/kinect-dk).

The virtual body was created using Make Human software (https://www.makehumancommunity.org) and was designed based on prior studies to represent a normal-weight body (*Figure 3*; Di Lernia et al., 2023; Keizer et al., 2016; Serino et al., 2017). The virtual scenario was developed in Unity 3D (https://unity.com). The virtual environment was a simple room with a large mirror on the front wall and no furniture of any kind. The mirror was large enough to reflect each limb of the body without showing the face and was placed approximately 1.5m in front of the user's position (Porras-Garcia et al., 2020).

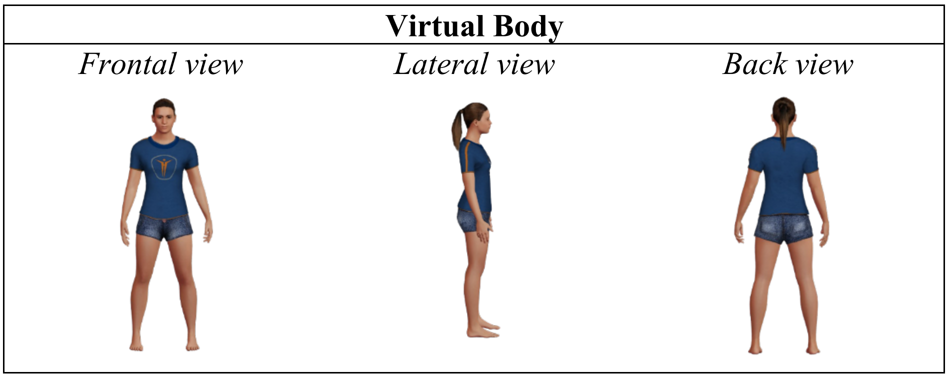

Figure 3. Virtual body measures. Waist-to-height ratio equal to 0.4606; Front chest distance = 26.58 cm; Bust circumference = 82.99 cm; Underbust circumference = 66.57 cm; Waist circumference = 73.95 cm; Nape to waist = 38.34 cm; Waist to hips = 19.01 cm; Shoulder distance = 14.14 cm; Age = 25, Muscle = 50%, Height = 160.54 cm; Hips = 96.72. These parameters were based on previous research (Di Lernia et al., 2023; Keizer et al., 2016; Serino, et al., 2017).

**** Functionality-Focused Mirror Exposure Procedure (FME) – Script**

Now I invite you to stand in front of this mirror. I will ask you to look carefully at different parts of your body, starting from the upper parts and then gradually working your way down. I'm going to ask you to focus on what each part of your body has allowed you to do in the past, and what it allows you to experience every day. In this exercise, you will be accompanied by my voice.

Your experience today may be different from the times you've looked in the mirror at home or elsewhere. In the past, exposure to the mirror may have been brief. In addition, you may have focused primarily on your "imperfections," i.e., those parts of your body that you don't like, fostering self-critical thoughts while looking at your reflection in the mirror. Because of our typical and habitual ways of examining ourselves when we are in front of the mirror, it is likely that we will experience critical emotions and thoughts, even during the exercise we will do together. That's okay, that's completely acceptable. While it can be unpleasant, research suggests that this discomfort is short-lived and that mirror exposure can be beneficial over time, even for those who experience discomfort in the process.

The purpose of this procedure is not to avoid or try to suppress your emotions. In case emotions and thoughts arise that make you feel uncomfortable, try to notice them, and then try to redirect your attention to my voice and instructions: think of all the positive things that your body has allowed you and allows you to do and experience.

The goal of this exercise is to help you recognize and appreciate what your body does for you in your daily life.

Start by making sure you see your entire body in the mirror.

Now start looking downwards and stopping to look at your chest. Think not only about your outward appearance but about what's under your skin. [Pause]

Think about the vital organs that are housed in your chest cavity. [Pause]

Can you hear your heartbeat? [Pause] Do you feel your lungs expand and contract with every breath you take? [Pause] Think of the ribs, which help protect those vital organs. [Pause] Think about how your heart rate and breathing speed help you handle physical challenges, giving your muscles more oxygen when needed, and how they slow down to allow you to be calm when you're at rest. [Pause]

What other internal organs that help you survive are protected by your chest? [Pause]

Now, move your eyes a little further downwards, at the level of your stomach. [Pause] How are you feeling? [Pause] Take some time to think about the function of your stomach. [Pause] What does it allow you to do regularly? [Pause] How does it keep you healthy? [pause] How do you feel when you respect the messages he sends you? [Pause] How do you feel when you ignore what your stomach is telling you? [Pause]

Think about how your stomach helps break down basic nutrients, so you can have the vitamins and minerals your body needs, how it helps you break down the amino acids that form proteins that are essential for muscles and other organs in the body, how it allows you to break down fats for hormonal function to ensure brain function, and how it helps you break down the glucose that provides the body and brain with fundamental and necessary energy. [Pause]

Now look at your shoulders and arms. [Pause] What do these body parts help in your daily life? [Pause] Do you have hobbies or activities such as a sport you like to do where you rely on your arms and shoulders? [Pause]

Now shift your attention to your lower arms, wrists, hands, all the way to your fingertips. [Pause] What have these parts, designed for dexterity, fine movements, and touch, allowed you to do and still do? [Pause] How many items have you picked up and put down? [Pause] How have these body parts helped you in the past to carry out your daily activities? [Pause] Have you typed, written, or texted someone you cared about? [Pause]

Did they allow you to play an instrument or play a game? [Pause] Or draw or paint? [Pause] Did you build anything? [Pause] Have you opened jars and containers for soap, and toothpaste, which have helped you take care of your body? [Pause]

Now, think about the pleasant feeling you had when you held something you held in your arms, hands, and fingertips. What has allowed you to appreciate your sense of touch? [Pause] Try to imagine the sensation of running your hand over a soft, fluffy surface, whether it's your pet's, a loved one's hair, or a beloved object. [Pause]

Now think about all your arms: from your shoulder to your fingertips [Pause] How do they work together? [Pause] Do they work together in perfect harmony? [Pause] When you move your arms and hands, do you see how the parts move and work together? [Pause] What things did you enjoy doing that your arms, wrists, hands, and fingers allow you to do every day? [Pause].

Try to remember a positive time when you held a friend, family member, or pet, or caressed a loved one. [Pause].

Finally, direct your gaze towards your legs. We often criticise ourselves for our upper legs and thighs, rather than focusing on their strength and capacity. [pause]. Think about how many good things have enabled and enabled you to have strong legs [Pause]. What activities have helped and helped you do? [Pause]. For example, did they allow you to go for walks in nature, ride a bike, run, or ski? [Pause]. Did they allow you to take a dance class or just have fun dancing with your friends? [Pause]. Did they help you sit up and get up today? Did they help you to go up and down the stairs? [Pause]. Now think about how your legs work together, from your thighs to your knees, calves, ankles, and feet. [Pause]

Think about every bone, joint, ligament, and tendon that makes up your leg. [Pause] What do these body parts working together allow you to do? [Pause] Do they all serve a purpose together? [Pause] What do your legs allow you to do? [Pause] How do your legs support you? [Pause] Did your legs and feet carry you from one place to another? [Pause] To what safe and positive place did your legs and feet take you? [Pause]. Where did your legs and feet take you today? in the past? [Pause]. Where do you want those legs and feet to take you in your future? Try to imagine what your legs will allow you to do in the future, where they can take you and what life goals they will help you achieve [Pause].

Now, it is time to look at your whole body, to observe and appreciate all its parts, together [Pause].

We often spend time criticising our own bodies and judging the bodies of others for their appearance. We are socialized to this by others, such as family, friends and the media. However, this prevents us from taking the time to appreciate our body for what it can do for us, for the experiences it gives. Examining your body as a whole, think about the things you are grateful for that it has allowed you and will allow you to do and experience. [Pause]

Think back to a time when you felt proud of your body's capabilities or strength. What were you doing at that moment? [Pause] What are you grateful to your body for today? [Pause] What will you be able to do tomorrow? [pause] What about next week? next year? [Pause] Focus on a moment when you showed kindness to your body. [Pause] How did it make you feel to take care of yourself? [Pause] Now, try to imagine a future version of yourself: what goals can your body allow you to achieve? [Pause] What characteristics or habits do you think this future self that achieves all these goals might have?

Qualitative data – Briefing and debriefing

Pre-Assessment

- **What do you expect from this experience?**
- **Do you think using virtual reality will help improve your relationship with your body?**
- **Have you ever used virtual reality before?**

Post - Final session

- **How did it go?**
- **How did you feel?**
- **Do you have any suggestions?**
- **Do you think virtual reality will help improve your relationship with your body?**
- **Would you participate in another protocol like this?**

Table 1. Multidisciplinary therapeutic-rehabilitation program (Brusa et al., 2023).

Standard therapeutic-rehabilitation program	
Activity	*Goal*
Individual dietary programme	Personalized diet aimed at body weight restoration and monitoring of eating behaviors.
Nutritional educational	Psychoeducation sessions about the importance of eating, food consumption, and calories.
Individual psychological sessions	Sessions aim to make the patient aware of her condition, recognizing the aspects that contributed to the onset of symptoms and understanding the necessary steps to facilitate change.
Physical activity	Walks according to the DCA ergometer and postural gymnastics once a week.
Educational groups	Psychoeducational activity, motivational group, therapeutic group, reading group.
Psychiatric evaluations	Weekly psychiatric evaluation during the multidisciplinary visit.
Pharmacological therapy	Citalopram 40 mg and Olanzapine 2.5 mg

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