

Aline Tiemann

I've Gut a Feeling: Relevance and Trainability of Gastric Interoception in the Context of Eating Behavior



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I'VE GUT A FEELING: RELEVANCE AND TRAINABILITY OF
GASTRIC INTEROCEPTION IN THE CONTEXT OF EATING BEHAVIOR

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*“there is a conversation
happening inside you
pay deep attention
to what your inner world
is saying”*

— Rupi Kaur, *Home Body*, p. 154

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Abstract

Eating disorders (EDs) are associated with high morbidity, mortality, and chronicity, yet treatment efficacy has plateaued under current approaches. Disordered and maladaptive eating behaviors often precede the onset of eating disorders, and targeting underlying factors may offer a promising approach. Interoception, defined as the sensing of internal bodily signals, has been proposed as one such underlying factor contributing to disordered eating. Interoception is multidimensional, including the sensing, interpretation, and integration of internal bodily signals. In particular, the sensing of signals originating from the stomach (i.e., gastric interoception), such as hunger, satiety, and fullness are highly relevant for eating behavior. However, gastric interoception remains understudied in its multidimensional aspects (including physiological, behavioral and self-report measures), with most research focusing solely on self-report. The goal of **Study 1** was to examine the relevance of multidimensional gastric interoception for maladaptive eating behavior in a sample comprising healthy individuals, individuals with bulimia nervosa (BN) and binge-eating disorder (BED). Results indicated that multidimensional gastric interoception, assessed through physiological, behavioral, and self-report measures, was the strongest predictor of maladaptive eating behavior (emotional, external and restrained eating). Notably, the gastric attribution of interoceptive sensations (i.e., negative affect after water ingestion) emerged as the most significant predictor for emotional, external and restrained eating.

Additionally, gastric motility has been proposed as a key mediator of hunger and satiety, with individuals with EDs exhibiting altered gastric motility patterns. Interventions aimed at regulating gastric motility, such as gastric biofeedback using electrogastrogram (EGG), hold promise in the context of gastric interoception and eating behaviors. However, this approach remains largely understudied, with only one known study to date (Stern et al., 2004). Therefore, the aim of **Study 2** was to develop a novel EGG-based gastric biofeedback paradigm. We assessed its feasibility, effectiveness, and subjective experience in a healthy sample. We compared three groups: a virtual reality (VR) group, a 2D screen-based group, and a control group (CG). Results demonstrated technical feasibility and positive evaluations of the gastric biofeedback paradigm. In **Study 3**, we examined the downstream effects of the gastric biofeedback paradigm between the VR, 2D and CG. We assessed the effects of gastric biofeedback on multidimensional cardiac and gastric interoception (physiological, behavioral, and self-report), general self-reported interoception, eating behavior (emotional, external, restrained, and intuitive eating), and ED symptoms. Results indicated promising effects of the

2D condition on satiation and fullness perception, body listening, and intuitive eating. Overall, the findings of this thesis suggest that gastric interoception plays a key role in eating behavior and that gastric biofeedback is both feasible and well accepted. The 2D condition, in particular, appears promising for enhancing satiation and fullness perception, body listening, and intuitive eating. It also offers a potentially accessible option for home-based use and early intervention. Future research should further develop gastric biofeedback and evaluate its clinical utility in populations with EDs.

Abbreviations

2D	2D Group (television)
AN	Anorexia Nervosa
B-FCC	Body-Food Choice Congruency
BE	Binge-Eating group
BED	Binge-Eating Disorder
BMI	Body Mass Index
BN	Bulimia Nervosa
CG	Control Group
CNS	Central Nervous System
cpm	Cycles Per Minute
DALYs	Disability-Adjusted Life Years
DASS	Depression, Anxiety, Stress Scale
DEBQ	Dutch Eating Behaviour Questionnaire
DSM-V	Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition
ECG	Electrocardiogram
EDE-Q8	Eating Disorder Examination Questionnaire, short 8-item version
EDIP-Q	Eating Disorder-specific Interoceptive Perception Questionnaire
EDs	Eating Disorders
EE	Emotional Eating
EEG	Electroencephalogram
EGG	Electrogastrogram
EMM	Estimated Marginal Means
EX	External Eating
FFT	Fast Fourier Transform
fMRI	Functional Magnetic Resonance Imaging
Full ml	Additional water volume until maximum fullness (ml)
GLP-1	Glucagon-like peptide-1
HBCT	Heartbeat Counting Task
HEP	Heartbeat-Evoked Potential
HFnu	High Frequency normalized units
HP	Healthy Participants
HR	Heart Rate
HRV	Heart Rate Variability
IES-2	Intuitive Eating Scale 2
IPQ	Igroup Presence Questionnaire
LASSO	Least Absolute Shrinkage and Selection Operator
MAE	Mean Absolute Error
MAIA-2	Multidimensional Assessment of Interoceptive Awareness questionnaire 2
MBDF	Multidimensional Mood Questionnaire
NA	Negative Affect
PAC	Phase-Amplitude Coupling
POMP	Percent of Maximum Possible

RE	Restrained Eating
RHSC	Reliance on Hunger Satiety Cues
RMSE	Root Mean Squared Error
RMSSD	Root Mean Square of Successive Differences
Sat ml	Ingested water volume until satiety (ml)
Total ml	Total ingested water volume (ml)
UAQ	User Acceptance Questionnaire for Biofeedback
UPE	Unconditional Permission to Eat
VR	Virtual Reality
VRSQ	Virtual Reality Sickness Questionnaire
WLT-II	Two-step Water Load Test

List of publications

This cumulative dissertation is based on the following three publications

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Publication 3

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1 INTRODUCTION

“The stomach is a muscle, and that muscle initially has to relax [...] to receive the food.”

— K.L. Koch, 2020

Eating disorders (EDs) represent a major public health concern, characterized by high morbidity, mortality, and chronicity (Arcelus et al., 2011; Fichter & Quadflieg, 2016; Herpertz-Dahlmann, 2015; Sparti et al., 2019; K. Wang et al., 2024). EDs are increasingly prevalent and remain difficult to treat, with treatment outcomes having reached a plateau under traditional treatments (Alharbi et al., 2024; Leichsenring et al., 2022; Linardon et al., 2016, 2017; Schuler et al., 2024). This highlights the urgent need to shift focus toward early intervention and prevention, particularly by addressing disordered and maladaptive eating behaviors that often precede the onset of EDs (Herpertz-Dahlmann, 2015; Leichsenring et al., 2022; Nolan et al., 2023). A critical step in this direction involves identifying and targeting underlying mechanisms that contribute to disordered and maladaptive eating (Leichsenring et al., 2022; Munsch et al., 2025). Interoception has been proposed as one such mechanism, with growing evidence suggesting its role in the development and maintenance of EDs and subclinical disordered eating behavior (Cusack et al., 2022; Herbert et al., 2013; Jacquemot & Park, 2020; Linardon et al., 2021; Martin et al., 2019; Robinson, Foote, et al., 2021). Interoception is a multidimensional concept, including the sensing, interpreting and integration of internal bodily signals (Khalsa et al., 2018). Multiple types of assessment (such as physiological, behavioral and self-reported) are necessary to comprehensively capture interoception (Suksasilp & Garfinkel, 2022). In particular, the sensing of signals originating from the stomach (i.e., gastric interoception), such as hunger, satiety and fullness seem to be highly relevant for eating behavior (Cusack et al., 2022; Janssen et al., 2011; Khalsa et al., 2022; Martin et al., 2019; Poovey et al., 2022; Smith et al., 2021; van Dyck, Vögele, et al., 2016). Yet, most research focuses on a single dimension (e.g., self-report) and studies assessing the multidimensional nature of interoception remain scarce. Additionally, gastric motility has been proposed as an

important mediator of hunger and satiety, and individuals with EDs show altered gastric motility patterns (Janssen et al., 2011; Ogawa et al., 2004; van Dyck et al., 2021). As a result, interventions to regulate gastric motility, such as gastric biofeedback, are promising in the context of gastric interoception and eating behaviors. However, gastric biofeedback trainings remain understudied, with only one attempt reported so far (Stern et al., 2004), which was conducted in a healthy sample. To address these research gaps, the present thesis investigates both the relevance and trainability of gastric interoception in the context of eating behavior (Stern et al., 2004).

1.1 Eating disorders and eating behaviors

Eating behaviors can range from healthy or intuitive eating, through disordered eating to EDs and a range of intermediate behaviors in between. In this chapter, we will first briefly outline the most common EDs, followed by a discussion of various maladaptive and adaptive eating behaviors.

1.1.1 Eating disorders

The most well-known types of EDs are anorexia nervosa (AN), bulimia nervosa (BN) and binge-eating disorder (BED). EDs constitute severe mental health conditions which are becoming increasingly prevalent, especially since the Covid 19-pandemic where individuals experienced an increase in stress, routine disruption and social isolation (McLean et al., 2022; Nolan et al., 2023; Schuler et al., 2024; F. Solmi et al., 2021; Todisco & Donini, 2021). EDs are associated with substantial health consequences, including elevated risks of depression, anxiety, suicide, substance use, and increased mortality, and they represent a significant contributor to disability-adjusted life years (DALYs; Alharbi et al., 2024; Arcelus et al., 2011; Fichter & Quadflieg, 2016; Herpertz-Dahlmann, 2015; Santomauro et al., 2021; K. Wang et al., 2024). Without timely and adequate treatment, EDs are often marked by high relapse rates and a tendency toward chronicity (Santomauro et al., 2021). With around half of affected individuals not reaching full or lasting recovery, there is a critical need for early identification and the development of accessible, low-threshold interventions (Herpertz-Dahlmann, 2015; Linardon et al., 2016, 2017).

These findings on ED treatment efficacy are consistent with a recent umbrella review and meta-analysis on psychotherapeutic and pharmacological interventions for mental health conditions (Leichsenring et al., 2022). Results show that response rates often stay at or below 50%, with mostly small to medium effect sizes, suggesting a plateau in treatment effectiveness

under traditional approaches (Leichsenring et al., 2022). The authors argue for a paradigm shift in treatment development and research (Leichsenring et al., 2022). Proposed directions include tailoring interventions to individual needs, testing innovative approaches and implementing preventive strategies (Leichsenring et al., 2022). One example demonstrating that meaningful progress is possible through prevention comes from recent findings on the prevention of psychosis in individuals identified as being at high clinical risk (Catalan et al., 2021; Estradé et al., 2022; Fusar-Poli et al., 2020). In support of early intervention more broadly, a large-scale meta-analysis showed that the majority of mental health disorders have their peak onset before the age of 21, emphasizing the critical importance of prevention and early treatment in youth (M. Solmi et al., 2022).

We are, therefore, at a point where a paradigm shift in mental health treatment and research is needed to move beyond the current plateau in efficacy (Leichsenring et al., 2022). There is growing recognition that relying solely on interventions for full-clinical disorders may be insufficient, particularly given the modest treatment outcomes for EDs (Herpertz-Dahlmann, 2015; Leichsenring et al., 2022; Linardon et al., 2016, 2017). This has led to growing support for earlier intervention strategies that target subclinical symptoms and individuals at risk before the onset of fully developed mental disorders (Leichsenring et al., 2022; Munsch et al., 2025). This requires a reorientation toward prevention, early detection, and the treatment of subclinical symptoms (Leichsenring et al., 2022). Developing low-threshold, accessible, and scalable interventions is, therefore, a critical step, both within the context of EDs and for mental health more generally. In the next section, we examine maladaptive and adaptive eating behaviors as key targets within this preventive framework.

1.1.2 Disordered Eating Behaviors

Disordered eating behaviors (such as binge-eating, restricting and compensatory behaviors) that do not meet diagnostic criteria of the DSM-5 (American Psychiatric Association, 2013) are a serious and increasingly widespread issue, particularly among young women, and are associated with an elevated risk for the later development of EDs (Alharbi et al., 2024; Nolan et al., 2023; Schuler et al., 2024). Disordered eating behaviors often appear early, are prevalent in the general population, and may serve as early indicators of emerging EDs (Glazer et al., 2019; Peschel et al., 2024; Schuck et al., 2018; Schuler et al., 2024; Sparti et al., 2019; van der Ster Wallin et al., 1994). Additionally, these behaviors have been linked to symptoms such as depression, anxiety, body dissatisfaction and low self-esteem (Hansson et al., 2016; Nagata et al., 2018; Paans et al., 2018). Early identification is thus essential, as treatment initiated in

earlier stages is generally linked to better outcomes (Duggan et al., 2025; Öst et al., 2024), and full-clinical EDs are more difficult to treat (Leichsenring et al., 2022). Next to EDs and subclinical disordered eating behaviors, which are still considered to be problematic (such as binge-eating, purging, excessive exercise, heavy restricting) there are other eating behaviors that may not meet diagnostic criteria or be clearly disordered, but are still potentially maladaptive and may contribute to overeating and binge-eating (Kärkkäinen et al., 2018; van Strien et al., 1986). Examples for such eating behaviors are emotional eating (i.e., eating in response to emotions), external eating (i.e., eating in response to external stimuli instead of internal hunger and satiety cues) and restrained eating (i.e., restricting food intake to control body weight; van Strien et al., 1986).

1.1.3 Emotional, External, and Restrained Eating (maladaptive eating behaviors)

Emotional, external and restrained eating are frequent in the general population, but are more pronounced in individuals with EDs and seem to contribute to overeating and binge-eating (Nagl et al., 2016; van Strien et al., 2005). There are three theories that are derived from emotional, external and restrained eating that have been proposed to explain the etiology of overeating: psychosomatic theory, externality theory and restraint theory (van Strien et al., 1986). According to psychosomatic theory, emotional eating occurs as a maladaptive response to stress, where food is used to regulate emotions (e.g., sadness, worry or anger), instead of a typical decrease in appetite when an organism is faced with stress (Harrist et al., 2013; van Strien et al., 1986). This may lead to food becoming comfort and negative emotions being interpreted as hunger (Braet et al., 2008; van Strien & Oosterveld, 2008). Externality theory proposes that certain individuals are more prone to eat in response to external stimuli (e.g., walking by a bakery and buying food despite lack of hunger) instead of listening to their internal hunger and satiety cues (van Strien et al., 1986). An example of how an increased reliance on external cues is developed is through early parental practices, such as pressuring children to eat despite satiety (van Strien & Oosterveld, 2008). Finally, restraint theory suggests that individuals who attempt to control their food intake will eventually fail to maintain the necessary cognitive control, leading to episodes of overeating (van Strien et al., 1986). In line with this, higher levels of emotional and restrained eating have been linked to a higher Body Mass Index (BMI; Dakanalis et al., 2023; Dong et al., 2016; Ergun et al., 2023; Snoek et al., 2013; van Strien et al., 2005). It remains uncertain whether restrained eating disrupts adaptive eating behaviors and internal hunger and satiety cues due to the goal of weight control, or whether individuals adopt dietary restraint because of strong food preferences and metabolic

factors that increase their risk of weight gain (Stroebe et al., 2013). Restrained eating has also been linked to the development of both emotional and external eating behaviors, which in turn have been associated with difficulties in emotion regulation (Harrist et al., 2013; van Strien et al., 1986). When restraint fails, it can trigger negative emotions that further promote emotional and external eating behavior (Braet et al., 2008). Across these forms of maladaptive eating behaviors, internal bodily signals are often misinterpreted, overlooked, or suppressed (van Strien et al., 2005; Young et al., 2017). Taken together, these perspectives suggest that disruptions in the processing of bodily signals (i.e., altered interoception) may play a central role in the development and maintenance of maladaptive eating behaviors.

1.1.4 Intuitive Eating

In addition to eating behaviors typically considered as maladaptive, there are also patterns of eating considered adaptive, such as intuitive eating (Tylka & Wilcox, 2006; van Dyck, Herbert, et al., 2016). Intuitive eating can be defined as eating in response to hunger and satiety cues, instead of emotional or external cues (Tylka & Kroon Van Diest, 2013; Tylka & Wilcox, 2006). Intuitive eating has been proposed to consist of four components, including *eating for physical rather than emotional reasons*, *unconditional permission to eat*, *reliance on hunger and satiety cues* and *body-food choice congruence* (i.e., to eat in accordance with one's bodily needs; Tylka & Kroon Van Diest, 2013). People who eat intuitively would, therefore, not diet, not eat for emotional reasons or use food as emotion regulation, but rather listen to their internal hunger and satiety cues (Tylka & Wilcox, 2006).

As outlined by Tylka and Wilcox (2006), intuitive eating is in line with approaches of positive psychology (Seligman & Csikszentmihalyi, 2000), highlighting the need to focus on strength when considering mental well-being, instead of solely focusing on the absence of psychopathology. Given the aforementioned challenges of mental health treatment in general and EDs specifically (Leichsenring et al., 2022), comprehensive prevention should, therefore, target early signs of disordered and maladaptive eating behaviors while also encouraging and sustaining healthy eating behaviors (Tylka & Wilcox, 2006). Intuitive eating has been found to be positively associated with well-being and negatively associated with ED symptomatology and disordered eating behaviors (such as binge-eating, restricting or compensatory behaviors), while still being a distinct construct from ED symptoms (Bennett & Latner, 2022; Denny et al., 2013; Linardon et al., 2021; Tylka & Kroon Van Diest, 2013; Tylka & Wilcox, 2006; van Dyck, Herbert, et al., 2016). In more detail, higher levels of intuitive eating have been linked to a range of adaptive psychological traits, including body appreciation, positive affect, mindfulness, self-

compassion, self-esteem, and overall well-being (Linardon et al., 2021; Linardon & Mitchell, 2017). It has also been associated with long-term weight stability (Giacone et al., 2024), whereas lower levels of intuitive eating have been observed in individuals with obesity (Joshi et al., 2024b). Intuitive eating tends to show inverse associations with BMI and general indicators of psychopathology, including stress, negative affect, anxiety, and depressive symptoms (Joshi et al., 2024a; Linardon et al., 2021). It is also negatively related to body dissatisfaction and maladaptive eating behaviors, such as emotional, external, and restrained eating, as well as ED symptoms, including binge-purge behaviors (Bennett & Latner, 2022; Denny et al., 2013; Linardon et al., 2021; Robinson, Marty, et al., 2021). Individuals with EDs typically report lower intuitive eating, with certain differences between diagnoses (Richard et al., 2019; van Dyck, Herbert, et al., 2016). For instance, individuals with BN and BED have been found to display lower scores of *eating for physical rather than emotional reasons* than individuals with AN, which is consistent with negative emotions as triggers for binge-eating episodes (van Dyck, Herbert, et al., 2016). Consistent with lower restricting behavior, individuals with BED have shown higher levels of *unconditional permission to eat* than individuals with AN and BN (van Dyck, Herbert, et al., 2016). Importantly, intuitive eating has been found to improve during the course of treatment (Koller et al., 2020). This suggests that additionally focusing on adaptive eating behaviors, and not solely on reducing maladaptive ones, may be valuable for treatment and relapse prevention in the context of EDs (Koller et al., 2020).

It is important to acknowledge that practicing intuitive eating is particularly challenging in today's obesogenic food environment, where highly processed foods activate the brain's reward system and may override internal cues of hunger and satiety (Calcaterra et al., 2023; Kelly et al., 2022; Rego et al., 2023). Despite these environmental barriers, higher levels of intuitive eating have been associated with healthier dietary patterns (Jackson et al., 2022). For instance, *greater body-food choice congruence* has been linked to improved diet quality, and *eating for physical rather than emotional reasons* has been positively associated with higher vegetable intake (Jackson et al., 2022). Intuitive eating may contribute to weight maintenance by reducing maladaptive behaviors such as overeating and emotional eating, through increased attunement to internal bodily signals (Herbert et al., 2013; Linardon et al., 2021; Robinson, Marty, et al., 2021).

This means that individuals who eat more intuitively tend to rely more on their internal bodily signals to guide eating behavior (Herbert et al., 2013; Linardon et al., 2021; Robinson,

Marty, et al., 2021). Sensing and interpreting internal bodily signals, known as interoception, has also been associated with various other adaptive and protective psychological processes, including stress regulation and emotion regulation (Davey et al., 2023; Nayok et al., 2023; Opdensteinen et al., 2021; Pollatos et al., 2015; Price & Hooven, 2018; Schultchen, Bayer, et al., 2019).

1.2 Interoception

Interoception encompasses the complex process through which bodily signals, such as those from the cardiac, respiratory, and gastrointestinal systems, as well as pain and touch, are sensed, interpreted, and integrated within the central nervous system (CNS; Khalsa et al., 2018). The term "interoceptive" was first introduced by Sherrington (1906) to differentiate sensations arising from internal organs (i.e., interoception) from proprioception (i.e., the sense of body position) and exteroception (i.e., the perception of external stimuli; Khalsa et al., 2018). Interoceptive processes occur across multiple organ systems, including the cardiac, respiratory, gastrointestinal, nociceptive, genitourinary, chemosensory, osmotic, thermoregulatory, visceral, immune, and autonomic domains (Khalsa et al., 2018). Interoceptive processes are essential for maintaining homeostasis and allostasis (predicting bodily needs) by allowing continuous monitoring and regulation of internal bodily states (Khalsa et al., 2018). Some of these processed are conscious, while others remain unconscious (Engelen et al., 2023; Khalsa et al., 2018).

Interoceptive signals originating from visceral organs, detected by chemoreceptors, mechanoreceptors, thermoreceptors, and others, are transmitted to the brain via afferent pathways, with the vagus nerve being the most prominent one (Berntson & Khalsa, 2021; Jänig, 1996). These pathways project into brainstem regions, such as the nucleus of the solitary tract, from where the signal is transmitted to subcortical, cortical and limbic regions, such as the thalamus, insula, hypothalamus and amygdala (for a review, see Berntson & Khalsa, 2021). Neuroimaging research consistently highlights the insular cortex, particularly its anterior portion, as a crucial region for the processing of interoceptive signals (Aguilar-Rivera et al., 2020; Critchley et al., 2004; Dobrushina et al., 2021; Hashimoto et al., 2015; Hassanpour et al., 2018; Kuehn et al., 2016; Simmons et al., 2013; X. Wang et al., 2019). These cortical projections contribute to the representation of internal bodily states, which may occur outside of conscious sensing or give rise to subjective experiences. Importantly, this communication is bidirectional. Recent findings emphasize the dynamic interaction between bottom-up (afferent) and top-down (efferent) signaling (Berntson & Khalsa, 2021; Dobrushina et al., 2021; Weng et al., 2021).

Incoming visceral input shapes top-down modulation (through networks or emotional and cognitive control), which in turn influences subsequent afferent processing (Berntson & Khalsa, 2021; Dobrushina et al., 2021; Weng et al., 2021). A concrete example given by Garfinkel & Eccleston (2025) is the following: hunger has been found to amplify the perception and appeal of food-related stimuli, highlighting how internal physiological states shape sensory processing, cognitive evaluation, and emotional experience. (Stoeckel et al., 2007; X. Weng et al., 2019).

Altered interoception, including heightened sensing, misinterpretation, or reduced accuracy in sensing internal states, is considered a cross-diagnostic factor in disorders such as depression, anxiety, substance use, somatic symptom disorders, schizophrenia, post-traumatic stress disorder, obsessive-compulsive disorder, suicidality, and emotion regulation difficulties (Adams et al., 2022; DeVille, Khalsa, et al., 2021; Keski-Rahkonen & Mustelin, 2016; Khalsa et al., 2018; Martin et al., 2019; Paulus & Stein, 2010; Pollatos et al., 2009; Reinhardt et al., 2020; Schaefer et al., 2014; Schuette et al., 2021; Schultchen, Zaudig, et al., 2019). Beyond diagnosis-specific observations, interoceptive impairments, along with associated neural alterations involving the mid-dorsal insula, have been proposed as a process that may contribute to shared vulnerability for psychiatric disorders across various psychiatric conditions (Brewer et al., 2021; Heim et al., 2023; Khalsa et al., 2018; Nord et al., 2021). Relatedly, interoceptive dysfunction has been suggested to underlie a general psychopathology “p-factor”, reflecting a continuum of symptom severity linked to disruptions in interoceptive neural pathways (Caspi et al., 2015; Murphy et al., 2017). One example of altered interoceptive processing is anxiety, where heightened sensitivity to bodily signals and their misinterpretation, such as perceiving normal heart rate changes as threatening, can intensify fear and contribute to panic symptoms (Garfinkel et al., 2020; Stein et al., 2021). Altered interoception also plays a central role in EDs where disrupted hunger and satiety perception are core symptoms (Cusack et al., 2022; Jacquemot & Park, 2020; Martin et al., 2019).

1.2.1 Interoceptive Dimensions and Modalities

In the past, different dimensions of interoception have often been used interchangeably, which has led to challenges in comparing research findings. Consequently, contemporary models distinguish between levels of processing within the CNS and peripheral nervous systems, as well as the methods by which interoception is measured, including physiological, behavioral, or self-report (Suksasilp & Garfinkel, 2022). Garfinkel et al. (2015) introduced a three-step model of interoception, comprising *interoceptive accuracy* (the actual ability to perceive bodily signals, measured through behavioral tasks), *interoceptive sensibility* (now known as

interoceptive self-report, i.e., the self-reported ability to perceive bodily signals, typically assessed with questionnaires), and *interoceptive awareness* (metacognitive insight into the correspondence between accuracy and self-report; now known as *interoceptive insight*). This model has since been refined and extended to include additional physiological and neural dimensions (see Table 1; Suksasilp & Garfinkel, 2022). In this thesis, we adopt the updated terminology proposed by Suksasilp & Garfinkel, 2022; see their publication for an overview), with two exceptions: we include *interoceptive sensitivity* for the perception of gastric signals, as defined by Schulz and Vögele (2024; see Table 1), and we refer to the strength of afferent signals as *objective physiological states*, as proposed by Forkmann et al. (2016). Forkmann and colleagues (2016) added *objective physiological states* as a fourth dimension in addition to the original three-step model by Garfinkel et al. (2015). They propose that interoceptive sensations depend on the nature and strength of the corresponding physiological signals (Forkmann et al., 2016). Simply put; to perceive a heartbeat, the heart must produce a signal in the first place. In the cardiac domain, electrocardiogram (ECG) is most commonly used to measure heart rate (HR) or heart rate variability (HRV). In the gastric domain, electrogastrogram (EGG) can be used to extract different gastric power bands (bradygastria, normogastria and tachygastria) as the percentage of the total EGG power band within each frequency range (Wolpert et al., 2020). In this thesis, we will focus on the following dimensions, marked **in bold** in Table 1: *objective physiological states (cardiac and gastric)*, *cardiac interoceptive accuracy*, *gastric interoceptive sensitivity*, *interoceptive self-report (cardiac and gastric)*, *attribution of interoceptive sensations (gastric)* and *interoceptive insight (cardiac and gastric)*. For an overview of interoceptive dimensions and their definitions, see Table 1.

Table 1

Interoceptive dimensions and their definition

Dimensions	Definition
Neural representations	Central nervous activity associated with interoceptive processing, including the coupling of central activity with afferent physiological signals.
Strength of afferent signals, here: objective physiological states (Forkmann et al., 2016)	The strength and nature of signals originating from the periphery that communicate interoceptive states to the central nervous system (e.g., cardiac or gastric activity).

Table 1 (continued)

Dimensions	Definition
Preconscious impact of afferent signals	The effect of fluctuations in afferent signals on their central neural representation and the processing of external stimuli.
Interoceptive accuracy	Correct and precise monitoring, i.e. the correspondence between objectively measured physiological events and individuals' reported experience of those events, ascertained through behavioral tests (e.g., a heartbeat counting task)
Interoception sensitivity	Minimal intensity of an interoceptive signal required for it to be consciously detected, e.g., a person's sensitivity to gastric signals on the two-step water load test (van Dyck et al., 2016) – meaning their individual satiation or fullness threshold.
Self-report and interoceptive beliefs	Measures of beliefs, both available to and beyond conscious access, concerning individuals' interoceptive sensations and experiences. Includes self-report measures, such as questionnaires, confidence ratings, and task-based measures of (implicit) prior beliefs thought to influence interoceptive perception.
Interoceptive insight	Metacognitive evaluation of experience/performance e.g., the correspondence <i>interoceptive accuracy/sensitivity</i> and <i>interoceptive self-report</i>, e.g., via difference scores of heartbeat detection accuracy and confidence, or using individual satiation thresholds (amount of water drunk until satiation) and corresponding self-reported rating of satiation (Suksasilp & Garfinkel, 2022; van Dyck, Vögele, et al., 2016).
Interoceptive attention	Observing internal bodily sensations. Includes purposefully attending to interoceptive sensations when instructed, as well as habitual tendency to attend to interoceptive sensations, relative to exteroceptive sensations.
Dimensions	Definition
Attribution of interoceptive sensations	Interpretation of interoceptive sensations and their causes, such as perceived threat (e.g., negative affect after drinking certain amounts of water).

Note. Adapted from “Towards a comprehensive assessment of interoception in a multi-dimensional framework” by C. Suksasilp and S. N. Garfinkel, *Biological Psychology*, 168, 108262, p.2, 2022, Copyright 2022 by Elsevier. Dimensions used in this dissertation are marked in bold.

1.2.2 Cardiac and Gastric Interoception

Not only were different interoceptive dimensions used interchangeably in the past, cardiac interoception was often used as a proxy for general interoception (Crucianelli & Ehrsson, 2023). This was due to the ease of measuring cardiac signals and also because early research suggested that the ability to perceive signals from different organ systems was closely related (Herbert, Muth, et al., 2012; Whitehead & Drescher, 1980). However, more recent research shows that the abilities to perceive different organ systems only weakly correlate (Ferentzi et al., 2018; Iatridi et al., 2021; van Dyck, Vögele, et al., 2016), and that performance in one interoceptive domain does not necessarily predict performance in another (Prentice & Murphy, 2022). This is supported by recent findings from cardiac and gastric interoception, which show distinct patterns of neural processing, using electroencephalogram (EEG) and magnetic resonance imaging (MRI; Haruki & Ogawa, 2023; Todd et al., 2021). This underscores the need to differentiate not only between interoceptive dimensions, but also organ systems.

In the context of EDs and eating behavior, cardiac and gastric interoception seem to play important roles. Cardiac interoception has been linked to emotion processing, an important factor in the development and maintenance of EDs and maladaptive eating behaviors such as binge-eating (Aldao et al., 2010; Bernatova & Svetlak, 2017; Dingemans et al., 2017; Goossens et al., 2016; Lavender et al., 2015). Cardiac interoception has also been linked to emotion regulation, as cardiac signals may influence how emotional states are perceived (Critchley & Garfinkel, 2017; Greenwood & Garfinkel, 2025; Lazzarelli et al., 2024; Pollatos et al., 2005). Indeed, better abilities in heartbeat detection have been associated with stronger emotional experiences (Pollatos et al., 2005). In turn, poorer cardiac interoception has been linked to alexithymia (Brewer et al., 2016; Shah et al., 2016). The association between emotions and perception of bodily signals has a long history, with roots in theories such as those by Damasio, Schachter and Singer, and Lange and James (Damasio, 1994, 1999; Lange & James, 1967; Schachter & Singer, 1962), all of which posit that bodily signals play a central role in the experience and formation of emotions.

Gastric interoception refers to the sensing of internal signals originating from the stomach (van Dyck et al., 2021). Gastric interoception plays a central role in EDs and eating behavior, as it underpins the detection of internal signals related to hunger, satiety, and fullness (Cusack et al., 2022; Janssen et al., 2011; Khalsa et al., 2022; Martin et al., 2019; Poovey et al., 2022; Smith et al., 2021; van Dyck, Vögele, et al., 2016). However, emerging evidence suggests that its relevance extends beyond EDs and disordered eating behaviors. Both EDs and

commonly co-occurring conditions, including anxiety and depression, have been linked to gastric dysrhythmia and gastrointestinal symptoms such as nausea, bloating, and abdominal pain (Herpertz-Dahlmann, 2015; Ly et al., 2015; Ogawa et al., 2004; Ruhland et al., 2008; Simpson & Stakes, 1987; van Dyck et al., 2021). Additionally, recent findings suggest that coupling between frontal-parietal brain regions and the gastric rhythm reflects a cross-diagnostic factor involved in mental health (including depression, anxiety, stress and well-being; Banellis et al., 2024). Further, a recent mixed-methods study highlighted the significance of gastric sensations in mental health contexts, with participants identifying gastrointestinal discomfort and muscle tension as key sources of distress, on par with sensations from the cardiac and respiratory systems (Hickman et al., 2025). These signals were considered to be as important as cardiac or respiratory signals (Hickman et al., 2025). These findings point to the need for a more systematic investigation of gastric interoception, as it appears to be a potential valuable intervention target to reduce distressing gastric symptoms.

There is a growing body of literature on gastric interoception (Ahlich et al., 2023; Ahlich & Rancourt, 2022; Brown et al., 2022; Davey et al., 2022; Haruki & Ogawa, 2023; Iatridi et al., 2021; Poovey et al., 2022; Smith et al., 2021; Todd et al., 2020, 2021; van Dyck et al., 2021). Despite this increasing interest, the vast majority of studies focus on a single dimension of gastric interoception, most commonly relying on self-report measures (Jenkinson et al., 2018; Martin et al., 2019; Poovey et al., 2022; Robinson, Marty, et al., 2021). Only a limited number of studies have employed behavioral methods, such as the two-step water load test (van Dyck, Vögele, et al., 2016), to assess *gastric interoceptive sensitivity* (Ahlich et al., 2023; Brown et al., 2022; Ferentzi et al., 2018; Herbert, Muth, et al., 2012), and even fewer studies have used a multidimensional approach (Datta & Lock, 2023; van Dyck et al., 2021). Especially the organ from which sensations of hunger, satiation and fullness emerge, the stomach itself, has been understudied in the context of gastric interoception and eating behavior and warrants further attention.

1.2.3 The stomach

Upon the ingestion of solid food, the proximal (upper) part of the stomach undergoes active relaxation to accommodate the incoming contents (Janssen et al., 2011). Subsequently, the stomach engages in the mechanical and chemical breakdown of food through a coordinated process involving hormonal signals, gastric acid secretion, sensory input from neural pathways, and rhythmic muscular contractions known as peristaltic waves (Hunt et al., 2015; K. L. Koch & Stern, 2004; Soybel, 2005). These mechanisms collectively transform the ingested material

into a viscous fluid that is then transferred to the duodenum for further digestion. In this thesis, we focus specifically on gastric motility. The stomach, just like the heart, has a rhythm. This rhythm is produced by interstitial cells of Cajal, a class of pacemaker cells, which generate gastric myoelectric activity (K. L. Koch & Stern, 2004). This myoelectric activity can be recorded noninvasively through EGG using surface electrodes (K. L. Koch & Stern, 2004; Wolpert et al., 2020). The typical frequency ranges which are extracted by EGG are normogastria (2-4 cycles per minute, cpm), bradygastria (1-2 cpm) and tachygastria (4-10cpm; Wolpert et al., 2020). During food intake, healthy individuals typically exhibit an increase in the amplitude of gastric myoelectric signals, accompanied by a stable rhythm of approximately three cpm, known as normogastria (K. L. Koch & Stern, 2004; Wolpert et al., 2020). The interstitial cells of Cajal are functionally linked to the smooth muscles of the stomach and to the afferent fibers of the vagus nerve (Hunt et al., 2015; Janssen et al., 2011; Soybel, 2005). Communication between the stomach and the brain occurs via continuous bidirectional signaling. Ascending (bottom-up) projections target regions such as the insula, hippocampus, occipital areas, and somatosensory cortices (Engelen et al., 2023; Janssen et al., 2011), while descending (top-down) influences originate from areas such as the insula, motor and somatosensory cortices, and the medial prefrontal cortex (Engelen et al., 2023; Janssen et al., 2011).

While rhythmic gastric activity (normogastria) is normally generated in healthy individuals following food intake, dysrhythmic gastric activity (such as bradygastria and tachygastria) is associated with symptoms such as nausea, bloating and gastric discomfort (K. L. Koch, 2021; K. L. Koch et al., 2023; K. L. Koch & Stern, 2004; van Dyck et al., 2021; Wolpert et al., 2020). Stress and relaxation seem to play an important role in these processes: relaxation has been shown to increase normogastria, while stress has been associated with an increase in dysrhythmic gastric activity (Muth et al., 1999; Yin et al., 2004). Gastric motility and muscle tone are also relevant for hunger, satiation and fullness, by playing a mediator role in adjusting gastric distention (Janssen et al., 2011). For example, artificially increasing gastric muscle tone (i.e., raising the tension of stomach muscles, making the stomach less able to relax and stretch), has been shown to produce earlier sensations of satiation in healthy individuals (Janssen et al., 2011; Tack et al., 2002). This makes modulation of the gastric rhythm an interesting potential target for interventions in the context of gastric interoception, especially regarding the modulation of hunger, satiation and fullness perception, but also for reducing symptoms such as nausea, bloating and gastric discomfort. Given their relevance for eating

behavior and EDs, the association of both cardiac and gastric interoception with eating behavior and EDs will now be discussed in more detail.

1.3 Interoception and eating behaviors

Interoceptive disturbances are not limited to clinically diagnosed EDs but may also emerge in individuals exhibiting subclinical disordered or maladaptive eating behaviors (Datta et al., 2021; Herbert & Pollatos, 2018; Stevenson et al., 2015). Although more research has focused on EDs, some studies have also examined how disordered and maladaptive eating behaviors relate to interoception. Preliminary evidence suggests that difficulties in interpreting internal bodily cues, such as hunger and fullness, can appear even at low levels of disordered eating symptoms (Datta et al., 2021). Irregular eating behaviors, dietary restraint, and rigid external food rules have been associated with weakened interoceptive capacities, which can disrupt the natural regulation of food intake and promote maladaptive behaviors such as emotional eating, external eating, or eating in the absence of hunger (Herbert & Pollatos, 2018; Stevenson et al., 2015). Additionally, short-term intake of high-fat, high-sugar diets has been linked to reduced sensitivity to hunger and satiety signals (Attuquayefio et al., 2017; Herbert & Pollatos, 2018).

For *cardiac objective physiological states*, emotional eating has been linked to lower HRV, indicating reduced autonomic regulation (Lutz & Vögele, 2012), which is similar to findings in individuals with BN and BED who have been found to show altered HRV responses before, during, and after stress exposure (Messerli-Bürgy et al., 2010). In contrast, normal to elevated HRV has been observed in individuals practicing restrained eating, mirroring patterns seen in starvation states such as AN and BN (Geisler et al., 2016; Lutz et al., 2019; Melanson et al., 2004; Murialdo et al., 2007; Scolnick et al., 2014; Vögele et al., 2009). In EDs, altered gastric motility and myoelectric activity, as well as reduced normogastric activity following water ingestion have been observed (Diamanti et al., 2003; Ogawa et al., 2004; van Dyck et al., 2021). Findings specifically testing the associations between *gastric objective physiological state* and eating behavior remain scarce.

Emotional eating has been associated with diminished *cardiac interoceptive accuracy* and reduced confidence in heartbeat perception (A. Koch & Pollatos, 2014; Young et al., 2017), though not many studies have examined this. For EDs, results are inconsistent. Individuals with AN display reduced (D. Fischer et al., 2016; Pollatos et al., 2008), intact, or even heightened heartbeat perception (Datta & Lock, 2023; van Dyck & Lutz, 2022). Findings for BN and BED

also vary, with some studies reporting impairments and others indicating preserved heartbeat perception (Martin et al., 2019; Ortmann et al., 2025).

Impairments in *gastric interoceptive sensitivity and self-report* have been found in restrained eaters, who showed a disconnection between subjective fullness and actual consumption (Datta et al., 2021), supporting the idea that bodily cues may be actively suppressed to maintain restrictive intake (van Strien et al., 1986). Individuals with AN show hypersensitivity to gastric cues, and reach perceived fullness with lower water volumes than controls (Brown et al., 2022). Individuals with AN also report heightened and negatively valenced sensitivity to gastric sensations such as fullness and satiation (Ortmann et al., 2024). They also report earlier and prolonged fullness after meals even when controlling for gastric volume (Jacquemot & Park, 2020). Individuals with AN also report lower hunger levels than controls (Halmi & Sunday, 1991; Ortmann et al., 2024). Individuals with BN and BED, however, may show patterns of hyposensitivity to gastric cues, with delayed satiation and greater water intake to feel satiated (van Dyck et al., 2021). Conversely, altered perception of hunger and fullness has been linked to uncontrolled eating and binge-eating behaviors (Jenkinson et al., 2018; Stevenson et al., 2023). Additionally, individuals with BN and BED showed reduced satiety sensitivity and struggled to distinguish hunger from emotions (Ortmann et al., 2024). For EDs, evidence from *general interoceptive self-report* (i.e., not organ specific) measures is rather consistent; a meta-analysis reported widespread impairments in the perceived ability to detect bodily signals across ED diagnoses, suggesting that disrupted interoceptive self-perception may represent a cross-diagnostic factor involved in EDs (Jenkinson et al., 2018).

Both *general and gastric self-reported interoceptive abilities* have been reported to predict emotional eating in some studies (Ahlich & Rancourt, 2022; Robinson, Marty, et al., 2021; Willem et al., 2021), while others did not find an association (Lyvers et al., 2022; Young et al., 2017). For external eating, no associations have been found with *general self-reported interoception* (Young et al., 2017). In children with overweight, but not in normal weight controls, *general interoceptive self-report* has been shown to predict emotional and external eating (A. Koch & Pollatos, 2014). This suggests in children with overweight, lower confidence and attention toward internal cues may contribute to a reliance on external eating triggers (A. Koch & Pollatos, 2014). Dietary restraint has been associated with reduced *gastric interoceptive self-report* (i.e., responsiveness to hunger and satiety signals; Jenkinson et al., 2018) and lower *general self-reported interoceptive abilities* (Lovan et al., 2022). Across these maladaptive eating behaviors, a common feature appears to be an altered physiological signal, perception or

interpretation of internal bodily signals, emphasizing the central role of interoceptive processing (van Strien et al., 2005; Young et al., 2017).

Interoception is also central to intuitive eating, meaning eating in accordance with one's bodily signals (Tylka & Kroon Van Diest, 2013). Research has shown that intuitive eating is consistently associated with higher *cardiac interoceptive accuracy* and mediates the link between interoception and disordered eating behaviors (DeVillle, Erchull, et al., 2021; Herbert et al., 2013; Joshi et al., 2024a). Conversely, lower *cardiac interoceptive accuracy* has been linked to reduced intuitive eating and higher BMI, suggesting that poor detection of internal hunger and satiety signals may compromise food-related decision-making, particularly in environments abundant in highly palatable foods (Robinson, Marty, et al., 2021). Moreover, intuitive eating and *general self-reported interoceptive abilities* together may reduce binge-eating and support healthier weight management (Joshi et al., 2024b). For the *gastric interoceptive domain* and its association intuitive eating, research is scarce. Together, evidence on maladaptive and adaptive eating behaviors and interoception suggests a discrepancy between actual physiological states, whether altered or intact, and the way in which individuals perceive these signals and incorporate them into food related decision-making and eating behavior.

1.4 Training Interoception via Biofeedback

The causal relationship between interoceptive deficits and the development of EDs or maladaptive eating behaviors remains unclear, with evidence supporting the possibility of bidirectional influences (Jenkinson et al., 2018). Early disruptions in somatic cue interpretation may progressively weaken the connection between bodily sensations and behavioral responses, particularly when rigid eating practices are present. For example, persistent suppression of hunger cues due to restrictive eating or weight-related concerns may diminish the capacity to detect hunger over time (Datta et al., 2021). Alternatively, individuals with reduced interoceptive abilities may have a diminished capacity to accurately perceive bodily states and emotions, predisposing them to maladaptive eating as a strategy for emotional regulation. A scenario that has been proposed is that disordered eating may reflect short-term attempts to regulate internal states, which ultimately disrupt the accurate processing of internal bodily signals over time (van Dyck & Lutz, 2022). Van Dyck and Lutz (2022) give the following example: in BN, a racing heart may be perceived as intense anxiety, prompting binge-eating to soothe the unpleasant emotion. The resulting discomfort and guilt are then relieved by purging. Over time, this cycle impairs gastric and cardiac function (through electrolyte imbalance and gastric distention), leading to distorted bodily signals, such as delayed satiety, which further

sustain disordered eating. Consistent with both perspectives, reduced self-reported interoception in a general population has been associated with increased ED risk one year later (Leon et al., 1995). Findings indicate that interoceptive deficits may persist even after recovery from EDs (Klabunde et al., 2013), although in patients with AN, improvements in interoceptive sensitivity and intuitive eating during treatment have been associated with longer treatment adherence and greater weight restoration (Richard et al., 2019). Independent of the direction of causality, early alterations in somatic cue interpretation may represent a critical window for preventive interventions in the context of disordered eating behaviors (Datta et al., 2021). Given the central role of gastric interoception in both EDs and eating behavior, targeted interventions aimed at improving gastric signal perception may represent a valuable preventative and therapeutic approach. This raises the question of how gastric interoception can be effectively trained.

As we have seen above, gastric motility plays a central role in mediating hunger, satiety, and fullness, and is often disrupted in individuals with EDs (Janssen et al., 2011; Ogawa et al., 2004; van Dyck et al., 2021). AN, BN, and BED are frequently accompanied by epigastric discomfort and nausea. In AN, discomfort is typically linked to early satiation and gastric hypersensitivity, whereas in BN and BED it is associated with overeating episodes and delayed gastric emptying (Brown et al., 2022; Diamanti et al., 2003; Jacquemot & Park, 2020; Janssen et al., 2011; Jenkinson et al., 2018; van Dyck et al., 2021; Zimmerli et al., 2006). Consistent with this, altered gastric myoelectrical activity has been observed in BN and BED, particularly reduced normogastria following water ingestion during laboratory tasks (Diamanti et al., 2003; Ogawa et al., 2004; van Dyck et al., 2021). As dysrhythmias are associated with nausea and gastric discomfort (K. L. Koch et al., 2023; K. L. Koch & Stern, 2004), modulating gastric rhythm directly may, therefore, represent a promising approach to improve gastric interoception and related symptoms (van Dyck & Lutz, 2022). Biofeedback provides individuals with real-time feedback of internal physiological signals, which are typically outside of conscious awareness. This external feedback may enhance the ability to detect bodily signals and support their regulation, potentially reducing somatic symptoms and alleviating symptom burden in conditions characterized by disrupted interoceptive processing (Meyerholz et al., 2019; Schaefer et al., 2014). Gastric biofeedback of gastric myoelectrical activity has emerged as a potential method for enhancing normogastria and reducing dysrhythmic activity and their associated symptoms, including nausea, epigastric discomfort, and stress (Stern et al., 2004; Vujic et al., 2020). Gastric biofeedback of EGG may, thus, offer a promising noninvasive method to support individuals in sensing gastric signals more accurately, thereby strengthening

interoceptive processing at the objective physiological level (van Dyck & Lutz, 2022). To date, only one study ($N = 26$) has been conducted on gastric biofeedback (Stern et al., 2004). Participants were able to successfully increase their amount of normogastria following 4 training sessions (Stern et al., 2004). However, no effect on interoception or any other psychological variable was assessed.

In the cardiac and respiratory domain, biofeedback of HR, HRV, and breathing rhythm has already been used to improve interoception (Hodossy et al., 2021; Leganes-Fonteneau et al., 2021; Meyerholz et al., 2019; Rominger et al., 2021; Schaefer et al., 2014; Schillings et al., 2022; Sugawara et al., 2020). These interventions typically involve displaying physiological signals on standard screens to support self-regulation. However, recent studies have begun exploring virtual reality (VR) as a more immersive and engaging alternative (Houzangbe et al., 2020; Kerr et al., 2023; Kothgassner et al., 2022; Lüddecke & Felnhofer, 2022; Rockstroh et al., 2021). This level of sensory engagement may enhance users' focus, motivation, involvement and more positive user experience, thereby supporting more effective training outputs (Lüddecke & Felnhofer, 2022). These advantages may be especially relevant for populations who struggle with stress regulation, such as individuals with EDs, by providing a more compelling and focused context for practicing bodily focus and relaxation (Behrens et al., 2022). The immersive nature of VR may help redirect attention away from external stressors and facilitate engagement with internal cues (Behrens et al., 2022). This may be particularly helpful for individuals who find it difficult to achieve a relaxed state through standard means (Behrens et al., 2022). However, discrepancies in experimental design, such as mismatched control conditions, like plain feedback designs or waitlist controls (Kerr et al., 2023; Rockstroh et al., 2019), have limited the strength of current evidence, highlighting the need for more studies that systematically compare equivalent feedback across VR and non-VR formats (such as Pratviel et al., 2024 and Weibel et al., 2023). To date, we are not aware of any VR gastric biofeedback paradigms.

2 STUDY AIMS

The present thesis includes three studies. Given the considerable challenges associated with the treatment of EDs, the identification of subclinical symptoms and maladaptive eating behaviors preceding clinical manifestations is critical and underscores the importance of prevention and an improved understanding of contributing factors (Leichsenring et al., 2022; Santomauro et al., 2021). Recent network analyses have consistently identified altered interoception as a

central component of ED symptomatology, highlighting the pivotal role of interoceptive processes in eating behavior across a spectrum ranging from intuitive to maladaptive eating and disordered eating (Cusack et al., 2022; DeVille, Erchull, et al., 2021; Herbert et al., 2013; Joshi et al., 2024b; Martin et al., 2019; Monteleone et al., 2019; Olatunji et al., 2018). Both cardiac and gastric interoception appear to play important roles in the context of eating, due to their involvement in emotional processing, emotion regulation and the perception of hunger, satiation, and fullness, respectively (Greenwood & Garfinkel, 2025; Janssen et al., 2011; Khalsa et al., 2022; Lazzarelli et al., 2024; van Dyck et al., 2021). However, our understanding of the interrelatedness between interoceptive dimensions (e.g., self-report, behavioral, physiological) and organ-specific modalities (e.g., cardiac, gastric) and associations with maladaptive eating behaviours remain insufficient. Most research has focused on cardiac interoception in a single dimension as a proxy for general interoception, which has led to inconsistent and inconclusive findings (Ahlich et al., 2023; Khalsa et al., 2022; Poovey et al., 2022; Vlemincx et al., 2021; Young et al., 2017).

Accordingly, Study 1 of this thesis addressed these gaps in two steps. First, it examined the relationship between cardiac and gastric interoception across multiple dimensions (behavioral, self-reported, and physiological). Second, it tested whether multidimensional gastric interoception is a stronger predictor of maladaptive eating behaviors (emotional, external, and restrained eating) compared to cardiac interoception. These behaviors are present in the general population, but occur more frequently and with greater severity in clinical samples, making them important targets for early intervention. We used a predictive model approach (LASSO regressions) to assess the importance of the different variables. LASSO regression was used to reduce overfitting and enhance predictive accuracy by creating more parsimonious models that exclude less relevant variables. This study has been accepted for publication in a peer-reviewed scientific journal:

Tiemann, A., Ortmann, J., Rubo, M., Meyer, A. H., Munsch, S., Vögele, C., & van Dyck, Z. (accepted). The relevance of cardiac and gastric interoception for disordered eating behavior. Accepted in: *Journal of Eating Disorders*.

Enhancing gastric interoception through targeted interventions appears to be a promising strategy for addressing maladaptive eating behaviors and ED symptoms. Gastric biofeedback, based on EGG, offers particular potential in this regard (van Dyck & Lutz, 2022; Vujic et al., 2020). However, to date, only one study with a small sample size has explored gastric biofeedback (Stern et al., 2004), despite its theoretical potential to regulate gastric

rhythms and, consequently, to contribute to improvements in gastric interoception, eating behaviors, and ED symptoms. Accordingly, Study 2 of this thesis employed a randomized controlled design to compare a VR version of the gastric biofeedback paradigm, the same paradigm presented on a 2D screen, and a control group. The objectives were to assess feasibility, efficacy, and participant experience. Specifically, we investigated whether participants could modulate gastric myoelectric activity and how they evaluated the intervention in terms of motivation, attention, mood, presence, user acceptance, and related factors. This study has been submitted to a peer-reviewed journal and is currently under review:

Tiemann, A., van Dyck, Z., Vögele, C., Munsch, S., & Rubo, M. (submitted). *Gastric biofeedback in virtual reality: Feasibility, efficacy and self-reported experience*. Manuscript in revision.

Following the assessment of technical feasibility, efficacy, and user experience of the gastric biofeedback intervention in Study 2, Study 3 aimed to examine its downstream effects. Study 3 is the result of the same laboratory experiment as Study 2. The objective was to evaluate the impact of gastric biofeedback training on multidimensional cardiac and gastric interoception, general interoception and a broad range of eating behaviors. This included ED symptoms, emotional, external, and restrained eating, and intuitive eating, in a healthy sample. To date, no studies have systematically investigated the effects of gastric biofeedback on interoception, eating behaviors, or ED symptoms. This study has been submitted to a peer-reviewed journal.

Tiemann, A., Rubo, M., Garfinkel, S., Vögele, C., van Dyck, Z., & Munsch, S. (submitted). *Listening to your stomach: Effects of gastric biofeedback training on interoception, eating behavior and eating disorder symptoms*. Manuscript submitted for publication.

The aim of this thesis is to investigate the role of gastric interoception in eating behavior and to explore whether targeted modulation of gastric activity could represent a novel approach in the prevention and treatment of maladaptive eating behaviors. Specifically, the three studies systematically examine (1) the relative importance of cardiac and gastric interoception in predicting maladaptive eating behaviors, (2) the feasibility and potential efficacy of a newly developed gastric biofeedback intervention designed to regulate gastric rhythms, and (3) the downstream effects of such modulation on interoceptive functioning and a broad spectrum of eating behaviors. By addressing these objectives, this work contributes to the field by

introducing and evaluating a novel physiology-based intervention approach that targets the fundamental level of gastric interoception, namely gastric rhythm, which is important for the perception of hunger, satiation, and fullness. Together, the three publications advance both theoretical understanding and the potential clinical application of gastric interoception and gastric biofeedback as a possible tool in the prevention and treatment of problematic eating behaviors and ED symptoms.

3 EMPIRICAL STUDIES

Study 1: The relevance of cardiac and gastric interoception for disordered eating behavior

Accepted as:

Tiemann, A., Ortmann, J., Rubo, M., Meyer, A. H., Munsch, S., Vögele, C., & van Dyck, Z. (accepted). The relevance of cardiac and gastric interoception for disordered eating behavior. *Journal of Eating Disorders*.

Abstract

Introduction: Gastric interoception (i.e., the perception of gastrointestinal signals such as hunger, satiety or nausea) in the context of eating has recently gained increasing research attention. Nevertheless, it remains poorly understood how different interoceptive dimensions (e.g., self-report) and organ systems (e.g., cardiac, gastric) relate to each other and to disordered eating behaviors such as emotional, external and restrained eating. We assessed multiple dimensions (behavioral, self-reported, and physiological) in the cardiac domain (interoceptive accuracy, interoceptive self-report, interoceptive insight and objective physiological state) and in the gastric domain (gastric interoceptive sensitivity, gastric attribution of interoceptive sensations, interoceptive self-report, interoceptive insight and objective physiological state). The first goal of this study was to examine the relationship between cardiac and gastric interoception measured via multiple dimensions (behavioral, self-reported, and physiological). The second goal was to investigate whether multidimensional gastric interoception was a more important predictor of emotional, external and restrained eating than multidimensional cardiac interoception.

Methods: Our sample ($N = 128$) was predominantly female ($n = 116$), included healthy individuals ($n = 87$) and individuals with an eating disorder or sub-clinical eating disorder ($n = 41$). Instruments included a heartbeat counting task, the two-step Water Load Test, electrocardiogram, electrogastrogram and the Dutch-Eating Behaviour Questionnaire. We used correlation analysis, multiple regressions, and LASSO regressions. The final sample included in the multiple regression and LASSO regressions resulted in $N = 89$.

Results: Results showed cardiac and gastric interoception to be distinguishable, yet not to be entirely independent processes. Results further suggest gastric and not cardiac interoception to be the most important predictor of emotional, external and restrained eating. Specifically gastric attribution of interoceptive sensations played the most important role in all disordered eating behaviors.

Conclusions: Our findings highlight the importance of the gastric system in the assessment and targeted treatment of disordered eating behaviors. Future research should consider adding additional interoceptive dimensions.

Keywords: Interoception, Cardiac interoception, Gastric interoception, Multidimensional, Disordered Eating Behavior, Emotional Eating, External Eating, Restrained Eating, Machine Learning

1 Introduction

Disordered eating behaviors pose a problem for both psychological and physical health (Kärkkäinen et al., 2018) and increase the risk for the development and maintenance of eating disorders (EDs; Martin et al., 2019). The mechanisms behind disordered eating behaviors, however, remain poorly understood and a better understanding may help to improve future treatment options (Martin et al., 2019). In this study, we specifically considered emotional eating (eating in response to emotions), external eating (eating in response to food stimuli regardless of hunger and satiety), and restrained eating (restricting food intake to control weight), which are key behaviors linked to EDs (Nagl et al., 2016; van Strien et al., 1986), contributing to overeating and binge-eating (van Strien et al., 2005). Altered interoception, which refers to the processing of internal bodily signals, has been suggested as a trans-diagnostic factor underlying disordered eating (Cusack et al., 2022; Jacquemot & Park, 2020; Khalsa et al., 2022; Martin et al., 2019).

Interoception refers to a multifaceted system comprising the accurate detection of cardiac (e.g., feeling one's own heartbeat), gastric, and respiratory signals, pain, or touch, as well as their interpretation and integration by the CNS (Khalsa et al., 2018). In the past, different facets of interoception were used interchangeably, leading to inconsistent findings. Thus, contemporary approaches tend to differentiate between different facets of interoception (Forkmann et al., 2016; Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022). In this study, we differentiate between *objective physiological states* (such as cardiac or gastric activity; Forkmann et al., 2016), *cardiac interoceptive accuracy* (accurate detection of those physiological states on a behavioral task, such as heartbeat detection tasks; Suksasilp & Garfinkel, 2022), *gastric interoceptive sensitivity* (e.g. sensitivity to gastric signals on a water load task; van Dyck, Vögele, et al., 2016), *interoceptive self-report* (measured via questionnaires or confidence scores and (implicit) prior beliefs believed to influence interoceptive perception in the context of behavioral tasks; Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022), *attribution of interoceptive sensations* (interpretation and attributed causality of interoceptive sensations, such as negative affect after ingesting water; Suksasilp & Garfinkel, 2022) and *interoceptive insight* (metacognitive level, i.e., the correspondence between *accuracy* and *self-report*, e.g., via difference scores of heartbeat detection accuracy and confidence; Suksasilp & Garfinkel, 2022). Interoception is, thus, considered both multidimensional (from physiological signal to detection and interpretation) and multimodal (encompassing multiple organ systems).

The multidimensional assessment of interoception is essential as interoceptive dimensions are distinct and reflect different aspects of interoceptive processes (Garfinkel et al., 2015; Khalsa et al., 2018; Suksasilp & Garfinkel, 2022). Specific dimensions may be impaired in certain mental disorders, including EDs (Khalsa et al., 2018; Martin et al., 2019). For instance, individuals with anorexia nervosa (AN) may exhibit relatively high interoceptive accuracy/sensitivity but low self-report and insight, struggling to interpret and rely on bodily cues (Datta & Lock, 2023). Recent findings (Ortmann et al., 2024) showed that gastric interoceptive self-report (perception of hunger and satiety) varies across ED types: AN patients report lower sensitivity of hunger and higher sensitivity to satiety, while those with bulimia nervosa (BN) and binge-eating disorder (BED) report lower sensitivity to satiety and difficulty distinguishing hunger from emotional states. Differentiating these facets can inform targeted interventions to specific interoceptive impairments (Khalsa et al., 2018).

Cardiac interoception is often used as a proxy for general interoception (Crucianelli & Ehrsson, 2023), though perceptions across organ systems may be distinct, yet sometimes show significant associations with small effect sizes (Ferentzi et al., 2018; Garfinkel et al., 2016; Herbert, Muth, et al., 2012; Pollatos et al., 2016; van Dyck, Vögele, et al., 2016). Prentice and Murphy (2022) concluded that performance in one domain does not predict performance in another, emphasizing the need to differentiate organ systems. In EDs, cardiac and gastric interoception seem to play distinct roles. The link between emotions and bodily signal awareness stems from theories by Lange and James (1967), Schachter and Singer (1962) and Damasio (1994). Cardiac interoceptive accuracy has been associated with emotional processes (Pollatos et al., 2005) with better heartbeat detection linked to stronger emotional experiences (Pollatos et al., 2005) and lower interoception associated with alexithymia symptoms (Brewer et al., 2016; Shah et al., 2016). Since emotional processing issues and dysregulation appear to be key aspects in ED development and maintenance (Lavender et al., 2015), cardioception may be linked to ED symptoms (Aldao et al., 2010; Bernatova & Svetlak, 2017; Lavender et al., 2015). Gastric interoception, key for sensing hunger, satiety, and fullness, is thus particularly relevant in ED contexts (Cusack et al., 2022; Khalsa et al., 2022; Martin et al., 2019; Poovey et al., 2022; Smith et al., 2021; van Dyck, Vögele, et al., 2016).

In line with this, certain authors propose that cardiac and gastric interoception are distinct (Ferentzi et al., 2018), as supported by neuroscientific findings (Haruki & Ogawa, 2023; Todd et al., 2021). For example, heart-beat evoked potentials (HEP) and gastric-alpha phase-amplitude coupling (PAC), measured via electroencephalogram (EEG), were found to be

unrelated, and directing attention to cardiac or gastric signals seems to elicit different neural activation patterns in magnetic resonance imaging (MRI) studies (Haruki & Ogawa, 2023; Todd et al., 2021). However, weak correlations between cardiac and gastric indices have been reported (Herbert, Muth, et al., 2012; Iatridi et al., 2021; van Dyck, Vögele, et al., 2016; Whitehead & Drescher, 1980). These mixed findings suggest that the relationship between cardiac and gastric interoception is not yet fully understood, necessitating further investigation. The first goal of this study is to explore the relationship between cardiac and gastric interoception using a multidimensional approach. Examining interoception across different levels and organ systems may help to clarify whether it represents a cohesive construct with distinct dimensions, addressing a fundamental premise in interoception research (Suksasilp & Garfinkel, 2022).

Interoceptive impairments have been observed across ED diagnoses, subclinical disordered eating behaviors, and post-recovery from EDs (Chang et al., 2018; Datta et al., 2021; Jenkinson et al., 2018; Martin et al., 2019). Thus, examining specific eating behaviors in different ED samples may offer valuable insights (Cusack et al., 2022; Young et al., 2017). Emotional eating, external eating, and restrained eating are well-established eating behaviors relevant to EDs (Nagl et al., 2016; van Strien et al., 1986). These behaviors contribute to overeating and binge-eating (van Strien et al., 2005) and are more pronounced in individuals with EDs compared to healthy controls (Dell’Osso et al., 2016; Elran-Barak et al., 2015; Ferrer-Garcia et al., 2017; Reichenberger et al., 2021; van der Ster Wallin et al., 1994; Wardle, 1987). Restrictive eating, in particular, is prevalent across the ED spectrum (Elran-Barak et al., 2015; van der Ster Wallin et al., 1994).

Emotional eating has been negatively associated with *cardiac interoceptive accuracy* (heartbeat counting) and *interoceptive insight* (A. Koch & Pollatos, 2014; Young et al., 2017). Additionally, emotional eating has been linked to obesity and overeating (van Strien et al., 2005), and body composition, including body mass index (BMI), weight, and percentage of body fat, may also influence heartbeat detection (Mölbart et al., 2016; Robinson, Foote, et al., 2021; Rouse et al., 1988), suggesting an interplay between these variables. Findings on self-reported interoceptive abilities are mixed, with some studies identifying associations (Ahlich & Rancourt, 2022; A. Koch & Pollatos, 2014; Robinson, Marty, et al., 2021; Willem et al., 2021) while other did not (Lyvers et al., 2022; Young et al., 2017). Additionally, higher emotional eating levels have been linked to lower *cardiac objective physiological states* (heart rate variability; HRV; Lutz & Vögele, 2012). These results suggest that emotional eating correlates

with various interoceptive impairments, including reduced cardiac signal detection abilities, poorer metacognitive insight, poorer general and gastric self-reported interoceptive abilities, and lower autonomic self-regulatory abilities.

Interoceptive self-report has been found to predict emotional and external eating in overweight children (A. Koch & Pollatos, 2014). This suggests that individuals who engage in more external eating often have lower confidence in perceiving their bodily signals and pay less attention to them, potentially due to a learned focus on external rather than internal cues. Dietary restraint was found to be associated with reduced reliance on hunger and satiety cues (Jenkinson et al., 2018), and higher self-reported interoceptive abilities were linked to lower levels of restrained eating (Lovan et al., 2022). Impairments in gastric interoception have also been observed in restrained eating, where fullness ratings and shake consumption quantity were not related in individuals with higher levels of restraint (Datta et al., 2021), consistent with theories suggesting bodily signals to be ignored to restrict food intake (van Strien et al., 1986). Additionally, heightened HRV has been found to be correlated with increased restrained eating, similar to patterns observed in AN and BN during starvation (Geisler et al., 2016; Melanson et al., 2004; Murialdo et al., 2007; Scolnick et al., 2014; Vögele et al., 2009).

These findings highlight distinct interoceptive impairments associated with emotional, external, and restrained eating. However, to the best of our knowledge, a systematic investigation into the roles of multidimensional cardiac and gastric interoception in these eating behaviors remains lacking. Understanding whether gastric interoception is more relevant than cardiac interoception in the context of emotional, restrained and external eating requires a comprehensive, multidimensional assessment of both. Most studies have focused on single domains (e.g., cardiac or gastric) and single dimensions (e.g., interoceptive accuracy or self-report; Ahlich et al., 2023; Khalsa et al., 2022; Poovey et al., 2022; Vlemincx et al., 2021; Young et al., 2017). Gastric interoception has typically solely been assessed via self-report (e.g. interoceptive awareness subscale on the Eating Disorder Inventory (Garner et al., 1983) (Jenkinson et al., 2018; Martin et al., 2019; Poovey et al., 2022; Robinson, Marty, et al., 2021) or behavioral measures (e.g., a water load test; Ahlich et al., 2023; Brown et al., 2022; Ferentzi et al., 2018). Thus, the second goal of our study was to determine whether multidimensional gastric interoception better predicts emotional, external, and restrained eating than multidimensional cardiac interoception.

1.1 Hypotheses

1. We expect significant associations between measures that reflect the same dimension of interoception (behavioral, self-reported, or physiological) across cardiac and gastric domains (Herbert, Muth, et al., 2012; van Dyck, Vögele, et al., 2016).
2. We expect gastric interoception to predict emotional, external and restrained eating better than cardiac interoception

2 Methods

2.1 Power analysis, participants and procedure

We used G*Power to conduct an a-priori power analysis. To achieve a medium effect size ($f = 0.15$) in linear multiple regression, with 12 predictors (see below) a sample size of $N = 127$ is required ($\alpha = 0.05$; $1 - \beta = .80$). One hundred and twenty-eight participants (116 females, 12 males) were recruited at the University of Luxembourg through flyers, university e-mail lists, posters and local newspapers. Due to missing data, eighty-nine participants were included in the final sample for multiple regression and least absolute shrinkage and selection operator (LASSO) analysis. The data for the current study was collected as part of two studies with the same design and instruments. One of the studies specifically targeted the recruitment of individuals with binge-eating episodes. The two studies were combined to increase statistical power through a larger sample size and to cover a broad spectrum of eating behavior. Participants were required to be at least 18 years of age and both individuals with and without ED symptoms were invited to participate. Exclusion criteria concerned gastrointestinal surgeries, chronic and/or current physical illnesses, as well as any treatment or condition strongly affecting weight or eating behavior, current or past psychotic disorders, bipolar disorder or suicidal ideation. The sample included 38 participants who met DSM-5 criteria for EDs, namely current BN ($n = 13$) and BED ($n = 25$). The sample also included subclinical BED ($n = 3$). The average illness duration was 26.9 months ($SD = 13.55$), 13 individuals had received treatment in the past, and four reported successful treatment completion. ED diagnoses were assessed through the Eating Disorder Examination (EDE; Cooper & Fairburn, 1987; Hilbert et al., 2004) and the Structured Clinical Interview for DSM-IV Axis I (SCID; First et al., 1995; Wittchen et al., 1997). Ethical approval was obtained from the Ethics Review Panel of the University of Luxembourg (substudy 1: ERP 22-017A EDIP). Before data collection commenced, written informed consent was provided by all participants and their participation

was compensated with 80€ and 60€, depending on the study. Participants were asked to fast at least 3 hours before and not to consume any beverages for at least 2 hours before taking part in the study. Participants first completed diagnostic interviews and questionnaires. This was followed by height and weight measurements. Next, a 5-minute resting electrocardiogram (ECG) recording was conducted, followed by a heartbeat counting task (Schandry, 1981). Participants then underwent the two-step Water Load Test (WLT-II; van Dyck, Vögele, et al., 2016) and completed the procedure with a 15-minute resting electrogastrogram (EGG) recording. The WLT-II was carried out at the end, as fasting states may affect heartbeat perception (Herbert, Herbert, et al., 2012).

2.2 Body Mass Index (BMI)

Participants were weighed and measured during laboratory testing to calculate their BMI as follows: kg/m^2 . The study used calibrated scales.

2.3 Cardiac Interoception

2.3.1 Cardiac Interoceptive Accuracy: Heartbeat Counting Task (HBCT; Schandry, 1981)

A heartbeat counting task (HBCT; Schandry, 1981) was used to measure cardiac *interoceptive accuracy*. Participants were asked to silently count their heartbeats without measuring their pulse during four time intervals (25s, 35s, 45s and 55s, randomized order). During the entire task, ECG was recorded at a sampling rate of 1000Hz with a BIOPACTM MP150 (Biopac Systems Inc., USA) and processed with the software Acqknowledge 4.2. Cardiac *interoceptive accuracy* was then calculated using the formula:

$$\frac{1}{4}(1 - (|actual\ heartbeats - reported\ heartbeats|) / (actual\ heartbeats))$$

The average of the four trials resulted in a mean cardiac *interoceptive accuracy* score for each participant (ranging between 0 and 1), with higher scores corresponding to a higher cardiac interoceptive accuracy.

2.3.2 Cardiac Interoceptive Self-report: Confidence ratings on the HBCT

To measure cardiac *interoceptive self-report*, after each trial, participants were asked to indicate their confidence in their performance on the HBCT on a Likert scale of 0 “not sure at all” to 8 “absolutely sure”. Higher mean scores indicate a higher self-reported confidence in one’s interoceptive ability during the HBCT.

2.3.3 Cardiac Interoceptive Insight

Cardiac *interoceptive insight* concerns the correspondence between cardiac *interoceptive accuracy* and *self-report* (Garfinkel et al., 2015). Higher *interoceptive insight* corresponds to higher insight into one's interoceptive abilities (Garfinkel et al., 2015). The correspondence between interoceptive accuracy and self-report can be operationalized via correlations (Garfinkel et al., 2015), though this comes with certain drawbacks. For instance, if a participant reports the same confidence level across all trials, no correlation can be calculated due to a lack of variance (Field, 2014). Additionally, intraindividual correlations reflect the covariation between confidence and performance but ignore the absolute discrepancy between them. For example, a participant with low interoceptive accuracy scores ("0.1", "0.2", "0.3", "0.4") and high confidence ratings ("5", "6", "7", "8") may achieve a perfect correlation of 1, indicating perfect interoceptive insight despite a significant mismatch between performance (mean of .25) and confidence (mean of 6.5). Due to these limitations, we propose a different method for calculating interoceptive insight, absolute difference scores. More specifically, to calculate *interoceptive insight*, we used the "Percent of Maximum Possible" (POMP) scoring method (Cohen et al., 1999), which has also been used by Weineck and colleagues (2019). POMP-Scores are calculated with the following formula:

$$POMP = ((x - \text{variable minimum score}) / (\text{maximum} - \text{minimum score})) * 100.$$

This results in scores ranging from 0 to 100. POMP-Scores prevent problems arising with z-standardization (R. Fischer & Milfont, 2010). To calculate cardiac *interoceptive insight*, cardiac *interoceptive accuracy* and *self-report* were first converted into POMP-scores. Then, absolute difference scores (Dowling, 1978) between the *accuracy* and *self-report* POMP-scores were calculated ($|CIA_{WPOMP} = CIS_{POMP} - ICA_{CPOMP}|$) (note: CIA_{WPOMP} = cardiac *interoceptive insight*, CIS_{POMP} = cardiac *interoceptive self-report*, CA_{CPOMP} = cardiac *interoceptive accuracy*). The resulting CIAw score was then subtracted from 100 (Weineck et al., 2019). This results in more intuitive values, as higher scores correspond to a higher *insight*.

2.3.4 Cardiac Objective Physiological State: Electrocardiogram

A five-minute resting ECG was recorded for every participant. Beforehand, participant's skin was cleaned with alcohol and three disposable electrodes (Ag / AgCl) were placed on the participant's chest in accordance with the "Einthoven Triangle" (Einthoven et al., 1913). The positive and ground electrodes were placed on the right and left costal margin on either side of

the abdomen, while the negative electrode was placed beneath the collar bone. Heart rate (HR) and HRV were analyzed with the software "ARTiiFACT" (Kaufmann et al., 2011). Through linear interpolation, artefacts of the "inter-beat-intervals" (IBIs) were removed. Two measures were extracted after Fast Fourier Transformation (FFT) of the RR-interval series: (1) the root mean square of successive differences (RMSSD) and (2) high frequency normalized units (HFnu). RMSSD is a time domain measure, while HFnu is a frequency domain measure. RMSSD and HFnu are highly correlated and have been suggested to represent indices of the parasympathetic nervous system on HRV (Allen et al., 2007; Cacioppo et al., 2000; Koval et al., 2013). RMSSD has been proposed to also reflect sympathetic activation (Koval et al., 2013).

2.4 Gastric Interoception

2.4.1 Gastric Interoceptive Sensitivity: two-step Water Load Test (WLT-II; van Dyck, Vögele, et al., 2016)

Gastric *interoceptive sensitivity* was measured using the WLT-II (van Dyck, Vögele, et al., 2016). Participants drank non-carbonated water at room temperature from a non-transparent 5-liter flask using a long straw to regulate swallowing size. The flask was filled with 1.5 liters of water, unbeknownst to the participants, to ensure their safety by not exceeding the 1.5-liter maximum, blind them to the actual amount consumed, and give an impression of unlimited water supply.

There were two 5-min drinking phases: until satiation and until maximum fullness. Participants were not informed about the second drinking phase beforehand. In the first phase, they were instructed to drink water until the first sign of satiation that corresponds to meal termination. During the second phase, participants were instructed to drink water until they reached the maximum point of stomach fullness. Each drinking phase was followed by a 10-min rest period, giving the experimenter the time to record the amount of consumed water. Indices that were calculated were: ingested water volume until satiety, additional water volume until maximum fullness, the total ingested water volume and the percentage of satiation to maximum fullness.

2.4.2 Gastric Interoceptive Self-report and Gastric Attribution of Interoceptive Sensations (WLT-II Questionnaire; van Dyck, Vögele, et al., 2016)

Gastric *interoceptive self-report* and *gastric attribution of interoceptive sensations* were assessed with the WLT-II questionnaire. This questionnaire is used to measure sensations

related to water ingestion. Participants are asked to focus on their current abdominal sensations and rate their current satiation, fullness and negative affect before (t0) and after the first drinking phase (t1) as well as after the second drinking phase (t2). We used satiation and fullness ratings for *gastric interoceptive self-report* and the negative affect scale for *gastric attribution of interoceptive sensations*. The negative affect (NA) scale consists of five items (guilt, nausea, discomfort, sluggishness, and arousal) on a 7 point-Likert scale (1 = no sensation / not at all, 7 = extremely). In the present study, WLT-II questionnaire ratings after water ingestion (t2) will be analyzed. In the current study, the NA scale showed acceptable internal consistency with $\alpha = .79$, which is comparable to previous research (van Dyck, Vögele, et al., 2016) with $\alpha = .81$.

2.4.3 Gastric Interoceptive insight

Gastric *interoceptive insight* was calculated using the same method as cardiac *interoceptive insight* (see section 2.3.3). For gastric *interoceptive accuracy* (in our case *gastric interoceptive sensitivity*), the percentage of satiation to maximum fullness from the WLT-II was used. For gastric *interoceptive self-report*, the corresponding satiation rating from the WLT-II questionnaire was taken. Both were converted into POMP-Scores, their absolute difference was calculated and subtracted from 100. This resulted in gastric *interoceptive insight* scores, where higher scores reflect higher *insight*.

2.4.4 Gastric Objective Physiological State: Electrogastrography (EGG)

Gastric activity is involved in the regulation of the development of satiation and in digestion and can be recorded using EGG (van Dyck et al., 2021). To consider the fourth dimension of gastric interoception (Forkmann et al., 2016; i.e., *objective physiological states*), gastric activity can be analyzed. In healthy individuals, the stomach usually contracts approximately three times per minute (3 cycles per minute; cpm; K. L. Koch & Stern, 2004). Ingesting water increases the amount of normal 3 cpm gastric activity (which is called normogastria) in healthy participants (K. L. Koch & Stern, 2004). Gastric myoelectrical activity was recorded during a 15-min resting phase before the first drinking phase of the WLT-II. Then, after the two drinking phases, another 15 min EGG was monitored. To enhance the transmission of the signal, participant's skin was cleaned with alcohol and gently abraded (Nuprep, D.O. Weaver and Co., Aurora, CO). Three abdominal electrodes (ConMed Cleartrace) were placed over the region of the gastric antrum (K. L. Koch & Stern, 2004). The first active electrode was positioned between the midpoint of the umbilicus and the xiphoid notch, while the second one was placed approximately 6cm left of the abdominal midline. The reference electrode was attached

approximately 10cm to the right from the midline electrode. For the EGG recording, participants sat in a half-reclining, comfortable chair at approximately 30-45°. They were asked to not to talk and minimize movement during the recording.

EGG data was recoded on a hard disk using two different amplifier systems: the BrainAmp ExG amplifier by Brain Products, Gilching, Germany, which sampled the data at 5,000 Hz, and the Biopac MP150 amplifier system by Biopac Systems, Inc., which had an EGG100C module for EGG assessment at 16-bit resolution and a sampling rate of 1 kHz. A hardware low-pass filter with a cut-off frequency of 1,000 Hz and no high-pass filter (DC recording) was used.

Data analysis was carried out using WinCPRS 1.160 software (Absolute Aliens Oy, Turku, Finland). The analysis was performed separately for both 15 min segments. The data was visually inspected to determine general quality and possible artifacts. Only continuous recordings without artifacts and visually identifiable waveforms were included. The data was software-filtered (0.016–0.25 Hz, i.e., 1-15 cpm; K. L. Koch & Stern, 2004), down-sampled (to 10Hz), linearly interpolated, tapered with a Hanning window as well as zero padded to the next power of 2. Then, to extract the different frequency power bands, a FFT was performed with runs of 240s and a 75% overlap (K. L. Koch & Stern, 2004). The following power bands were extracted: bradygastria (1.0–2.5 cpm), normogastria (2.5–3.75 cpm) and tachygastria (3.75–10.0 cpm). The power in each EGG band was calculated for the second time point (t2) as a percentage of the total EGG band power within the corresponding frequency range.

2.5 Dutch Eating Behaviour Questionnaire (DEBQ)

To assess emotional, external and restrained eating, the German version of the DEBQ was employed. The German DEBQ (Nagl et al., 2016) consists of 30 items with three sub-scales which play a role in EDs and obesity (Martin et al., 2019): Emotional Eating (10 items), External Eating (10 items) and Restrained Eating (10 items). Emotional Eating corresponds to eating in response to diffuse or clearly labelled emotions, usually to negative emotional content (e.g., “*Do you have the desire to eat when you are emotionally upset?*”). External Eating refers to eating in response to external food stimuli (e.g., “*Do you eat more than usual, when others are eating?*”). Restrained Eating corresponds to restricting food intake for the purpose of weight control (e.g., “*Do you take into account your weight with what you eat?*”). Response options are on a 5-point Likert-Scale (1 = “*never*”, 3 = “*sometimes*”, 5 = “*always*”). To obtain sub-scale scores, item scores are averaged, with higher mean scores corresponding to higher tendencies

of each eating behavior. Each sub-scale had high internal consistency. Emotional Eating (Cronbach's $\alpha = .94$ in (van Strien et al., 1986), vs $\alpha = .96$ in the present sample), External Eating ($\alpha = .80$ vs. $\alpha = .73$), Restrained Eating ($\alpha = .95$, vs. $\alpha = .88$). The total questionnaire showed good internal consistency with an $\alpha = .92$, which is comparable $\alpha = .94$ in the original study.

2.6 Data analysis

For Hypothesis 1, Spearman correlations were calculated due to multiple non-normally distributed variables. We tested normality through visual (Q-Q plots, histograms, box plots) and statistical inspection (Kolmogorov-Smirnov and Shapiro-Wilk tests). For Hypothesis 2, we first examined Spearman correlations between the predictors and outcome variables, before we compared two modeling approaches (1) standard multiple regression and (2) LASSO regression in their prediction performance. Both approaches were cross validated. Cardiac and gastric interoceptive dimensions were used as predictors and emotional, external and restrained eating as outcome variables. We tested the assumptions of multiple linear regression with the usual methods. Due to multicollinearity and aliasing issues, five variables with a variance inflation factor (VIF) over 10 were excluded and only one variable of interest per interoceptive dimension was retained in these cases (Field et al., 2012). This means that for the WLT -II indices, the percentage of satiation to maximum fullness was retained, while the following variables were excluded: ingested water volume until satiety, additional water volume until maximum fullness, the total ingested water volume. For the gastric objective physiological state, only normogastria was retained, while bradygastria and tachygastria were excluded. For the final regression analyses, the following 12 variables were used (see Table 1):

Table 1

Overview of retained variables for multiple linear regression and LASSO regression after adjusting for multicollinearity

	Cardiac	Gastric
Cardiac Interoceptive accuracy / Gastric Interoceptive Sensitivity	<i>HBCT Scores</i>	<i>Percentage of satiation to maximum fullness on the WLT-II</i>
Interoceptive Self-report	<i>HBCT confidence ratings</i>	<i>Satiation and Fullness of WLT-II Questionnaire</i>

Table 1 (continued)

	Cardiac	Gastric
Gastric Attribution of Interoceptive Sensations		<i>Negative Affect (NA) of WLT-II Questionnaire</i>
Interoceptive insight	<i>Cardiac Interoceptive insight</i>	<i>Gastric Interoceptive insight</i>
Objective Physiological State	<i>Mean HR, HRV (RMSSD), HRV (high frequency normalized units)</i>	<i>Normogastria</i>

LASSO regression was used as an additional analysis, as multiple regression often results in overfitting (Hastie et al., 2009), leading to low predictive accuracy. This can especially be the case when the number of predictors is relatively high compared to a rather small sample, such as in the present study (Babayak, 2004). LASSO performs variable selection; it shrinks regression coefficients of less important variables to 0. This can help generating models that are more parsimonious by discarding less important variables, and thus enable to build more robust predictive models with better predictive accuracy. As required by LASSO regression, we omitted missing values by listwise deletion and, thus, our final sample size for regression analyses consisted of $N = 89$. The following data was missing: questionnaire data (BMI $n = 5$, DEBQ $n = 8$), behavioral data (cardiac interoceptive accuracy $n = 15$, cardiac interoceptive self-report $n = 11$, gastric interoceptive sensitivity $n = 19$, gastric interoceptive self-report $n = 11$) and physiological data (ECG-parameters $n = 12$, EGG parameters $n = 19$). As cardiac and gastric interoceptive insight is calculated from interoceptive accuracy/sensitivity and self-report, missing data results as a sum of their missing data, resulting in $n = 15$ and $n = 20$, respectively. From the missing data, 9 individuals were dropouts with only questionnaire data, but no laboratory tasks data. The remaining missing data (excluding dropouts) for the WLT-II, HBCT and EGG- and ECG-parameters were due to technical issues during the testing sessions. For the EGG analysis, missing data in our dataset are attributable to recordings compromised by noise, artifacts, or poor signal quality.

Statistical analyses were carried out with IBM SPSS Statistics Version 26 (SPSS Inc. Chicago, IL) and R version 4.2.2 (R Core Team, 2022) for Windows 10. Cross-validated multiple regression and LASSO regression were estimated using the *caret* package version 6.0.93 (Kuhn, 2008). Variables were standardized to a mean of zero and a standard deviation of

1 to facilitate the interpretation of regression coefficients and obtain more interpretable and stable results (Hastie et al., 2009). For both regression types, a 10-fold cross-validation was used, meaning that the data was randomly partitioned into 10 equally sized subsets. The models were trained on the 9 subsets and tested on the remaining subset, with 10 repetitions. Predictive performance was evaluated based on (1) *R* squared (R^2), corresponding to the percentage of explained variance of the outcome variable by the model, with higher percentage indicating better model fit, on (2) Mean Absolute Error (*MAE*), reflecting the mean difference between predicted and actual values, with smaller values indicating better model fit and on (3) the Root Mean Square Error (*RMSE*), being similar to *MAE* but taking into account direction of error due to squaring of the differences between predicted and actual values (lower values also indicate better model fit). The significance level was set to $p < .05$.

3 Results

3.1 Demographic characteristics

Demographic characteristics can be found in Table 2.

Table 2

Socio-demographic characteristics of participants

	HP (<i>n</i> = 87)	ED total (<i>n</i> = 41)	BE (<i>n</i> = 28)	BN (<i>n</i> = 13)	Total (<i>N</i> = 128)	Difference HP and ED
Sex						
Female	79 (90.6%)	37 (90.2%)	23 (82.1%)	12 (92.3%)	116 (90.6%)	
Male	8 (9.4%)	4 (9.8%)	3 (17.9%)	1 (7.7%)	12 (9.4%)	
Age range						
18-30	39	17	10	6	56	
31-40	16	9	5	4	25	
41-50	14	7	5	3	21	
50+	18	8	8	0	26	

Table 2 (continued)

	HP (<i>n</i> = 87)	ED total (<i>n</i> = 41)	BE (<i>n</i> = 28)	BN (<i>n</i> = 13)	Total (<i>N</i> = 128)	Difference HP and ED
Age						
M (SD)	36.24 _a (13.29)	37.20 (12.23)	40.03 _a (13.15)	32.86 _a (8.02)	36.73 (12.91)	<i>p</i> = .210, η^2 = .02
BMI						
M (SD)	27.47 _a (6.96)	36.64 (12.93)	33.19 _b (7.71)	26.09 _a (6.62)	28.50 (7.43)	<i>p</i> = .001, η^2 = .10

Note. **BE** = Binge-Eating Group, including binge-eating disorder (BED) and sub-threshold BED. **BMI** = Body Mass Index. **BN** = Bulimia Nervosa. **ED** = Eating Disorder. **HP** = healthy participants. **M** = Mean. **SD** = Standard Deviation.

3.2 Descriptives

Descriptive statistics of the variables included in the analyses can be found in Table 3. Values were comparable to previous studies regarding the HBCT (Herbert, Muth, et al., 2012; van Dyck, Vögele, et al., 2016), ECG (Brinth et al., 2024), WLT-II (van Dyck et al., 2021; van Dyck, Vögele, et al., 2016) and EGG after the WLT-II (van Dyck et al., 2021). For the DEBQ, our sample was comparable to previous studies for the healthy individuals (emotional eating *M* = 2.44, *SD* = .97, external eating *M* = 3.04, *SD* = .55, restrained eating *M* = 2.72, *SD* = .75) and bulimic patients (emotional eating *M* = 3.75, *SD* = .75, external eating *M* = 3.43, *SD* = .55, restrained eating *M* = 3.08, *SD* = .82; Nagl et al., 2016; Wardle, 1987).

Table 3

Descriptive statistics of the different dimensions of cardiac and gastric interoception and emotional, external and restrained eating

	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max
Cardiac Interoceptive Accuracy	113	.59	.25	0.00	.98
Cardiac Interoceptive Self-report	117	3.94	2.06	0.00	8.00
Cardiac Interoceptive Insight	112	74.57	21.59	0.00	100
Cardiac Objective Physiological State					

Table 3 (continued)

	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max
Mean HR	116	67.62	11.10	44.00	99.22
HRV(RMSSD)	116	43.07	28.70	6.33	143.21
HRV (HFnu)	166	50.92	21.40	8.79	88.70
Gastric Interoceptive Sensitivity					
Ingested water volume until satiety (ml)	109	453.65	212.414	102	1210
additional water volume until maximum fullness (ml)	109	367.63	213.28	12	1498
total ingested water volume (ml)	109	821.28	344.40	169	1970
percentage of satiation to maximum fullness	109	56.03	14.31	23.96	94.09
Gastric Interoceptive Self-report					
Satiation	117	5.80	1.52	1.00	7.00
Fullness	117	5.79	1.59	1.00	7.00
Gastric Attribution of Interoceptive Sensations					
Negative Affect	117	2.88	1.19	1.00	6.20
Gastric Interoceptive Insight	108	75.09	17.11	23.36	99.74
Gastric Objective Physiological State					
Bradygastria (%)	109	41.20	14.89	12.01	84.35
Normogastria (%)	109	34.86	15.46	12.09	81.34
Tachygastria (%)	109	19.68	9.91	2.83	52.63
DEBQ					
DEBQ Emotional Eating	120	2.86	1.08	1.00	5.00
DEBQ External Eating	120	3.16	.58	1.50	4.70
DEBQ Restrained Eating	120	2.84	.79	1.30	4.60

3.3 Hypothesis 1: correlations between the same dimensions of cardiac and gastric interoception

For the complete correlation matrix, see Table 7 in supplement. Cardiac interoceptive accuracy did not correlate with gastric interoceptive sensitivity: ingested water volume until satiety (ml; $r = .12, p = .216$), additional water volume until maximum fullness (ml; $r = .14, p = .144$), total ingested water volume (ml; $r = .17, p = .090$) or the percentage of satiation to maximum fullness ($r = -.05, p = .651$). Cardiac interoceptive self-report did not correlate significantly with gastric interoceptive self-report (satiation; $r = -.08, p = .422$), fullness ($r = -.04, p = .672$) nor with gastric attribution of interoceptive sensations (negative affect; $r = -.11, p = .245$). Cardiac interoceptive insight did not significantly correlate with gastric interoceptive insight ($r = -.02, p = .820$). Mean heart rate (HR) did not correlate significantly with bradygastria ($r = .18, p = .067$), normogastria ($r = .05, p = .607$), or tachygastria ($r = -.12, p = .232$). HRV (RMSSD) showed a significant negative correlation with bradygastria ($r = -.20, p = .042$), but did not correlate significantly with normogastria ($r = .03, p = .727$) or tachygastria ($r = .13, p = .201$). HRV (HFnu) did not correlate significantly with bradygastria ($r = -.03, p = .795$), normogastria ($r = .05, p = .587$), or tachygastria ($r = .00, p = .997$).

3.4 Hypothesis 2: predicting emotional, external and restrained eating from cardiac and gastric interoception

The correlation matrix for all relevant variables can be found in Tables 8 and 9 in the supplements. In our statistical analyses with emotional, external and restrained eating, we noticed that controlling for BMI did not have an impact on our results. We, therefore, report the present results without controlling for BMI. However, there were significant correlations between BMI and emotional eating ($r = .35, p < .001$), external eating ($r = .20, p = .032$) and restrained eating ($r = .20, p = 0.035$). There were significant positive correlations between BMI and fullness ($r = .19, p = .042$) and a significant negative correlation between BMI and normogastria ($r = -.23, p = .019$). We did, however, control for sex by adding it as a covariate.

3.4.1 Outcome: Emotional Eating

3.4.1.2 Multiple Regression

Coefficients of the multiple linear regression model can be found in Table 4. The model significantly predicted emotional eating ($F(13, 75) = 2.75, p = .003$). NA was a significant

predictor of emotional eating, while fullness, normogastria and cardiac *interoceptive accuracy* were marginally significant.

3.4.1.3 LASSO regression

The LASSO regression selected 8 out of 12 predictor variables to predict emotional eating. The most important predictors were fullness and NA, followed by normogastria, cardiac *interoceptive insight*, HRV (HFnu), mean HR and *cardiac interoceptive accuracy* and satiation (see Table 4). LASSO regression ($R^2 = .227$, $RMSE = .917$, $MAE = .780$) outperformed multiple regression after cross-validation ($R^2 = .235$, $RMSE = .953$, $MAE = .791$) by demonstrating better predictive value based on *MAE* and *RMSE*.

Table 4

Results of multiple linear regression and lasso regression with emotional eating as outcome variable

	<i>Multiple linear regression model</i>				<i>LASSO</i>
	β	<i>SE</i>	<i>t</i>	<i>p</i>	β
	(N = 89)				
Fullness	.24	.14	1.700	.093	.21
Negative affect	.23	.11	1.997	.049*	.20
Normogastria	-.19	.10	-1.844	.069	-.14
Cardiac interoceptive insight	.14	.10	1.363	.177	.11
HRV(HFnu)	-.17	.11	-1.630	.107	-.10
Mean HR	-.20	.12	-1.642	.105	-.10
Cardiac interoceptive accuracy	-.18	.10	-1.753	.084	-.10
Sex	-.11	.11	-1.002	.320	-.07
Satiation	.03	.13	.208	.836	.001
Cardiac interoceptive self-report	.06	.11	.591	.557	.00
HRV(RMSSD)	-.04	.12	-.305	.761	.00
Percentage of satiation to maximum fullness	-.01	.10	-.051	.959	.00

Table 4 (continued)

	<i>Multiple linear regression model</i>				<i>LASSO</i>
	β (<i>N</i> = 89)	<i>SE</i>	<i>t</i>	<i>p</i>	β
Gastric interoceptive insight	.00	.10	-.011	.991	.00

3.4.2 Outcome: External Eating

3.4.2.2 Multiple Regression

Coefficients of the multiple linear regression model can be found in Table 5. The model did not significantly predict external eating ($F(13, 75) = 1.53, p = .130$).

3.4.2.3 LASSO regression

The LASSO regression selected 1 out of 12 predictor variables to predict external eating. The only important predictor was NA (see Table 5). LASSO regression ($R^2 = .190, RMSE = .984, MAE = .746$) showed better predictive value, based on R^2 and $RMSE$ and MAE , than the multiple regression after cross-validation ($R^2 = .163, RMSE = 1.076, MAE = .830$).

Table 5

Results of multiple linear regression and lasso regression with external eating as outcome variable

	<i>Multiple linear regression model</i>				<i>LASSO</i>
	β (<i>N</i> = 89)	<i>SE</i>	<i>t</i>	<i>p</i>	β
Negative affect	.38	.12	3.113	.003**	.16
Sex (covariate)	.10	.12	.831	.409	.01
Cardiac interoceptive self-report	.14	.11	1.230	.223	.00
Cardiac interoceptive accuracy	.03	.11	.253	.801	.00

Table 5 (continued)

	<i>Multiple linear regression model</i>				<i>LASSO</i>
	β	<i>SE</i>	<i>t</i>	<i>p</i>	β
	<i>(N = 89)</i>				
Cardiac					
interceptive	.13	.11	1.145	.256	.00
insight					
Mean HR	.07	.13	.520	.604	.00
HRV(RMSSD)	.16	.13	1.287	.202	.00
HRV(HFnu)	-.24	.12	-2.118	.038*	.00
Normogastrica	.10	.11	.907	.367	.00
Percentage of					
satiation to	.12	.11	1.154	.252	.00
maximum fullness					
Satiation	-.19	.14	-1.408	.163	.00
Fullness	.11	.15	.724	.471	.00
Gastric					
interceptive	-.03	.11	-.266	.791	.00
insight					

3.4.3 Outcome: Restrained Eating

3.4.3.2 Multiple Regression

Coefficients of the multiple linear regression models can be found in Table 6. The model significantly predicted restrained eating ($F(13, 75) = 1.94, p = .038$). NA significantly predicted restrained eating.

3.4.3.3 LASSO regression

The LASSO regression selected 3 out of 12 predictor variables to predict restrained eating. The most important predictors were NA, mean HR and HRV (RMSSD (see Table 6). LASSO regression ($R^2 = .235, RMSE = .930, MAE = .790$) showed better predictive value, based on R^2 and $RMSE$, than the multiple regression after cross-validation ($R^2 = .154, RMSE = 1.047, MAE = .880$).

Table 6

Results of multiple linear regression and lasso regression with restrained eating as outcome variable

	<i>Multiple linear regression</i>				<i>LASSO</i>
	β	<i>SE</i>	<i>t</i>	<i>p</i>	β
	<i>(N = 89)</i>				
Negative affect	.33	.12	2.735	.008**	.21
Sex (covariate)	-.19	.12	-1.579	.119	-.21
Mean HR	-.19	.13	-1.498	.138	-.13
HRV(RMSSD)	.15	.12	1.229	.223	.07
Cardiac interoceptive self-report	.02	.11	.218	.828	.00
Cardiac interoceptive accuracy	.07	.11	.652	.516	.00
Cardiac interoceptive insight	.01	.11	.101	.920	.00
HRV(HFnu)	-.05	.11	-.505	.615	.00
Normogastrica	-.04	.10	-.352	.726	.00
Percentage of satiation to maximum fullness	.10	.13	.779	.438	.00
Satiation	-.11	.15	-.736	.464	.00
Fullness	.03	.10	.289	.773	.00
Gastric interoceptive insight	.33	.12	2.735	.008**	.00

4 Discussion

The first goal of our study was to examine the association between cardiac and gastric interoception across the same dimensions (behavioral, self-reported, or physiological). We found no significant associations between cardiac accuracy and gastric sensitivity at the behavioral level. Similarly, there were no associations between cardiac self-report and gastric self-report or gastric attribution of interoceptive sensations (self-report level), nor between cardiac and gastric interoceptive insight. A small negative association was observed between cardiac and gastric objective physiological states. For the second goal of our paper, we expected

multidimensional gastric interoception to be a better predictor for emotional, external and restrained eating than multidimensional cardiac interoception, which was confirmed by our results.

We did not find an association between *cardiac interoceptive accuracy* and *gastric interoceptive sensitivity* indicating their distinctiveness. These results are in line with certain previous findings (Ferentzi et al., 2018), but differ from other studies which found (Herbert, Muth, et al., 2012; Iatridi et al., 2021; van Dyck, Vögele, et al., 2016; Whitehead & Drescher, 1980). For associations between *interoceptive accuracy / sensitivity* measures across other organ systems, such as respiratory and cardiac interoception, results are even more inconclusive (Garfinkel et al., 2016; Harver et al., 1993; Pollatos et al., 2016). The heterogeneity of results may stem from the fact that accuracy and sensitivity, although considered to be equivalent in the past, actually measure different processes. Indeed, while cardiac interoceptive accuracy reflects the “correspondence between objectively measured physiological events and individual’s reported experience of those events” (Suksasilp & Garfinkel, 2022), gastric interoceptive sensitivity, as measured by water load tests, primarily captures subjective sensitivity to gastric sensations (e.g., satiety and fullness), which is more difficult to link to objective physiological events (e.g., there is no objective satiety or fullness threshold). Future research should focus on developing tasks that measure comparable interoceptive accuracy/sensitivity capabilities in the cardiac and gastric domain. We did not find an association between cardiac and gastric *interoceptive self-report / attribution of interoceptive sensations*, suggesting that one type of *interoceptive self-report* (e.g., cardiac or gastric) may not necessarily be related to another. This aligns with recent findings (Robinson, Marty, et al., 2021), observing no significant link between general self-reported interoception and self-reported hunger and satiety responsiveness. For *interoceptive insight*, there were no significant associations. To our knowledge, there are no studies yet comparing cardiac and gastric *interoceptive insight*. For *objective physiological state*, we found a small negative association between cardiac and gastric indices (HRV RMSSD and bradygastria), which suggests that lower levels of HRV are associated with higher levels of bradygastria after water ingestion. This may be attributed to the involvement of both vagal and sympathetic pathways in HRV and gastric activity (Friesen et al., 2007). Our findings suggest that cardiac and gastric interoception are distinguishable, yet not entirely separate processes, operating independently while sharing certain biological pathways and abilities (Ferentzi et al., 2018). These processes warrant individual examination, which aligns with recent neuroscience research, according to which cardiac and gastric interoception are associated with distinct neural processes (Haruki &

Ogawa, 2023; Todd et al., 2021). Overall, these results underscore the importance of distinguishing both organ systems and interoceptive dimensions. They also cast doubt on generalizing interoceptive capacities from one organ system to another and across dimensions (Suksasilp & Garfinkel, 2022).

For emotional eating, we found gastric interoception to be a better predictor than cardiac interoception consistently across both the multiple regression and the LASSO regression. Multiple regression identified *gastric attribution of interoceptive sensations* (negative affect after water consumption) as the strongest predictor of emotional eating, followed by marginally significant predictors: gastric fullness ratings, normogastria, and cardiac interoceptive accuracy. Gastric attribution of interoceptive sensations (negative affect), gastric self-report (fullness ratings) and normogastria turned out to be key predictors but additional factors, including cardiac interoceptive insight, HRV (HFnu), mean HR, cardiac accuracy, and gastric satiation ratings are also of importance. In more detail, emotional eating was associated with higher levels of water ingestion until satiation, accompanied with corresponding higher levels of self-reported satiation, fullness and negative affect after water ingestion, as well as lower levels of the percentage of normogastria. This suggests that individuals with higher levels of emotional eating perceive their comfortable satiety and fullness thresholds less accurately, and, thus, drank beyond these. This was also mirrored in the EGG, where higher levels of emotional eating were associated with lower levels of normogastria after water ingestion. It is plausible that higher water ingestion led to nausea, which reduced normogastria (K. L. Koch & Stern, 2004). Indeed, we found higher water ingestion until satiation to be positively correlated with nausea ($r = .29$, $p = .013$), and negatively with normogastria ($r = -.20$, $p = .046$). Individuals with high emotional eating scores might notice their gastric sensations “too late”, aligning with patterns of losing control during eating (van Strien et al., 2005). In other words, they may lack a fine-grained perception of their satiety and fullness thresholds, leading to overconsumption. Another explanation could be that they display impairments in predictive coding (i.e., anticipation of future visceral sensations, based on previous experience and taking into account the current experience; Jacquemot & Park, 2020; Smith et al., 2021).

Although gastric interoception seems to play the lead role in emotional eating, the current results suggest that cardiac interoception is important as well – albeit to a smaller extent. This fits previous findings in the field (Ahlich & Rancourt, 2022; Lovan et al., 2022; Young et al., 2017). Cardiac and gastric interoception are both recognized as important in emotional processing, making their involvement in emotional eating logically consistent (Azzalini et al.,

2019; Vianna & Tranel, 2006). Gastric interoception is thought to play a role in food-related decision-making processes, as stomach distention activates vagal afferent neurons, which transmit information about stomach volume changes to the brain (Ritter, 2004). Cardiac interoception, on the other hand, is often considered as a measure of overall interoceptive abilities and has been associated with experienced hunger and intuitive eating styles (Herbert et al., 2013; Richard et al., 2019). In the current sample, emotional eating was associated with lower levels of HRV (HFnu), mean HR, and lower heartbeat detection accuracy, and corresponding higher levels of cardiac metacognitive insight. Enhanced cardiac interoception has been linked to more adaptive emotion regulation (Füstös et al., 2013), indicating that in the context of emotional eating, which arguably represents a maladaptive attempt of emotion regulation, it follows logically that lower cardiac interoceptive accuracy (and corresponding lower levels of HRV and mean HR) shows associations with higher level of emotional eating. Indeed, studies have shown that a range of negative emotions can increase the vulnerability to emotional eating, including depressive symptoms, anxiety/anger, boredom, shame but also, although to a lesser extent, positive emotions (Braden et al., 2018; Cecchetto et al., 2021; Dakanalis et al., 2023; Ergun et al., 2023; Salemi et al., 2022). However, it seems that metacognitive insight of a person's detection ability does not follow the same pattern, indicating once more that these dimensions are distinct and capture separate processes. BMI, which positively correlated with emotional eating in the present study, might also play a role in the relationship between emotional eating and cardiac interoception. While not significantly associated in the present study, previous studies have shown that a higher BMI is associated with lower heartbeat detection and HRV (Birch et al., 2012; Mölbert et al., 2016; Robinson, Foote, et al., 2021; Rouse et al., 1988), suggesting a possible mediating role of body composition in the relationship between cardiac interoception and emotional eating.

For external eating, gastric interoception also emerged as a more important factor than cardiac interoception. The multiple regression analyses did not yield significant results, and the LASSO regression only selected *gastric attribution of interoceptive sensations* (negative affect after water ingestion) as a predictor. When looking at the correlations, higher scores in external eating were associated with higher levels of ingested water volume until satiety, higher subjective fullness, and higher negative affect ratings after drinking water. Individuals more inclined towards external eating may have higher satiety thresholds, leading to greater fullness and more discomfort after drinking water. This aligns with theories and neuroscientific findings of external eating, suggesting that interoceptive cues are less considered in food consumption decisions, with individuals relying more strongly on external cues than on internal ones to

regulate hunger and satiety (Braet et al., 2008; Mata et al., 2015; van Strien et al., 1986; van Strien & Oosterveld, 2008). Another hypothesis is that individuals who score high on external eating - just as individuals scoring high on emotional eating – fail to integrate internal signals into the food-based decision making process due to prediction errors (i.e., failure to anticipate their future bodily states) and thus have to rely on external cues to gather information about their body and infer their internal state (e.g., body checking, portion size...; Cusack et al., 2022).

The multiple regression model significantly predicted restrained eating and found *gastric attribution of interoceptive sensations* (negative affect) to be a significant predictor. The LASSO regression selected three predictors: *gastric attribution of interoceptive sensations* (negative affect) and cardiac *objective physiological state* (HRV and HR), which is consistent with previous findings (Geisler et al., 2016; Melanson et al., 2004; Scolnick et al., 2014). Lower HR and higher HRV in restrictive eaters could result from increased HRV following fasting, which has been found in both healthy individuals and individuals with BN (Herbert, Herbert, et al., 2012; Vögele et al., 2009). Changes in HRV may be due to alterations in cardio-dynamic parameters induced by fasting (i.e., heightened cardiac sympathetic activity), which has been linked to increased *interoceptive accuracy* when experimentally induced through physical exercise or body tilting (i.e., putting the body at a different angle via a tilt-table; Herbert, Herbert, et al., 2012; R. Schandry & Bestler, 1995). These LASSO regression findings complete the regression analysis, showing that both gastric and cardiac interoception seem to play a role in restrained eating. The importance of negative affect after drinking water suggests that although individuals with high scores in restrained eating may exhibit normal or even “good” cardiac and gastric interoceptive abilities and *objective physiological parameters*, the main issue concerns the emotional response to gastric visceral signals. This has important implications for interventions, as it suggests that the signal-processing per se may be intact, but that emotional response to gastric interoceptive sensations is altered. This is in line with recent studies reporting the importance of feeling of safety in one’s body and trusting bodily signals—and that especially the absence of these factors is related to ED symptoms, such as restricting or purging (Brown et al., 2020; Willem et al., 2021). Findings on negative affect after drinking are also in line with two studies (Brown et al., 2022; Petry et al., 2017) according to which in individuals with AN (who display extreme levels of restricting), eating was related to negative emotions such as guilt, fear, anger and sadness. Indeed, the negative affect scale on the WLT-II (van Dyck, Vögele, et al., 2016) comprises items regarding guilt, nausea, feeling uncomfortable, sluggishness and arousal. Our results are also in line with a study (Ahlich et al.,

2023) which found that the WLT-II drinking indices (gastric interoceptive sensitivity) did not predict dietary restraint.

In summary, the three subscales of the DEBQ were associated with *gastric attribution of interoceptive sensations* (negative affect) after the WLT-II. This is consistent with previous findings (Datta et al., 2021) suggesting that individuals practicing cognitive restraint or enforcing dietary rules may experience heightened guilt around eating, leading to a stronger emotional connection to food. This heightened emotional connection to food may render it more susceptible to influence affective states beyond mere satiety, potentially leading to the use of food as a means to modulate emotions (Datta et al., 2021). Consequently, prolonged eating concern could alter the role of regular eating, shifting it away from improving feelings of happiness and instead associating it with negative emotionality, especially when individuals eat beyond the point of satiation (Datta et al., 2021). Overall, our results indicate that gastric interoception may indeed be more strongly related to emotional, external and restrained eating than cardiac interoception.

4.1 Strengths and limitations

Regarding strengths, our study used a multidimensional (*cardiac interoceptive accuracy, gastric interoceptive sensitivity, interoceptive self-report, gastric attribution of interoceptive sensations, interoceptive insight* and *objective physiological state*) and multimodal (cardiac and gastric) approach. This allows for a comprehensive examination of interoceptive processes in relation to emotional, external and restrained eating in the laboratory. Our sample comprised individuals with varying degrees of ED pathology. To our knowledge, we are the first study to use LASSO in the context of multidimensional interoception, providing a more nuanced perspective on the relationships between our variables by avoiding skewed results due to model overfit. Nevertheless, there are also limitations. First, our study comes with the usual limitations that apply to laboratory studies (Mitchell, 2012). Some of our correlations had high *p*-values and should thus be interpreted with care. Our sample comprised a large majority of females, making it difficult to generalize to males or other sexes. Although some studies (Prentice & Murphy, 2022) suggest limited sex differences in gastric interoception and mixed findings in cardiac interoception, future studies with more balanced samples are needed. This could help clarify whether any observed effects are generalizable across sexes or if they may be influenced by sex-specific interoceptive processing differences. Interoception changes over the lifespan (Murphy et al., 2018), and as our sample had a broad age-range, this may also play a role in our

results. We acknowledge the limitations imposed by our sample size and emphasize the importance of replicating our findings with a larger sample to enhance the statistical power and to ensure the stability of the coefficients and the overall robustness of the model. Post-hoc power analyses indicated that the study had adequate power for detecting effects in the emotional eating model (power = 0.91). The restrained eating model was significant but underpowered (power = 0.67), suggesting that while an effect was detected, smaller effects may not have been fully captured. The external eating model was non-significant and also underpowered (power = 0.71), indicating a higher risk of Type II error. Future studies should aim for larger samples (≥ 110 participants for restrained eating, ≥ 104 for external eating) to improve power and effect size estimation. Another important limitation of our findings is that they do not predict future disordered eating behaviors or objective food consumption. We therefore suggest that longitudinal studies could be particularly beneficial in the future, for example with treatment-seeking individuals with EDs, to examine the evolution of gastric interoception alongside ED symptoms over time and during recovery. It should be noted that the DEBQ captures only certain aspects of disordered eating behaviors and is not a comprehensive measure of ED symptoms. Future research should incorporate a broader range of disordered eating behaviors, including constructs such as loss of control eating and purging, to better represent the full spectrum of eating pathology. Finally, our sample included only a small number of individuals with BN and BED and did not include individuals with AN, other restrictive-type EDs, Avoidant/Restrictive Food Intake Disorder or other ED or feeding disorders. As a result, our findings may not fully generalize to ED and feeding disorder populations where dietary restriction is more pronounced or to individuals on the lower end of the weight spectrum.

4.2 Future research directions and clinical implications

The LASSO model demonstrated superior cross-validation performance compared to the multiple regression model, as anticipated given the large number of predictor variables. Multiple regression is susceptible to overfitting when handling high-dimensional datasets, which can compromise predictive accuracy. In contrast, LASSO's regularization technique effectively addresses this issue, enhancing model robustness (Babiyak, 2004; Hastie et al., 2009). Thus, we recommend considering the use of variable selection models in the context of multidimensional interoception, where the number of variables tends to quickly become large. Interoception encompasses additional dimensions (Murphy et al., 2020; Smith et al., 2021; Suksasilp & Garfinkel, 2022), which were not included in this study and which should be

integrated into future studies. Interoception is understood as not only including *accuracy, sensitivity, self-report, attribution of interoceptive sensations insight* and *objective physiological visceral states*, but also the neuronal representations, the preconscious impact of afferent signals and attention to interoception sensations (Suksasilp & Garfinkel, 2022). Future research should therefore consider adding gastric evoked potentials (Mayeli et al., 2023) and the Bayesian framework (active inference) applied to gastric interoception. This may shed light on individual differences in gastrointestinal signal processing and broaden our knowledge on body-brain interactions (Smith et al., 2021).

Interventions in individuals with BN and BED may benefit from exposure to gastric signals. This is supported by our results that especially negative emotions in response to gastric signals seem to be key factors in disordered eating behaviors (emotional, external and restrained eating). Thus, future interventions may directly target these negative emotions caused by food intake and gastric activity, for example through psychoeducation or bias modification intervention. Another possibility is interoceptive exposure, which seems to be a promising approach for addressing distress and negative emotions related to food intake and gastric sensations in individuals with EDs (Boswell et al., 2015, 2019; Hildebrandt et al., 2021; Reilly et al., 2017) and should be further explored in future studies. Regarding the gastric activity part, gastric biofeedback may be another promising approach to directly target the processing of afferent physiological signals. In gastric biofeedback, gastric signals are visualized and individuals learn to modulate their gastric signals (Stern et al., 2004). Gastric biofeedback may also be able to improve gastric interoception. Interventions such as Appetite Awareness Training (where individuals are trained to listen to their hunger and satiety cues) have shown promising results in individuals with BN (Poovey et al., 2022). Nevertheless, for any of these interventions to be effective, not only the improvement of interoceptive abilities should be targeted, but also the insight that visceral and emotional signals are trustworthy and useful (Willem et al., 2021). One reason is that anxiety, related specifically to gastrointestinal sensations, has been found to predict disordered eating behaviors (Brown et al., 2021).

4.3 Conclusion

In conclusion, our study explored the relationship between multidimensional cardiac and gastric interoception with disordered eating behaviors, focusing on emotional, external, and restrained eating. Cardiac and gastric interoception were found to be mostly independent. We found that gastric interoception plays a more important role in emotional, external and restrained eating

than cardiac interoception. These findings highlight the importance of the gastric system in the assessment and targeted treatment of disordered eating behaviors, with trainings such as gastric biofeedback being promising intervention approaches.

Study 2: Gastric Biofeedback in Virtual Reality: Feasibility, Efficacy and Self-reported Experience

Submitted as:

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Abstract

Normal gastric functioning (normogastria) is characterized by rhythmic gastric myoelectric activity, while dysrhythmic gastric activity (bradygastria and tachygastria) is associated with symptoms such as nausea, epigastric discomfort and fullness. Gastric Biofeedback using electrogastrography (EGG) has emerged as a promising tool to regulate gastric rhythm, but research remains limited with few experimental studies. The current study ($N = 94$) tested a novel gastric biofeedback training in virtual reality (VR). We used a randomized controlled study design with three groups: (1) VR gastric biofeedback training, (2) the same training on a 2D screen and (3) a relaxation control group. We examined (1) the trajectory of gastric activity before, during, and after training (2) participants' ability to increase normogastria and reduce dysrhythmic activity and (3) self-reported experiences (motivation, attention, mood, presence, user acceptance, etc.). Results showed the expected peak in normogastria and a nadir in dysrhythmic activity during training, with a significant reduction in dysrhythmic gastric activity across sessions. Participants reported improved dealing with physical discomfort over time. VR and 2D groups reported faster time perception and better concentration than controls. Spatial presence was higher in the VR group than in the 2D group. Enjoyment, concentration, and alertness were initially high but declined over time in all groups. The results demonstrate the general technical feasibility of the paradigm and positive evaluations. Further research is needed to better understand the underlying mechanisms and to determine whether and how training success may relate to beneficial outcomes in clinical populations.

Keywords: Gastric Biofeedback, Virtual Reality, Electrogastrography, Biofeedback

1 Introduction

1.1 Gastric Biofeedback

Normal gastric functioning (normogastria) is associated with rhythmic gastric myoelectric activity of three cycles per minute (cpm). By contrast, abnormal gastric functioning- typically presenting with symptoms such as nausea, epigastric discomfort and fullness - is linked to dysrhythmic gastric activity, namely bradygastria (1 - 2 cpm) or tachygastria (4 - 10cpm; K. L. Koch & Stern, 2004; Ogawa et al., 2004; van Dyck et al., 2020; Wolpert et al., 2020). In healthy individuals, water or food intake typically leads to an increase in normogastria (Diamanti et al., 2003; van Dyck et al., 2021) and a decrease in bradygastria and tachygastria (Diamanti et al., 2003; Mathur et al., 2001). Relaxation increases normogastria (Yin et al., 2004), while physiological stress seems to increase dysrhythmic gastric activity (Muth et al., 1999; Yin et al., 2004).

A promising approach to increase normal gastric activity and to reduce dysrhythmic activity (and, therefore, associated symptoms such as nausea, epigastric discomfort and stress) may involve gastric biofeedback (Stern et al., 2004; Vujic et al., 2020). Regulating the gastric rhythm may be beneficial in a range of conditions associated with gastric dysrhythmia, including eating disorders, functional dyspepsia, nausea and vomiting syndromes (Carson et al., 2022; Diamanti et al., 2003; Janssen et al., 2011; Ogawa et al., 2004; van Dyck et al., 2021). During biofeedback training, individuals learn to voluntarily modify their physiological activity (more commonly heart functioning or breathing) as they receive continuous visual or auditory feedback on their physiological activity (Schwartz, 2010). To date, research on gastric biofeedback is scarce, although some study results are promising in terms of feasibility (Stern et al., 2004; Whitehead & Drescher, 1980). The only non-invasive approach with cutaneous electrodes (without the need for swallowing tubes or inflating gastric balloons, such as in Whitehead & Drescher, 1980) was conducted by Stern et al. (2004) and has not been replicated since. In this study, healthy young students ($N = 26$) were able to increase their normal 3cpm gastric myoelectrical activity using gastric biofeedback of EGG signals (Stern et al., 2004).

1.2 Virtual Reality Biofeedback

An additional question is how the mode of visualization may affect training effects in biofeedback training. A particularly immersive and attention-capturing form of visual representation can be achieved using virtual reality (VR; Cipresso et al., 2018; Freeman et al.,

2017; Gradl et al., 2018). For multiple forms of biofeedback, VR implementations are gaining popularity. This includes, for example, biofeedback of heart rate variability (HRV), heart rate (HR), paced breathing or electrodermal activity (Lüddecke & Felnhofer, 2022). A recent comprehensive review reports higher motivation, involvement, attentional focus and more positive user experience in VR biofeedback compared to 2D feedback (Lüddecke & Felnhofer, 2022). We would assume, therefore, that self-reported evaluations are more positive in biofeedback involving VR than in those using other modes of implementation. These advantages may have a beneficial effect on training outcomes and may lead to lower dropout rates and higher compliance. Although some studies do indeed report better training outcomes for VR-biofeedback (Rockstroh et al., 2019; Weibel et al., 2023) other researchers are more hesitant regarding this conclusion (Cortez-Vázquez et al., 2024; Lüddecke & Felnhofer, 2022; Pratviel et al., 2024).

One reason for this caution concerns the fact that in the frequently used control 2D condition the presented scene differed substantially from the VR condition. For instance, it often consisted of a simplistic feedback signal (e.g., a pulsating dot on a dark background; Rockstroh et al., 2019) or simply involved an inactive control group (e.g., waitlist condition; Kerr et al., 2023). These mismatches complicate the interpretation of the results, as differences between conditions could stem from discrepancies in sensory input or engagement effects, rather than from the immersive quality of the VR environment per se. Thus, more studies comparing the same visual feedback, such as a recent study by Weibel et al., (2023) and Pratviel et al., (2024) on different mediums, are necessary. To the best of our knowledge, there are no studies to date implementing a gastric biofeedback paradigm in VR.

2 The present study

The goal of our study was to replicate the findings of Stern et al. (2004) regarding the feasibility and efficacy of gastric biofeedback in a group of healthy young adults, and to investigate potential additional effects of a novel form of visual representation using VR. In contrast to the study by Stern et al., (2004) where the EGG signal was visualized as a 2D wave signal, we implemented visual feedback into a nature environment. Nature environments have been suggested to provide a favorable balance between promoting relaxation while being sufficiently engaging (Gaume et al., 2016; Rockstroh et al., 2019; Yoon & Jeon, 2025). Therefore, our study design involved three experimental groups: (1) a VR gastric biofeedback group, (2) a 2D gastric biofeedback group (same scene as in VR but displayed on a TV screen) and (3) a relaxation

control group (CG). Biofeedback paradigms in VR are rarely compared with the same scene in 2D, with a few recent exceptions (Weibel et al., 2023). Therefore, the goal of the present paper was to assess the technical feasibility and efficacy as well as self-reported evaluations of the gastric biofeedback paradigm in VR, and to test whether it has advantages over the same 2D visualization and a relaxation condition in young healthy adults. Outcomes included (1) changes in the percentages of normogastria, bradygastria and tachygastria at baseline, during, and after the training, (2) group differences (VR, 2D and CG) in the percentages of normogastria, bradygastria and tachygastria across the four training sessions and (3) self-reported evaluations (including motivation, attention, mood, presence, user acceptance, etc.) between groups (VR, 2D and CG) across the four training sessions.

- (1) *Hypothesis 1*: We expected normogastria to be lowest after fasting, to increase during the training and to decrease again after a water load test until fullness (as this may cause nausea, and nausea is associated with less normogastria and more dysrhythmic activity). Respectively, we expected bradygastria and tachygastria to decrease from baseline to training, and to increase again following water ingestion until fullness.
- (2) *Hypothesis 2*: We expected participants in the VR group to show more pronounced increases and reductions in normogastric and dysrhythmic activity, respectively, across sessions than participants in the 2D group. We also hypothesized that participants in the 2D group would respond with stronger increases and reductions in normogastric and dysrhythmic activity, respectively, compared to the CG.
- (3) *Hypothesis 3*: We expected that participants in the VR group would show the most positive self-reported evaluations, followed by the 2D group and finally the CG.

3 Methods

3.1 Power Analysis and participants

We used G*Power to conduct an a-priori power analysis. To achieve a medium effect size ($f = 0.15$), with 3 groups (VR, 2D and CG) and 4 repeated measurements (4 sessions) a sample size of $N = 78$ is required ($\alpha = 0.5$; $1 - \beta = .80$). The study procedure, sample size, hypothesis 2 and hypothesis 3 were pre-registered (<https://doi.org/10.17605/OSF.IO/JSKPZ>). In addition, we also report on the trajectory of gastric activity before, during, and after training (hypothesis 1). 96 participants were recruited at the University of Fribourg through university platforms and flyers. Two participants were excluded because their four training sessions were more than two

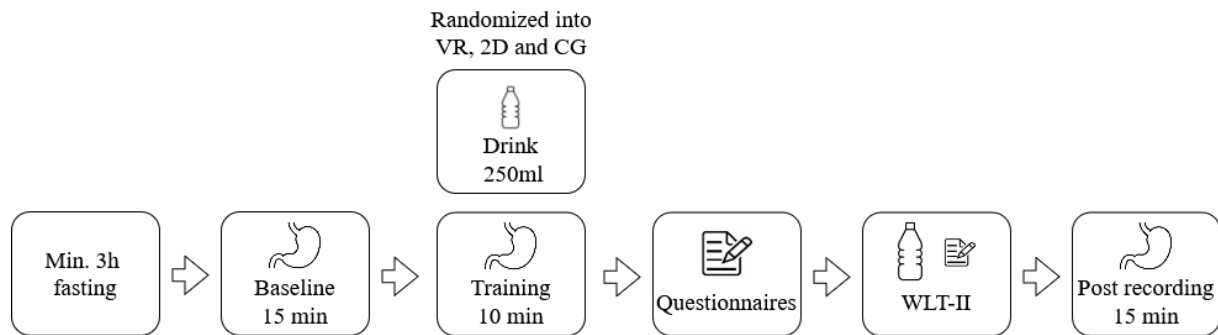
weeks apart, resulting in 94 participants (73 females, 21 males). Due to technical issues, data of 9 participants could not be used for the Igroup Presence Questionnaire (Schubert et al., 2001). For being included in the study participants needed to be at least 18 years of age. Exclusion criteria were a history of gastrointestinal illnesses or surgeries, medication that may modify gastric myoelectrical activity (e.g., prokinetics, antiemetics, narcotics, anticholinergic drugs, and nonsteroidal anti-inflammatory drugs), psychotropic medication, bipolar disorder, current or past psychotic disorders, current suicidal ideation, epilepsy, physical conditions or treatments affecting eating behavior or body weight. (e.g., diabetes mellitus) and pregnancy or breastfeeding. These exclusion criteria were based on similar studies using similar techniques/tasks (Blum et al., 2019; van Dyck et al., 2021) and recent guidelines for EGG by Wolpert et al. (2020). Ethical approval was obtained from the Internal Ethics Review Board of the Department of Psychology of the University of Fribourg (2023-824 R1) and the study was conducted in accordance with the declaration of Helsinki. Participants provided written informed consent before the start of the study.

3.2 Procedure

Participants were asked to fast and refrain from consuming any beverages for at least 3 hours before the study. They were compensated with a snack after the study and with study participation credits if applicable. Participants were randomly allocated to one of the following groups via block randomization (1) VR gastric biofeedback paradigm ($n = 30$), (2) 2D gastric biofeedback paradigm ($n = 32$) or (3) a relaxation CG ($n = 32$). The study consisted of four laboratory sessions within 2 weeks. Upon arriving in the laboratory, participants underwent a 15min baseline rest EGG measurement. Participants then drank 250ml of water, followed by a 10min training session (VR, 2D or CG). After the training, participants completed questionnaires. Finally, they performed the two-step water load test (van Dyck, Vögele, et al., 2016) involving water intake until fullness, followed by another 15min rest EGG. The same procedure was repeated in sessions 2, 3 and 4. The study procedure is depicted in figure 1.

Figure 1

Study procedure

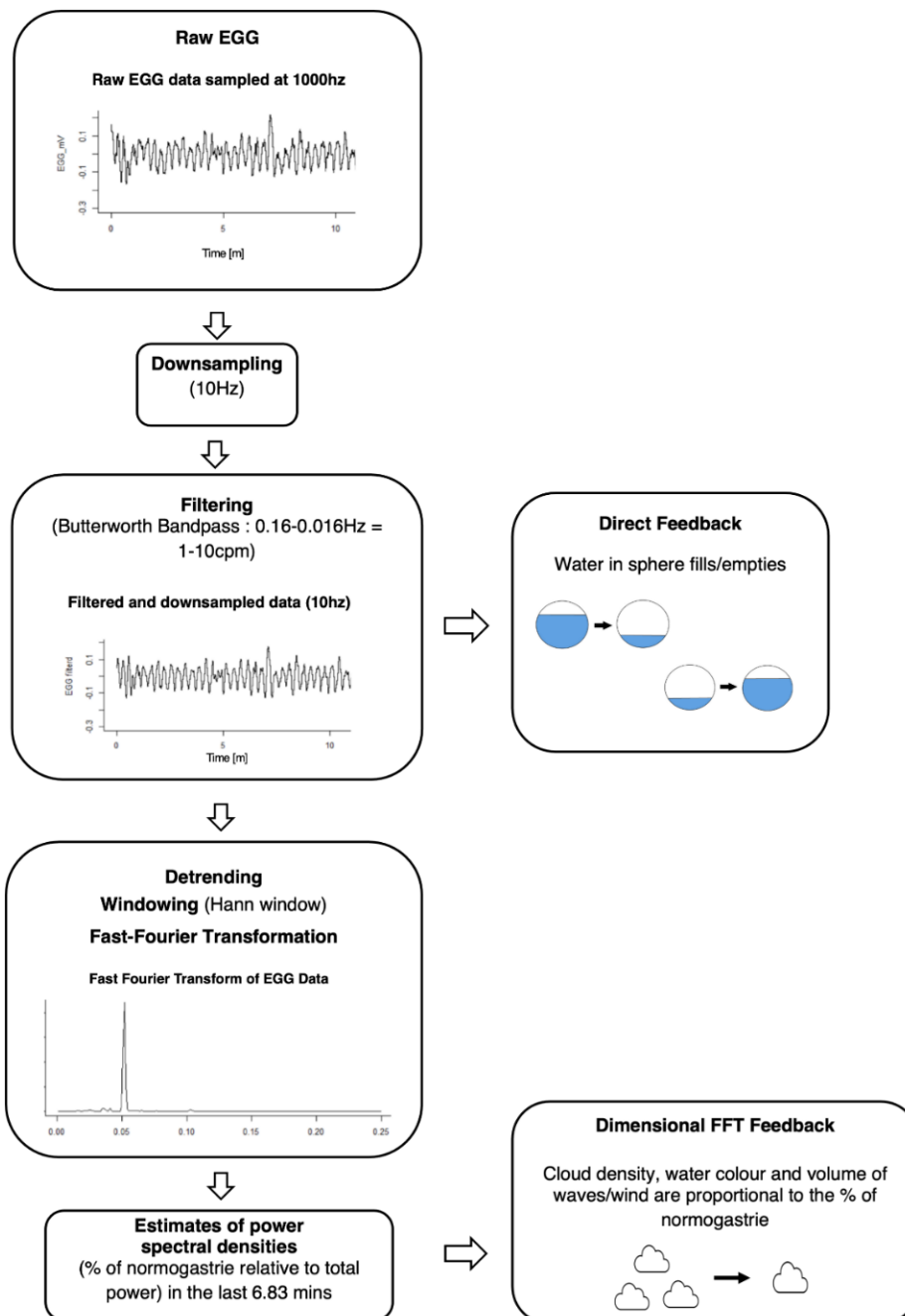


3.3 Materials

In our experimental setup, we employed a Windows 10 computer with 32 gigabytes of RAM, an Intel Core i5-12600K processor and a Nvidia GeForce RTX 3060 Ti graphics card. For the VR condition, participants watched the gastric biofeedback scene through an HTC Vive XR Elite VR headset (www.vive.com), with a resolution of 1920*1920 pixels per eye and a frame rate of 90 frames per second. In the 2D condition, participants were seated in front of a 31.5-inch TV screen, at a distance of 120 centimeters. During the baseline EGG measurement and during the VR, 2D or CG training session, all participants sat in a Lafuma RSX reclining chair (www.lafuma.com). Gastric myoelectric activity was measured using a Bluetooth BITalino device (Batista et al., 2019; da Silva et al., 2014) with a sampling rate set to 1000Hz and a 16-bit resolution. The gastric biofeedback paradigm was programmed using the Unity3D game engine (<https://unity.com/>). EGG raw data were livestreamed to the VR application using the PLUX Unity API (<https://github.com/pluxbiosignals/unity-sample>), and custom C# scripts were written to process real-time EGG data and translate them into the biofeedback visualization for participants (see figure 2). The same data processing was used for the baseline, training and post-training EGG recordings.

Figure 2

Signal processing for the direct feedback elements (transparent sphere) and the dimensional Fast Fourier Transform feedback elements (weather / environment). The raw EGG signal was sampled at 1000Hz. The signal was then downsampled to 10 Hz and filtered with a bandpass Butterworth filter with a frequency range of 0.016 to 0.16 Hz. This signal was used for the direct feedback. The signal was then detrended, Hann-windowed and Fast Fourier transformed. The plot shows the frequency components of normogastric activity with a peak frequency around 0.05 Hz. Finally, the result of the power spectral density estimation was used for the dimensional Fast Fourier transformed feedback



3.4 EGG baseline and post training recordings

For the 15 min rest EGG periods (baseline and after the training), we used the OpenSignals (r)evolution software for signal acquisition, a recommended choice for BITalino. Prior to electrode placement, respective areas of the skin were cleaned with alcohol and gently abraded using Nuprep gel (D.O. Weaver and Co., Aurora, CO, USA). As detailed in guidelines by Riezzo et al. (2013), we placed three abdominal electrodes (ConMed Cleartrace) over the gastric antrum region. The first active electrode was carefully positioned midway between the umbilicus and the xiphoid notch, while the second one was applied approximately 5cm to the right at an upper 45-degree angle. The ground electrode was placed on the left costal margin. During EGG recording, participants assumed a semi-reclining position in a comfortable chair tilted at an angle of approximately 30-45° (see figure 3). Participants were instructed to remain silent and minimize body movements throughout the recording process.

Data preprocessing of the two 15 min rest EGG periods was conducted using R (version 4.3.2, R Core Team, 2024), incorporating established data processing procedures (K. L. Koch & Stern, 2004; van Dyck et al., 2021; Wolpert et al., 2020). Signal data were visually inspected to assess overall quality and identify potential artifacts. Only continuous recordings devoid of artifacts and characterized by visually discernible waveforms were retained for analysis. The data was then down-sampled to a rate of 10Hz, subjected to detrending, and filtered using a bandpass Butterworth filter with a frequency range of 0.016 to 0.16 Hz (equivalent to 1-10 cpm as per Koch and Stern, 2004). We then applied a Hanning window and zero-padding to the nearest power of 2. To extract distinct frequency power bands, we performed a Fast Fourier Transformation (FFT). Specifically, we extracted the following power bands: bradygastria (1-2 cpm), normogastria (2-4 cpm), and tachygastria (4–10.0 cpm; as proposed by Wolpert et al., 2020). The power within each EGG band was subsequently computed as a percentage proportion of the total EGG band power within its corresponding frequency range.

3.5 Two Step Water-Load Test (WLT-II; van Dyck et al., 2016)

The WLT-II was administered after the training sessions. We used the WLT-II to measure changes in EGG frequency bands between the fasted state, training state and fullness state (after WLT-II, post-training, which might induce nausea and therefore increase dysthymic activity). The WLT-II consists of drinking water in two steps. First, participants drink water until satiation and then, in a second step, continue to drink until they experience fullness. The procedure is described in detail in (van Dyck, Vögele, et al., 2016).

3.6 Gastric Biofeedback Paradigm (VR and 2D)

Participants viewed biofeedback embedded into a virtual nature environment, a common design choice in this field (Blum et al., 2019; Lüddecke & Felnhofer, 2022; Rockstroh et al., 2019; Weibel et al., 2023). Due to their restorative and stress-reducing properties, as well as their ability to prevent monotony and boredom associated with simpler visualizations, (virtual) nature environments should be both relaxing and sufficiently engaging (Gaume et al., 2016; Rockstroh et al., 2019; Yoon & Jeon, 2025). Following the rationale by Rockstroh and colleagues (2019), we also considered attention restoration theory for nature environments. This theory emphasizes how certain environmental qualities can support cognitive recovery, such as the feeling of being away, stimuli that elicit involuntary attention or fascination, extension of space and to be aligned with one's goals (here biofeedback; R. Kaplan & Kaplan, 1989; S. Kaplan, 1995).

For both the VR and 2D groups, the experimental setup remained the same, differing only in the display medium (VR headset vs. television). Participants viewed an immersive nature environment featuring a lake and mountains (see figure 4), designed to provide biofeedback through different visual elements. Participants received direct feedback (Filtered Raw Signal) of their stomach activity, where two transparent spheres filled and drained with water in a rhythmic manner, floating above the lake. The left sphere acted as a pacemaker, maintaining a steady rhythm of three cpm (corresponding to the normogastric rhythm), while the right sphere reflected the participant's own EGG activity in real time (see figure 2). Participants also received dimensional FFT Feedback, in which participants' percentage of normogastric activity was represented through environmental changes, such as cloud density, water color, and variations in wind and water sounds (see figure 2). Higher normogastria resulted in sunnier weather with clearer skies.

Participants were instructed in German (see supplementary material S1), and were guided to use relaxation and controlled breathing to influence their own stomach activity (sphere on the right), aligning it with the pacemaker sphere's rhythm (sphere on the left). They were encouraged to focus on calm breathing and avoid stressing over perfect synchronization, as progress was indicated by the right spheres' movement and increasingly pleasant weather conditions.

3.7 Relaxation control group (CG)

The EGG data of participants in the CG was recorded in Unity and processed through the same pipeline as the other two groups. However, they did not see the scene and instead received spoken instructions (see supplementary material S1), to use relaxation and mental effort to influence their stomach activity, aiming to match the normal rhythm of three contractions per minute. They were guided to achieve this by breathing calmly, thinking of pleasant imagery like a beach day, and visualizing their stomach contracting like a balloon or water-filled ball inflating and deflating three times per minute, while minimizing movement and abdominal muscle contractions.

Figure 3

Experimental setup for the VR gastric biofeedback paradigm. The participant is seated in a reclining chair, wearing a VR headset and equipped with EGG electrodes



Figure 4

Virtual nature environment depicted in the gastric biofeedback paradigm



3.8 Questionnaires

3.8.1 Satisfaction with the gastric biofeedback paradigm

Three aspects of the gastric biofeedback paradigm were assessed on a visual analogue scale (VAS) from 1 to 10. This included a question about relaxation “*I found the scene relaxing*”, one on the visualization of the direct feedback “*I found the ball to be an intuitive visualization of my stomach activity*” and a final one on the FFT feedback “*I found the environmental visualizations (clouds, water, sounds) helpful in understanding my stomach activity*”. These questions were only administered in the two biofeedback (VR and 2D) groups, not in the CG.

3.8.2 General State Questions for Biofeedback Based on Rockstroh et al., (2019)

Motivational aspects and attentional focus were assessed based on items proposed by Rockstroh et al., (2019). Motivational aspects were measured with four questions regarding *general liking* (0 = *not at all*, 10 = *a lot*), *intention to use* (0 = *rarely*, 10 = *very often*), *recommendation to others* (0 = *not at all*, 10 = *very strongly*) and *time perception* (0 = *very slowly*, 10 = *very quickly*). Attentional focus was assessed with two items, *concentration* and *distraction* (0 = *not at all*, 10 = *completely*).

3.8.3 Multidimensional mood questionnaire (MDBF; Steyer et al., 1997).

Participants' mood was assessed with the MDBF. The MDBF consists of two parallel versions, making it useful for repeated measurements. Versions A and B were randomized. The questionnaire has three subscales, each consisting of four items, on a five-point Likert scale (1 = *not at all*, 5 = *very much*): *calmness vs. restlessness (RU)*, *good vs. bad mood (GS)* and *alertness vs. fatigue (WM)*. Higher values indicate better mood.

3.8.4 Igroup Presence Questionnaire (IPQ ; Schubert et al., 2001)

The sense of presence that individuals experience in a virtual environment was assessed with the IPQ. It consists of 14 items and three subscales (Likert Scale 1-6, with higher values indicating higher agreement): *spatial presence (SP; 5 items)*, which refers to feelings of physical presence in the virtual environment, *involvement (INV; 4 items)* measuring both attention to and involvement with the virtual scene, *experienced realism (REAL; 4 items)* to capture how real the environment is experienced and lastly, a single item measuring the sense of being there. The IPQ was only administered in the VR and 2D group to not confuse participants in the CG. The IPQ was also only administered in the VR and 2D group to avoid confusion in the CG group.

3.8.5 Virtual Reality sickness questionnaire (VRSQ; Kim et al., 2018)

Motion sickness symptoms in VR environments were assessed through the VRSQ. The questionnaire has two subscales: *oculomotor* (4 items: general discomfort, fatigue, eyestrain, difficulty focusing) and *disorientation* (5 items: headache, fullness of head, blurred vision, dizzy (eyes closed), vertigo). Answering options are on a 4-point Likert scale (1 = *not at all*, 4 = *very*).

3.8.6 User Acceptance Questionnaire for Biofeedback (UAQ; Klewinghaus & Martin, 2022)

User acceptance of the gastric biofeedback paradigm was assessed with the UAQ, which was designed to measure user acceptance of HRV biofeedback training. The questionnaire consists of seven items on a five-point Likert-scale (1 = *not at all*, 5 = *very strongly*). The questionnaire captures different aspects of user acceptance, including the influence of the biofeedback training on mood, stress, bodily state and bodily symptoms. It also assesses how satisfied participant are with the biofeedback training, how much they would transfer their acquired skills to everyday life and whether they experienced any unpleasant side effects.

3.9 Data Analysis

Statistical analyses were carried out with IBM SPSS Statistics Version 26 (SPSS Inc. Chicago, IL) and R version 4.3.2 (R Core Team, 2022) for Windows 11. The R packages lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), emmeans (Lenth, 2025), and ggplot2 (Wickham, 2016) were used for data analysis and visualization. For EGG data, outliers above or below three standard deviations from the group mean were set to their respective upper or lower value of three standard deviations.

For *hypothesis 1* (differences in EGG activity before, during and after training between groups), mixed-effects models were fitted to examine the fixed effects of group (VR, 2D and CG), and timepoint (pre-training, during training, post-training) for normogastria, bradygastria and tachygastria, and their interaction, with random intercepts for participants to account for repeated measures.

For *hypothesis 2* (changes of EGG activity during training along the four sessions between groups), we fitted mixed-effects models to examine the fixed effects of group (VR, 2D and CG) and session (sessions 1,2,3 and 4) for normogastric, bradygastric and tachygastric activity, and their interaction, with random intercepts for participants to account for repeated measures.

For *hypothesis 3* (differences in self-reported experiences between groups), we fitted mixed-effects models to examine the fixed effects of group (VR, 2D and CG) and session (sessions 1,2,3 and 4) and their interaction for self-report variables, again with random intercepts for participants to account for repeated measures.

Significance was set to 0.05. To follow up on significant effects, we used post-hoc pairwise comparisons using the estimated marginal means (EMM) with adjusted p-values through Tukey's HSD, in addition to effect sizes calculated with Cohen's d using the effsize package (Torchiano, 2020). Prior to the analyses, dependent variables were z standardized.

4 Results

4.1 Demographic characteristics

Table 1

Socio-demographic characteristics of participants

	VR (<i>n</i> = 30)	2D (<i>n</i> = 32)	CG (<i>n</i> = 32)	Total (<i>N</i> = 94)
Sex				
Female	26 (86.7%)	21 (65.6%)	26 (81.3%)	73 (77.7%)
Age	22.83	26.13	24.34	24.47
<i>M</i> (<i>SD</i>)	(3.53)	(12.38)	(7.05)	(8.57)
BMI	21.78	22.74	22.75	22.44
<i>M</i> (<i>SD</i>)	(2.37)	(3.01)	(2.79)	(2.75)

Note. **2D** = 2D Group (television). **BMI** = Body Mass Index. **VR** = Virtual Reality Group. **CG** = Control Group. *M* = Mean. *SD* = Standard Deviation.

4.2 Descriptives

Descriptive statistics of the variables included in the analyses can be found in Table 2 in the supplement S2.

4.3 Hypothesis 1: EGG Timepoint and Group Analysis

4.3.1 Normogastria

Normogastric activity significantly differed between Timepoints ($F(2, 966.93) = 86.56, p < .001$). Scores were significantly lower pre-training compared to during training ($p < .001, d = -1.00, 95\% \text{ CI } [-1.15, -0.85]$) and lower pre-training compared to post-training ($p < .001, d = -0.46, 95\% \text{ CI } [-0.61, -0.31]$). Conversely, scores were significantly higher during training compared to post-training ($p < .001, d = 0.55, 95\% \text{ CI } [0.39, 0.69]$; see figure 5). Normogastria did not significantly differ between Groups ($F(2, 93.81) = .07, p = .937$), albeit the interaction between Group and Timepoint was significant ($F(4, 966.70) = 4.25, p = .002$; see Table 3 in supplement S3).

4.3.2 Bradygastria

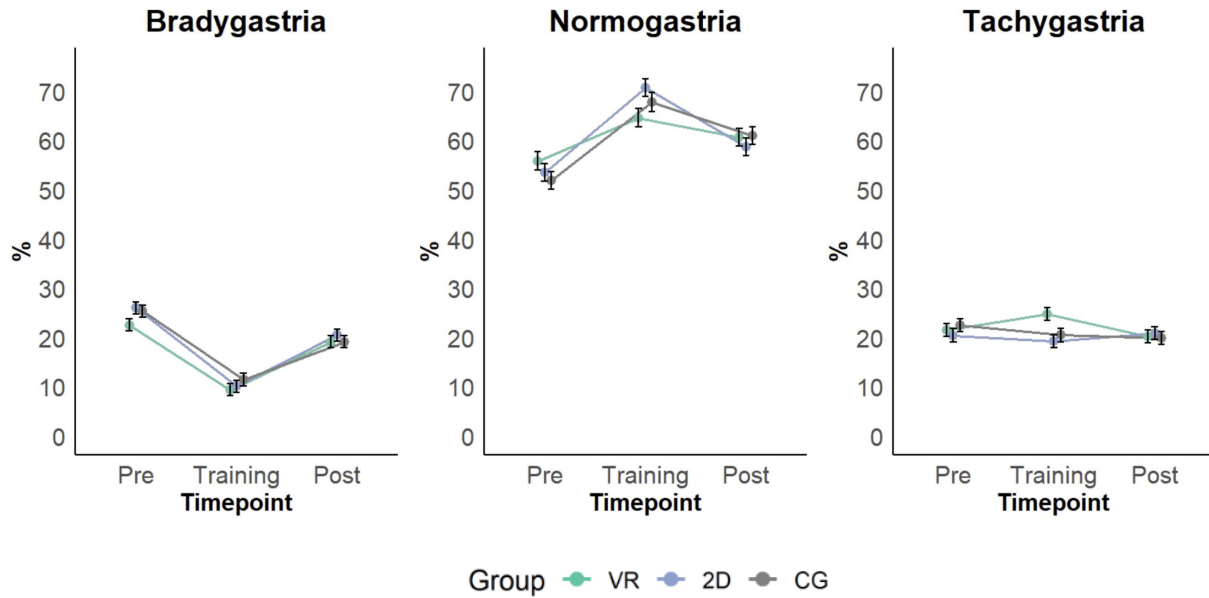
Bradygastria significantly differed between Timepoints ($F(2, 968.93) = 184.00, p < .001$). Scores were significantly higher pre-training compared to during training ($p < .001, d = 1.44, 95\% \text{ CI } [1.29, 1.59]$) and significantly higher pre-training compared to post-training ($p < .001, d = 0.50, 95\% \text{ CI } [0.36, 0.66]$). Conversely, scores were significantly lower during training compared to post-training ($p < .001, d = -0.93, 95\% \text{ CI } [-1.09, -0.78]$; see figure 5). Neither did bradygastric activity differ between Groups ($F(2, 94.29) = 1.11, p = .335$) nor was the interaction between Group and Timepoint significant ($F(4, 968.66) = 1.20, p = .310$).

4.3.3 Tachygastria

Tachygastria did not significantly differ between Timepoints ($F(2, 966.77) = 1.30, p = .272$) or Groups ($F(2, 91.68) = .86, p = .429$). Nevertheless, the interaction between Timepoint and Group was significant ($F(4, 966.50) = 3.33, p = .010$), with significantly lower values of tachygastric activity during training compared to after for the VR group ($p = .004, d = 0.41, 95\% \text{ CI } [0.16, 0.67]$; see figure 5). The difference between the VR group and 2D group during training was marginally significant ($p = .09, d = 0.50, 95\% \text{ CI } [0.16, 0.83]$), with the 2D group showing marginally significantly lower percentages of tachygastria than the VR group.

Figure 5

Bradygastria, Normogastria and Tachygastria for the VR, 2D and CG group before, during and after the gastric biofeedback training. Values were aggregated across the 4 sessions. Error Bars represent standard error of the mean (SEM)



4.4 Hypothesis 2: EGG Group and Session effects

4.4.1 Normogastria

Normogastria did not differ between Sessions ($F(3, 959.35) = .99, p = .394$) or Groups ($F(2, 92.51) = .22, p = .801$), nor was there an interaction effect between Session and Group ($F(6, 960.32) = .98, p = .435$; see figure 6).

4.4.2 Bradygastria

Bradygastria did not significantly between Sessions ($F(3, 962.15) = .28, p = .838$) and Groups ($F(2, 93.22) = 1.55, p = .217$). The interaction effect between Session and Group was not significant either ($F(6, 963.54) = .77, p = .596$; see figure 6).

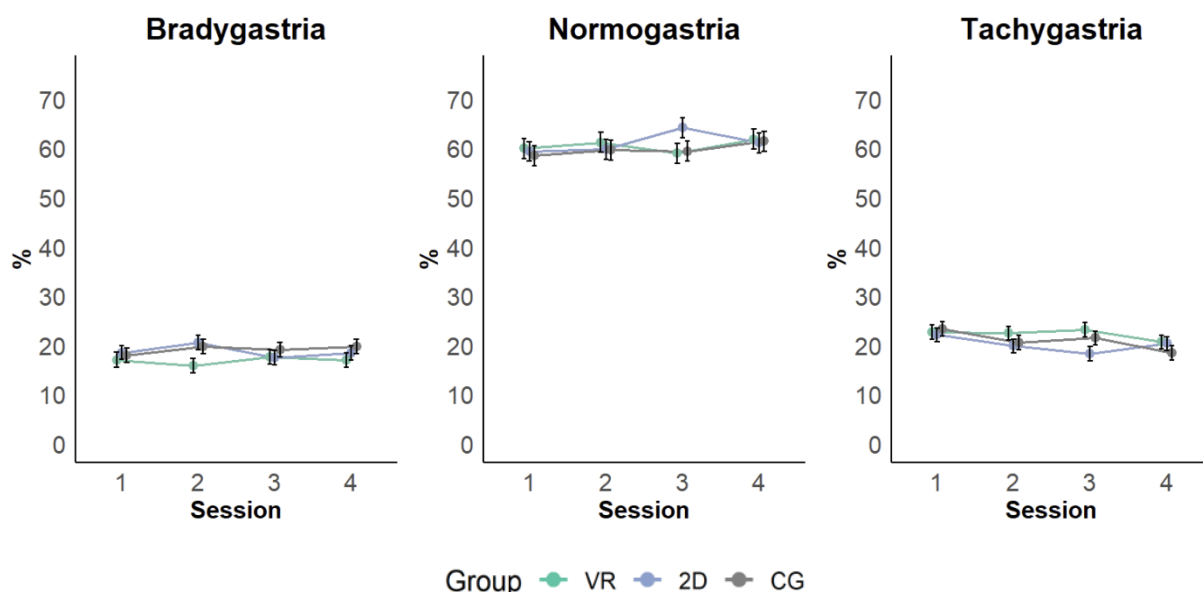
4.4.3 Tachygastria

Tachygastria significantly differed between Sessions ($F(3, 958.14) = 3.20, p = .023$). Scores in Session 1 were significantly higher compared to Session 4 ($p = .011, d = 0.27, 95\% \text{ CI } [0.10,$

0.44]; see figure 6). Tachygastria did not differ between Groups ($F(2, 91.26) = .99, p = .375$) and there was no interaction effect between Session and Group ($F(6, 959.13) = 1.33, p = .240$).

Figure 6

Bradygastria, Normogastria and Tachygastria for the VR, 2D and CG group during the gastric biofeedback training. Error bars indicate standard error of the mean (SEM)



4.5 Hypothesis 3: Self-reported Experience Variables

The results of the mixed models are presented in detail in Table 4 in the supplement S4. Here, we report the post-hoc comparisons derived from these models.

4.5.1 Satisfaction with the gastric biofeedback paradigm

There were no significant Timepoint, Group or Timepoint*Group effects for *how relaxing participants found the scene* and *how intuitive they found the visualization of their stomach activity* (see Table 4 in supplement S4). There was a significant main effect of Session for ratings of *perceived helpfulness of the environmental visualizations (clouds, water, sounds) in understanding stomach activity*. Scores were significantly lower in Session 1 compared to Session 3 ($p = .009, d = -0.58, 95\% \text{ CI } [-0.94, -0.22]$) and in Session 2 compared to Session 3 ($p = .019, d = -0.53, 95\% \text{ CI } [-0.89, -0.17]$). The difference between Session 1 and Session 4 was marginally significant, with scores being lower in Session 1 ($p = .094, d = -0.42, 95\% \text{ CI } [-0.78, -0.06]$).

[-0.78, -0.06]). No significant effects were observed for Group or Timepoint $\times$ Group (all $ps > .05$; see Table 4 in supplement S4).

4.5.2 Motivational aspects

We found a significant main effect of Session for *general liking* of the program. Scores for *general liking* were significantly higher in Session 1 compared to Session 3 ($p = .023$, $d = 0.42$, 95% CI [0.13, 0.71]) and Session 4 ($p = .021$, $d = 0.43$, 95% CI [0.14, 0.71]). No significant differences were observed between the other sessions (all $ps > .05$). There was no Group or Session $\times$ Group effect (see Table 4 in supplement S4). There were no Session, Group or Session $\times$ Group effects for *Intention to use* or *Recommendation to others* (see Table 4 in supplement S4). For *time perception*, the main effect of Session was marginally significant and there was a significant main effect of Group. Time was perceived as passing significantly faster in the 2D group compared to the CG ($p = .042$, $d = 0.59$, 95% CI [0.11, 1.07]) and the difference between the VR and CG was marginally significant, with time passing faster in the VR group ($p = .084$, $d = 0.53$, 95% CI [0.04, 1.02]). No significant differences were observed between the other Session or Group comparisons and the interaction between Session and Group was not significant (all $ps > .05$; see Table 4 in supplement S4).

4.5.3 Attentional focus

For *concentration*, we found significant main effects of Session and Group. Individuals indicated being significantly more concentrated in Session 1 compared to Session 3 ($p = .018$, $d = 0.43$, 95% CI [0.14, 0.72]) and Session 4 ($p < .001$, $d = 0.63$, 95% CI [0.34, 0.92]). They also indicated being significantly more concentrated in Session 2 compared to Session 4 ($p = .008$, $d = 0.47$, 95% CI [0.18, 0.76]). The difference in concentration between the VR and CG was marginally significant ($p = .064$, $d = 0.62$, 95% CI [0.08, 1.16]), and the 2D group compared to the CG was also marginally significant ($p = .093$, $d = 0.57$, 95% CI [0.03, 1.10]). No significant differences were observed between the other Session or Group comparisons and the Session by Group interaction was not significant (all $ps > .05$; see Table 4 in supplement S4). For *distraction*, there were no significant Session, Group or Session $\times$ Group effects (see Table 4 in supplement S4).

4.5.4 Mood: Multidimensional mood questionnaire (MDBF; Steyer et al., 1997)

For how *alert* individuals indicated to be, there was a significant effect of Session. Participants reported significantly more alertness in Session 1 compared to Session 3 ($p = .007$, $d = 0.47$, 95% CI [0.19, 0.76]) and Session 4 ($p = .025$, $d = 0.42$, 95% CI [0.13, 0.70]). The difference in

alertness between Session 1 and Session 2 was marginally significant, with people being more alert in Session 1 ($p = .056$, $d = 0.37$, 95% CI [0.08, 0.66]). No significant differences were observed between the other Session comparisons and there was no significant main effect of Group or Session $\times$ Group (all $ps > .05$). There was no significant main effect of Session, Group or Session $\times$ Group for *good mood* and *Rest (unrest)*; see Table 4 in supplement S4).

4.5.5 Presence: Igroup Presence Questionnaire (IPQ ; Schubert et al., 2001)

For *spatial presence*, there was a significant effect of Group, with individuals in the VR group reported higher levels of spatial presence than individuals in the 2D group ($p = .005$, $d = 1.22$, 95% CI [0.37, 2.07]). However, there was no significant effect of Session or Session $\times$ Group. There was no significant Session, Group or Session $\times$ Group effect of *involvement* or *realness* for the VR and 2D groups (see Table 4 in supplement S4).

4.5.6 VR Sickness Virtual Reality sickness questionnaire (VRSQ; Kim et al., 2018)

For the VRSQ, there was a marginally significant effect for Session, there was no significant main effect of Group, but there was a significant interaction between Session and Group, with significantly lower levels of VRSQ values in the CG in session 1 compared to session 2 ($p = .020$, $d = 1.06$, 95% CI [0.47, 1.64]; see Table 4 in supplement S4).

4.5.7 User Acceptance Questionnaire for Biofeedback (UAQ; Klewinghaus & Martin, 2022)

Participants reported that the training *improved how they dealt with physical discomfort (UAQ1)*, with a significant main effect of Session. Ratings were significantly increased from Session 1 to Session 3 ($p = .052$, $d = -0.38$, 95% CI [-0.67, -0.09]) and Session 4 ($p < .001$, $d = -0.61$, 95% CI [-0.90, -0.32]). Significant differences were also observed between Session 2 and Session 4 ($p < .001$, $d = -0.61$, 95% CI [-0.90, -0.32]) and was marginally significant compared to Session 3 ($p = .058$, $d = -0.37$, 95% CI [-0.66, -0.08]). No significant differences were found between Session 3 and Session 4 ($p = .362$, $d = -0.24$, 95% CI [-0.53, 0.05]). However, no significant main effect was found for Group or the interaction between Session and Group. For *UAQ 2-7*, there were no significant effects (see Table 4 in supplement S4).

5 Discussion

The present study examined the technical feasibility, efficacy and self-reported experience of a novel gastric biofeedback paradigm in VR, 2D and in a CG. In line with our hypotheses, normogastria significantly increased during training compared to baseline and significantly

decreased again post-training, while bradygastria followed an inverse pattern. Contrary to our hypothesis, we found no significant differences in the trajectory of EGG measures between experimental conditions, but a trend for tachygastria, which was lower in the 2D group than in the VR group during the training (medium effect, marginally significant). Additionally, tachygastria significantly decreased across sessions. We found no group differences for normogastria and bradygastria during training. As hypothesized, regarding self-reported assessment measures, both VR and 2D groups perceived time as passing more quickly and reported higher concentration compared to the CG. Additionally, spatial presence was higher in the VR group than in the 2D group. Contrary to our hypothesis, we did not find the VR condition to be superior to the 2D, and the 2D group to be superior to the CG for the remaining self-reported assessment measures. However, participants found the visualization of their stomach activity increasingly helpful over the course of the sessions and reported improved ability to manage physical discomfort across groups. Enjoyment, concentration, and alertness were initially high across groups but declined over time.

The first hypothesis could be confirmed for normogastria and bradygastria. Normogastria followed the expected trajectory, with scores peaking during training after a significant increase from pre-training and decreasing significantly post-training. The lower pre-training scores can be attributed to participants fasting at least three hours before arriving at the laboratory (K. L. Koch & Stern, 2004; Wolpert et al., 2020). Right before the training, participants ingested 250ml of water to stimulate gastric activity. The combination of water ingestion and training likely stimulated the observed increase in normogastria (K. L. Koch & Stern, 2004; Stern et al., 2004; van Dyck et al., 2021). After the training, participants performed the two-step water load test (van Dyck, Vögele, et al., 2016) which consists of ingesting water until fullness. Participants' normogastria significantly decreased afterward, likely due to the large volume of water consumed, which may have caused slight nausea and discomfort (K. L. Koch & Stern, 2004). Bradygastria showed an inverse pattern to normogastria, with levels significantly decreasing during training, reaching their lowest point during training, and increasing again post-training. This aligns with previous findings on bradygastria reductions following water ingestion (Diamanti et al., 2003). For tachygastria, the picture is more complex, which will be discussed below.

Regarding group differences, normogastria levels during training were highest in the 2D group and lowest in the VR group, although the differences between groups did not reach significance. For bradygastria, the active groups (VR and 2D) exhibited lower levels of

bradYGastria than the CG during training, although these group differences did not reach significance either. Although going in the expected direction, these results could not confirm our hypothesis, according to which participants would have the highest normogastria values in the VR group, followed by the 2D group and finally the CG (and an inverse pattern for bradYGastria).

For tachyGastria, we found a significant decrease from session 1 to session 4, indicating that levels of tachyGastria decreased across training sessions. During training, we found a trend for the 2D group, which showed lower levels of tachyGastria compared to the VR group, with a medium effect size that was marginally significant. This suggests that the VR condition had an arousing effect, counteracting the relaxation effect of the intervention and leading to higher sympathetic activation and corresponding elevated tachyGastria levels (Ruhland et al., 2008). Conversely, participants in the 2D group may have been able to focus on the task without being distracted by VR arousal, resulting in higher relaxation and thus parasympathetic activation (McCorry, 2007) reflected by a decrease in tachyGastria (Mazur et al., 2012).

Our results are difficult to compare to the gastric biofeedback paradigm of Stern et al., (2004) as they did not report sufficient details on bradYGastria and tachyGastria levels. Nevertheless, they observed a significant increase in normogastria during training in their experimental group compared to the CG, which featured a 2D visualization of a stereotypical 3cpm wave. While we observed a similar pattern for the 2D group for normogastria, and while bradYGastria was lowest in the active groups (VR and 2D), these effects did not reach significance. TachyGastria was lowest in the 2D group, which was marginally significant with a medium effect size compared to the VR group. Although not strongly pronounced, it is still possible that VR group experienced some degree of VR-related dizziness and nausea, which may have increased tachyGastria. Stern and colleagues (2004) reported that there were no differences in tachyGastria levels following gastric biofeedback training. It is possible that our training acted more on gastric dysrhythmias, while the training by Stern et al. (2004) had an effect on normogastria. It should also be noted that in their study, the mean percentage of normogastria during training was much lower (between 20% and 35%) than in the present study (around 60-70%). We would argue, therefore, that individuals with lower levels of normogastria are capable to increase their levels of normogastria more than individuals who already have high levels (ceiling effect, law of initial values). Notwithstanding these considerations, it seems possible that individuals are capable to reduce their levels of dysrhythmias through gastric biofeedback training (2D group) despite having high levels of normogastria.

Regarding the finding that the VR group was not superior to the 2D group, though contrary to our hypothesis, our results are consistent with a recent study on guided breathing in a sample of $N = 39$ healthy young sports students, which did not find additional beneficial effects on physiological changes in VR compared to non-VR biofeedback (Pratviel et al., 2024).

In conclusion, our findings indicate that gastric biofeedback training may help reduce gastric dysrhythmias in healthy young adults, as evidenced by a significant decrease in tachygastria across sessions. The lowest tachygastria levels were observed in the 2D group (medium effect size, marginally significant), suggesting that this condition may be particularly effective, without additional benefit of the VR condition. Additionally, both normogastria and bradygastria followed the expected trajectory from pre-training to post-training, supporting the validity of our EGG measurements. Importantly, gastric biofeedback based on EGG (independent of the mode of delivery) proved to be technically feasible and a low incidence of VR-related nausea reported.

For self-reported experiences, ratings were overall positive, with participants increasingly finding the *visualization of their stomach activity and environmental cues helpful* throughout the sessions. Participants also reported improved *management of physical discomfort* over time across all groups. This could be explained by the fact that in all groups, participants were asked to focus on their gastric sensations, independently on whether they received feedback or not. In this group of healthy young adults, this alone may have led to an improvement of body perception and emotion regulation, as shown by a recent intervention that demonstrated that especially attention to gastrointestinal activity improved body awareness and emotion regulation (Davey et al., 2023) and in our case plausibly may have improved subsequent dealing with uncomfortable physical sensations.

General liking, concentration, and alertness declined over the sessions, likely due to the long testing sessions (2.5 hours for sessions 1 and 4, and 1.5 hours for sessions 2 and 3). This decline may be explained by the novelty effect, where users have a preference for novel experiences (Bianchi, 1998; M. Koch et al., 2018). Greater *spatial presence* was reported in the VR group, which is in line with previous findings regarding spatial presence differences between VR and 2D (Kuhne et al., 2023). However, the 2D and VR group were comparable for *involvement* and *realness*. Both VR and 2D training formats demonstrated usefulness in increasing *concentration* and *reducing perceived time*. Overall, the VR did not show significant advantages over 2D regarding training outcomes or self-reported experience – indicating that a

2D version of gastric biofeedback may be a cost-effective and accessible option for broad application.

5.1 Strengths and limitations

The current study is the first implementation and evaluation of a gastric biofeedback training in VR, demonstrating the technical feasibility and promising effects of this novel method. Participant feedback was generally positive, indicating acceptability and engagement, especially in the first sessions. The study employed a randomized controlled trial design, ensuring comparable groups and reducing bias (Stolberg et al., 2004). A key strength was the inclusion of a highly controlled comparison group, together with a 2D condition that provided an identical visual experience for the VR group, which was missing in past VR biofeedback studies (such as Rockstroh et al., 2019). Nevertheless, there are also important limitations. As already noted, the VR condition may have induced arousal, potentially counteracting the intended relaxation effect of gastric biofeedback. In the future, this could be addressed by allowing more time for participants to habituate to the virtual environment. Moreover, the study lacked an accuracy test to confirm whether participants were truly able to link the feedback to their interoceptive sensations. While the strict control condition in this study enhances internal validity, it is possible that participants actively engaging in imagining and focusing on their stomach activity may have resulted in them undergoing some degree of unintentional training (Davey et al., 2023). Other VR based biofeedback studies used less stringent control conditions, such as inactive control conditions, non-contingent visual input, or plain 2D feedback, making their beneficial effects difficult to compare to stricter control conditions, such as the one in our study (Kerr et al., 2023; Rockstroh et al., 2019). These setups often do not control for participants' active engagement or expectations, making it difficult to disentangle the specific effects of VR biofeedback. In the present study, however, the CG received a similar degree of structure and instruction but without actual biofeedback, allowing for a more rigorous comparison. This stricter control might explain why differences between groups were smaller than those reported in studies with less controlled baselines.

Participants may have experienced monotony over time due to repeated exposure to the same visualization, particularly during the relatively lengthy sessions. This could have impacted engagement, as also reflected in the self-report questionnaires. Shorter but more frequent training sessions, aligned with participants' individual needs and contexts, may be more feasible and effective in real-world applications. Increasing variety within the environment, offering

alternative biofeedback visualizations, or enabling home-based training, particularly if 2D delivery proves sufficient, could further enhance usability and adherence. More sessions may also have supported deeper engagement and learning effects. As a laboratory-based study, our design is subject to the general limitations of such settings (Mitchell, 2012). Finally, a larger and more diverse sample would be beneficial in future studies, as the current sample may have been underpowered; observed effect sizes were smaller than the expected medium effects.

5.2 Future research directions and clinical implications

First, reducing participants' testing burden may be crucial in future research employing the gastric biofeedback paradigm to enhance its positive effects. Future studies could benefit from shorter, fewer and less demanding sessions. Most importantly, future studies should focus on testing the intervention in a clinical population with more pronounced gastric motility issues, as the current sample may have exhibited a ceiling effect, limiting the potential for measurable improvements. Especially in eating disorders, the gastric rhythm seems to be altered (Ogawa et al., 2004; van Dyck et al., 2021). Applying gastric biofeedback in the treatment of patients with eating disorders may be a valuable application of the current paradigm. Patients with depression (Ruhland et al., 2008), diabetes (Mathur et al., 2001), schizophrenia (Peupelmann et al., 2009) or other conditions that are accompanied by disturbances of the gastric rhythm could potentially also benefit from the intervention.

5.3 Conclusions

This study demonstrates that a novel gastric biofeedback paradigm is technically feasible and well accepted by participants. Expected changes in gastric activity during the sessions could be clearly generated. We observed group effects for time perception and concentration, with time passing faster in the 2D group compared to controls, and higher concentration in the biofeedback groups (2D and VR). All participants reported improvements in dealing with physical discomfort over time. Additionally, the training appears potentially promising in reducing dysrhythmic gastric activity (tachygastria) over time. We found a trend according to which the 2D group (and not the VR group) showed the greatest improvements, indicating that this format might be promising. It also suggests that a higher sense of presence in the scene might not be required for gastric biofeedback success in this sample. Yet, future studies will need to explore this further. These results offer new insights into the feasibility, efficacy, and experience of gastric biofeedback training, a perspective not yet extensively evaluated. Future research should focus on testing clinical populations to further confirm its efficacy.

Study 3: Listening to your stomach: Effects of gastric biofeedback training on interoception, eating behavior and eating disorder symptoms

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Abstract

Gastric interoception, the sensing of signals from the stomach, plays a central role in regulating hunger, satiety, and fullness and is closely linked to eating behaviors and symptoms of eating disorders (EDs). Gastric motility has been identified as a key mediator of hunger and satiety, with altered gastric rhythms being observed in individuals with EDs. Enhancing gastric interoception by targeting gastric rhythms may therefore offer a promising intervention strategy. This study examined the effects of a novel electrogastrography (EGG)-based gastric biofeedback training delivered using virtual reality (VR) or a two-dimensional (2D) display, compared with a control condition. A sample of healthy university students ($N = 94$) participated in four biofeedback sessions over two weeks. We assessed cardiac, gastric, and general interoception, together with self-report measures of eating behavior (emotional, external, restrained, and intuitive eating) and ED symptoms. We expected biofeedback training to improve interoception, eating behaviors, and to reduce ED symptoms, with the strongest effects in the VR group, followed by the 2D group, and the weakest effects in the control group. Linear mixed model analyses revealed that the 2D condition was the most effective, showing the greatest improvements in gastric and general interoception (specifically satiation and fullness sensing, and body listening), as well as intuitive eating. These findings suggest that 2D gastric biofeedback may be an effective and accessible approach to interoception training which can potentially be applied in home settings. Future research should explore its clinical utility in populations with EDs.

Keywords: Gastric Biofeedback, Biofeedback, Interoception, Interoception Training, Eating Behavior, Eating Disorders

1 Introduction

Disordered eating behavior represents a severe and increasingly prevalent health issue, particularly among young women, which often progresses to an eating disorder (ED; Alharbi et al., 2024; Nolan et al., 2023; Schuler et al., 2024). EDs include anorexia nervosa (AN), bulimia nervosa (BN) and binge-eating disorder (BED; American Psychiatric Association, 2013); they often follow a chronic course with high relapse rates (Santomauro et al., 2021). In addition, EDs are associated with substantial health burdens, including increased risk of depression, suicide, substance use, and mortality, and they contribute significantly to disability-adjusted life years (DALYs; Alharbi et al., 2024; Arcelus et al., 2011; Fichter & Quadflieg, 2016; Herpertz-Dahlmann, 2015; Santomauro et al., 2021; K. Wang et al., 2024). With approximately 50% of patients failing to achieve full or sustained recovery, particularly in restrictive disorders such as AN, early detection and the development of accessible, low-threshold interventions remain essential (Herpertz-Dahlmann, 2015; Linardon et al., 2016, 2017).

An important process for healthy eating, which has been shown to be altered in disordered eating, concerns interoception (Cusack et al., 2022; Herbert et al., 2013; Jacquemot & Park, 2020; Linardon et al., 2021; Martin et al., 2019; Robinson, Foote, et al., 2021). Interoception refers to the sensing, interpretation, and integration of internal bodily signals, including cardiac, gastric, and respiratory cues, as well as pain and touch, processed by the central nervous system (Khalsa et al., 2018). Altered interoception such as over-, misinterpretation, or the inability to correctly sense inner bodily processes has been suggested as a transdiagnostic factor contributing to mental health conditions, including depression, anxiety, substance abuse, and emotion dysregulation (Keski-Rahkonen & Mustelin, 2016; Khalsa et al., 2018; Martin et al., 2019; Pollatos et al., 2009; Schuette et al., 2021). There is further evidence that altered interoception plays an essential role in the etiology of EDs and ED symptoms, where hunger and satiety regulation problems represent the core symptoms (Cusack et al., 2022; Jacquemot & Park, 2020; Martin et al., 2019). This aligns with network analysis findings, which have consistently identified altered interoception as a central component of ED symptomatology (Cusack et al., 2022; Monteleone et al., 2019; Olatunji et al., 2018).

While evidence-based treatments for ED often directly focus on regulating food intake (DGPM & DGKJP, 2022), it has been suggested to further explore, and possibly target, underlying maladaptive mechanisms such as disturbed interoception which may give rise to ED symptoms (Cusack et al., 2022; Martin et al., 2019; Olatunji et al., 2018; van Dyck & Lutz, 2022). Previously, the interchangeable use of different interoceptive dimensions has led to

inconsistencies in findings, necessitating a more precise distinction between them (Forkmann et al., 2016; Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022). To specify the role of different interoceptive dimensions on eating behavior and ED symptoms, our study differentiates between *objective physiological states* (e.g., cardiac activity), *cardiac interoceptive accuracy* (behavioral performance in sensing physiological signals, such as heartbeat tracking), *gastric interoceptive sensitivity* (sensitivity to gastric signals, measured through water load tasks), *interoceptive self-report* (subjective self-reports of interoceptive abilities, assessed via questionnaires or confidence ratings), *gastric attribution of interoceptive sensations* (cognitive interpretation and causal attribution of bodily sensations, such as associating gastric fullness with negative affect) and *cardiac interoceptive insight* (metacognitive evaluation of interoceptive ability, typically assessed through the correspondence between accuracy and confidence; Forkmann et al., 2016; Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022; van Dyck, Vögele, et al., 2016). For a summary of current definitions, see Suksasilp & Garfinkel (2022).

Clinical and subclinical ED symptoms have been associated with broad interoceptive impairments across different interoceptive domains, including the gastric domain, the cardiac domain, and pain (Datta et al., 2021; Jenkinson et al., 2018; Martin et al., 2019). Gastric interoception appears to play a role in the sensing and regulation of eating-specific signals, such as hunger, satiety and fullness (Poovey et al., 2022; van Dyck et al., 2021) and seems especially important in the context of eating behavior and ED symptoms (Ahlich et al., 2023; Brown et al., 2022; Davey et al., 2023; Iatridi et al., 2021; Poovey et al., 2022; Todd et al., 2020; van Dyck et al., 2021). For example, difficulty in recognizing and responding to hunger and satiety signals has been associated with a higher likelihood of engaging in disordered eating (Poovey et al., 2022). Likewise, women with an ED tend to rely less on hunger and satiety cues than those without the disorder (van Dyck, Vögele, et al., 2016), and individual differences in hunger sensing have been associated with uncontrolled eating (Stevenson et al., 2023). Recent evidence suggests that gastric interoceptive self-report (i.e., sensing of hunger and satiety) differs across ED diagnoses (Ortmann et al., 2024). Individuals with AN report lower hunger sensitivity and elevated satiety sensitivity, whereas those with BN and BED tend to show reduced satiety sensitivity and difficulties distinguishing hunger from emotional states (Ortmann et al., 2024).

At a physiological level (*objective physiological state*), gastric motility has been proposed as key mediator of hunger and satiety (Janssen et al., 2011). In line with this, the gastric rhythm (myoelectric gastric activity) seems to be altered in women with BN and BED

(Alyami et al., 2023; K. L. Koch et al., 1998), with lower levels of normal gastric activity after ingesting water (water load task) in the laboratory (Diamanti et al., 2003; Ogawa et al., 2004; van Dyck et al., 2021). Thus, targeting this gastric rhythm to improve gastric interoception in the context of eating behavior appears to be a promising approach.

In the cardiac and respiratory domains, interventions targeting the feedback of physiological signals to improve interoception regarding heart rate and breathing rhythm show promising results (Hodossy et al., 2021; Leganes-Fonteneau et al., 2021; Meyerholz et al., 2019; Rominger et al., 2021; Schaefer et al., 2014; Schillings et al., 2022; Sugawara et al., 2020). Biofeedback enables individuals to view otherwise invisible bodily signals (e.g., gastric and cardiac activity). This may lead to improved body signal sensing and might allow their modulation, possibly leading to an improvement in somatic symptoms and lower symptom burden in conditions associated with impaired interoceptive accuracy (Meyerholz et al., 2019; Schaefer et al., 2014). While biofeedback is well established in the cardiac and respiratory domain, only a few studies on gastric biofeedback have been conducted so far (Stern et al., 2004; Whitehead & Drescher, 1980) and none have examined the effects on interoception, eating behavior or ED symptoms. It remains unclear which mechanisms of interoceptive functioning are specifically linked to particular eating styles, individual symptoms, or distinct types of EDs. While the display of body signals on computer screens is a viable option in biofeedback, recent research has additionally explored the use of virtual reality (VR) to further enhance its efficacy due to increased immersiveness (Houzangbe et al., 2020; Kerr et al., 2023; Kothgassner et al., 2022; Lüddecke & Felnhöfer, 2022; Rockstroh et al., 2021). Higher immersion may increase motivation and potentially enable an increased identification with the biofeedback signal and thus promote better training effects (Rockstroh et al., 2019); however, from an accessibility standpoint, 2D formats are more easily scalable and can be applied by users independently on their personal devices (e.g., computer screens, television screens, or smartphones). The present study thus examines the effects of a novel gastric biofeedback paradigm in a VR, 2D and a relaxation control group (CG) on interoception, eating behavior and ED symptoms in a large sample of young students. Given known associations between interoception and individual factors such as BMI and depression (Furman et al., 2013; Pollatos et al., 2009; Robinson, Foote, et al., 2021) as well as sex differences in the prevalence and clinical presentation of EDs (Welch et al., 2015), these variables were controlled for in the present study.

2 Hypotheses

1. Gastric biofeedback training is associated with improved interoception relative to a CG. Among the two gastric biofeedback conditions, the VR condition is associated with greater improvement compared to the 2D condition.
2. Gastric biofeedback training is associated with improved eating behavior scores relative to a CG. Among the two gastric biofeedback conditions, the VR condition is associated with greater improvement compared to the 2D condition.
3. Gastric biofeedback training is associated with reduced in ED symptoms relative to a CG. Among the two gastric biofeedback conditions, the VR condition is associated with greater improvement compared to the 2D condition.

3 Methods

3.1 Power analysis, participants and procedure

We performed an a priori power analysis using G*Power. To detect a medium effect size ($f = 0.15$) with three groups (VR, 2D, and CG) and four repeated measures across sessions, a sample size of $N = 78$ was determined to be necessary ($\alpha = 0.5$, $1-\beta = 0.80$). The study sample size, procedure and hypotheses were pre-registered <https://doi.org/10.17605/OSF.IO/3SXMT>. Additionally, we added sex as a covariate and removed the EDI-2 as an outcome variable due to conciseness reasons as one instrument to assess ED symptoms was considered sufficient. A total of 96 volunteers were recruited from the University of Fribourg through online university platforms and flyers. Two participants were excluded because their four training sessions were spaced more than two weeks apart, leaving a final sample of 94 participants (73 women, 21 men). Three participants failed to complete the post-questionnaire.

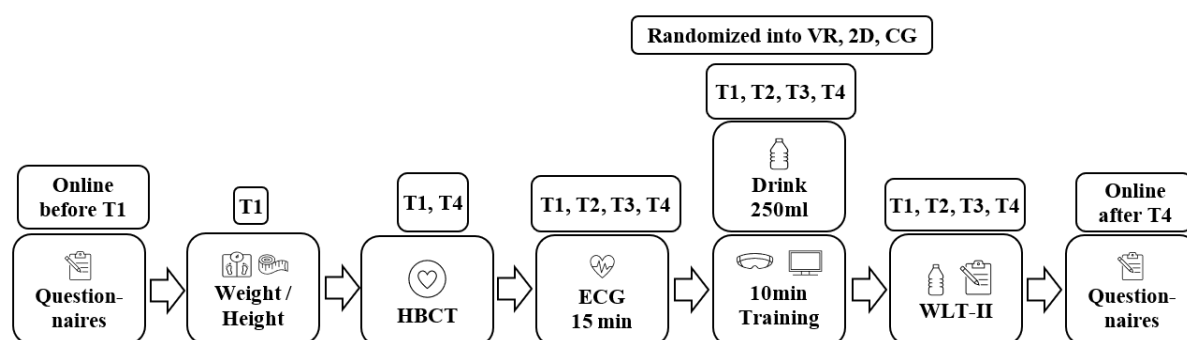
Eligibility required participants to be at least 18 years old. Exclusion criteria included pregnancy or breastfeeding, a history of gastrointestinal disorders or surgeries, the use of medications that could affect gastric myoelectrical activity (e.g., prokinetic agents, antiemetics, narcotics, anticholinergic drugs, and nonsteroidal anti-inflammatory drugs), psychotropic drugs, bipolar disorder, current or previous psychotic disorders, suicidal ideation, epilepsy, medical conditions or treatments that warrant prior treatment and might influence eating or weight (e.g., diabetes).

The study design received ethical approval from the Internal Ethics Review Board of the Department of Psychology at the University of Fribourg (2023-824 R1) and adhered to the principles outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants before the study began. Participants received course credits if eligible and were additionally compensated with a snack upon completion.

Participants were instructed to fast and avoid drinking any liquids for at least three hours before the experiment. The study followed a randomized controlled laboratory design. Participants were assigned through block randomization to one of three groups: (1) VR-based gastric biofeedback ($n = 30$), (2) 2D gastric biofeedback ($n = 32$), or (3) relaxation CG ($n = 32$). The study involved four laboratory sessions; all conducted within a two-week period. The study procedure is depicted in Figure 1.

Figure 1

Study procedure



Note. CG = control group. ECG = electrocardiogram. HBCT = heartbeat counting task (Schandry, 1981; implemented by Legrand et al., 2021). WLT-II = two-step water-load test (van Dyck et al., 2016). T1 = Time 1. T2 = Time 2. T3 = Time 3. T4 = Time 4. VR = Virtual Reality.

3.2 Gastric Biofeedback Paradigm (VR and 2D) and CG

The gastric biofeedback paradigm is described in more detail elsewhere (Tiemann et al., 2025). In short, electrogastragram (EGG) recordings were obtained using a Bluetooth BITalino device (1000Hz, 16-bit resolution; Batista et al., 2019; da Silva et al., 2014) connected to Unity 3D (<https://unity.com>). Following standard protocols (Riezzo et al., 2013), three electrodes were placed near the gastric antrum, and participants were instructed to remain still in a semi-reclined position during recording. Real-time data analysis in Unity 3D involved resampling (10Hz),

detrending, bandpass filtering (0.016-0.16Hz), and Fast Fourier Transform (FFT) to compute power across Bradygastria (1-2 cycles per minute; cpm), Normogastria (2-4 cpm), and Tachygastria (4-10 cpm) frequency bands (Stern et al., 2004; Wolpert et al., 2020). Normogastria values were then fed back to the participants. The experimental setup was the same for both the VR and 2D groups, with the difference being the display medium (VR headset vs. television). Participants were immersed in a relaxing nature scene featuring a lake and mountains (see figure 2). The gastric biofeedback consisted of two spheres floating above the lake, filling and emptying with water in a rhythmic way. The left sphere represented the pacemaker rhythm (three contractions per minute, indicating normal gastric rhythm i.e., Normogastria), while the right displayed the participant's real-time filtered EGG signal. Additional feedback was provided through cloud density, watercolor, and variations in environmental sounds, which changed based on how well their stomach activity aligned with the pacemaker. Participants were instructed to relax, breathe calmly, and reduce movement to influence their stomach activity and to adapt their own rhythm to the pacemaker. In the CG, participants received no visual feedback but were given similar spoken instruction. They were encouraged to relax, imagine stomach contractions at a rhythm of three per minute, and minimize movement.

Figure 2

Visualization in the gastric biofeedback paradigm



3.3 Interoception

3.3.1 Gastric interoceptive sensitivity: Two-step Water Load Test (WLT-II; van Dyck et al., 2016)

Participants underwent the WLT-II following the protocol described elsewhere (van Dyck, Vögele, et al., 2016). Participants were provided with non-carbonated water at room temperature, served in a non-transparent 5-liter flask with a long straw to control the size of each swallow. The flask was filled with 1.5 liters of water, though participants were unaware of this limit to ensure both their safety and the impression of an unlimited water supply. The procedure involved two 5-minute drinking phases: one until satiation and the other until maximum stomach fullness. During the first phase, they were asked to stop drinking when they felt the initial sensation of satiety, like when one would end a meal. In the second phase, they were instructed to continue drinking until they reached their maximum level of stomach fullness. The calculated indices included water volume ingested until satiation, additional volume consumed until maximum fullness, total water intake, and the percentage of water ingested at satiation relative to maximum fullness.

3.3.2 Gastric interoceptive self-report and gastric attribution of interoceptive sensations: Two-step Water Load Test (WLT-II) Questionnaire

Gastric interoceptive sensitivity and the attribution of interoceptive sensations were evaluated using the WLT-II questionnaire, which assesses sensations related to water consumption. Participants were instructed to focus on their abdominal sensations and rate their levels of satiation, fullness, and negative affect at three time points: before water ingestion (t_0), after the first drinking phase (t_1), and after the second drinking phase (t_2). Ratings of satiation and fullness were used to measure gastric interoceptive sensitivity, while the negative affect (NA) scale was used to assess the attribution of interoceptive sensations. The NA scale consists of five items (guilt, nausea, discomfort, sluggishness, and arousal) rated on a 7-point Likert scale (1 = no sensation, 7 = extreme sensation). In this study, we focused on the ratings obtained at t_2 (after water ingestion). The NA scale demonstrated poor internal consistency ($\alpha = .66$), which is lower than previous findings by van Dyck et al. (2016; $\alpha = .81$).

3.3.3 Gastric interoceptive self-report: Eating disorder-specific interoceptive perception questionnaire (EDIP-Q; Ortmann et al., 2024)

The eating disorder-specific interoceptive perception questionnaire (EDIP-Q; Ortmann et al., 2024) measures self-reported interoceptive sensations specifically related to EDs through four

subscales: Emotions (perception of emotions; seven items), Hunger (perception of hunger signals; five items), Satiety (perception of satiety signals; seven items), and Discrimination (i.e., discrimination between hunger and emotions; six items). Subscale scores are calculated by averaging responses on a 7-point scale (1 = *never* to 7 = *always*). Lower scores correspond to greater difficulties in EDIP. In the original validation study, Cronbach's alpha values for internal consistency were reported as $\alpha = .86$ for the emotions subscale, $\alpha = .93$ for both hunger and satiety, and $\alpha = .88$ for discrimination, indicating excellent reliability. In our study, Cronbach's alpha coefficients were $\alpha = .91$ for emotions, $\alpha = .70$ for hunger, $\alpha = .93$ for satiety, and $\alpha = .83$ for discrimination, suggesting good to excellent reliability overall. However, the internal consistency for the hunger subscale was slightly lower than in the original study.

3.3.4 Cardiac objective physiological state: mean heart rate (HR) and heart rate variability (HRV)

Electrocardiogram (ECG) was recorded during the training for each participant with a Bluetooth BITalino device (Batista et al., 2019; da Silva et al., 2014) with a sampling rate set to 1000Hz and a 16-bit resolution, connected to Unity 3D (<https://unity.com>). Before the recording, the participant's skin was cleaned with alcohol, and three disposable Ag/AgCl electrodes were applied to the chest following the Einthoven Triangle configuration (Einthoven et al., 1913). The positive and ground electrodes were positioned along the right and left costal margins, while the negative electrode was placed below the collarbone. Heart rate (HR) and heart rate variability (HRV) were analyzed using the software Kubios HRV 3.0 (Ranta-aho et al., 2014). Signals were visually inspected to identify and remove artifacts. The time series of inter-beat intervals (IBI) was detrended using the smooth priors' method ($\lambda = 500$). A FFT was performed with Welch's periodogram, using a window width of 300 seconds, 50% overlap, and a 4 Hz resampling rate. The following HRV measures were derived from the RR-interval series: (1) the root mean square of successive differences (RMSSD) and (2) high-frequency normalized units (HFnu). RMSSD is a time-domain measure, while HFnu is a frequency-domain measure. Both are closely linked and are considered indicators of parasympathetic nervous system activity (Allen et al., 2007; Cacioppo et al., 2000; Koval et al., 2013). Additionally, RMSSD has also been suggested to reflect sympathetic nervous system activation (Koval et al., 2013).

3.3.5 Cardiac interoceptive accuracy and cardiac interoceptive self-report: Heartbeat Counting Task (HBCT; Legrand et al., 2022) and confidence ratings

The Heartbeat Counting Task (HBCT) is a widely used method to assess cardiac interoceptive accuracy. The task was administered via computer using the Cardioception software, running on the latest installation of Anaconda for Python 3.7 (Legrand et al., 2022). Participants' heart rate was recorded using a Nonin 3012LP Xpod USB pulse oximeter paired with Nonin 8000SM soft-clip finger sensors. In addition to the standard on-screen instructions provided by the software, participants received verbal instructions to ensure clarity. The task was divided into six randomly ordered intervals of varying durations (25s, 30s, 35s, 40s, 45s, and 50s). At the start and end of each interval, an auditory cue signaled participants when to begin and stop counting their heartbeats. After each interval, participants reported the number of heartbeats they sensed on the computer interface. Cardiac interoceptive accuracy was calculated using the following formula, where the score reflects the correspondence between the actual number of recorded heartbeats and the participant's reported count. A score of 1 indicates a perfect match: $Score = 1 - ((actual\ heartbeats - reported\ heartbeats) / ((actual\ heartbeats - reported\ heartbeats) / 2))$. To assess cardiac interoceptive self-report, participants were asked to rate their confidence in their performance after each trial of the on the HBCT. Ratings were given on a scale from 0 to 9. Higher average scores reflect greater confidence in one's ability to perceive heartbeats during the HBCT.

3.3.6 Cardiac metacognitive insight

Cardiac metacognitive insight (known as the metacognitive evaluation of interoceptive ability) was calculated as the within-person Pearson correlation between cardiac interoceptive accuracy and cardiac interoceptive self-report (confidence rating on the HBCT), as is common in the field (Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022).

3.3.7 General interoceptive self-report: Multidimensional Assessment of Interoceptive Awareness – Version 2 (MAIA-2; Mehling et al., 2018)

The MAIA-2 (Mehling et al., 2018) is a revised self-report instrument designed to assess various facets of interoceptive body awareness. It includes 37 items across eight subscales: (1) Noticing (e.g., "I notice when I am uncomfortable in my body"), (2) Not-Distracting (e.g., "I distract myself from sensations of discomfort"), (3) Not-Worrying (e.g., "I can notice an unpleasant body sensation without worrying about it"), (4) Attention Regulation (e.g., "I am able to consciously focus on my body as a whole"), (5) Emotional Awareness (e.g., "I notice

how my body changes when I am angry"), (6) Self-Regulation (e.g., "*I can use my breath to reduce tension*"), (7) Body Listening (e.g., "*I listen for information from my body about my emotional state*"), and (8) Trusting (e.g., "*I feel my body is a safe place*"). Participants rated how often these statements applied to their daily experiences, using a scale from 0 ("never") to 5 ("always"). Higher scores indicate greater body awareness for each subscale. The MAIA-2 has shown improved psychometric properties over the original version, with improved internal consistency reliability (Mehling et al., 2018). In the present study, the German version of the MAIA-2 was used (Eggart et al., 2021). Internal consistency for the subscales ranged from $\alpha = .64$ to $\alpha = .83$, which was comparable to the present study, where values ranged from $\alpha = .68$ to $\alpha = .88$.

3.4 Eating behavior

3.4.1 Dutch Eating Behaviour Questionnaire (DEBQ; Nagl et al., 2016)

To measure emotional, external, and restrained eating behaviors, we used the German version of the Dutch Eating Behaviour Questionnaire (DEBQ; Nagl et al., 2016). This version comprises 30 items divided into three subscales: Emotional Eating (10 items), External Eating (10 items), and Restrained Eating (10 items). The Emotional Eating subscale assesses eating in response to emotional states, often negative (e.g., "*Do you have the desire to eat when you are emotionally upset?*"). External Eating captures eating triggered by external food-related cues (e.g., "*Do you eat more than usual, when others are eating?*"), while Restrained Eating evaluates attempts to limit food intake for weight management (e.g., "*Do you take into account your weight with what you eat?*"). Responses are rated on a 5-point Likert scale (1 = "*never*", 3 = "*sometimes*", 5 = "*always*"). Subscale scores are calculated by averaging the item responses, with higher scores indicating stronger tendencies for the respective eating behavior. The internal consistency of each subscale was high. In the German validation study by Nagl et al., (2016) Cronbach's alpha values were reported as .94 for Emotional Eating, .89 for External Eating, and .92 for Restrained Eating. In our sample, values were .96, .77, and .89, respectively. The overall questionnaire demonstrated good reliability, with an alpha of .93, comparable to the .94 reported in the original validation.

3.4.2 Intuitive eating scale – 2 (IES-2; van Dyck, Herbert, et al., 2016)

The Intuitive Eating Scale – 2 (IES-2) was used to assess participants' subjective estimation of intuitive eating across 23 items (Tylka & Kroon Van Diest, 2013). We employed the German version of the questionnaire (van Dyck, Herbert, et al., 2016). The IES-2 is structured around

four dimensions: (1) *Eating for Physical Rather than Emotional Reasons* (eating in response to physical hunger rather than to cope with emotional distress; eight items), (2) *Reliance on Hunger and Satiety Cues* (trusting internal physiological signals to determine when and how much to eat; six items), (3) *Unconditional Permission to Eat* (allowing oneself to eat when hungry and to choose desired foods without restrictions; six items), and (4) *Body-Food Choice Congruence* (the tendency to make food choices that support bodily health and functioning; three items). The total IES-2 score is calculated by averaging the scores from the four subscales. Participants responded using a 5-point Likert scale ranging from 1 ("*strongly disagree*") to 5 ("*strongly agree*"). Higher scores indicate greater intuitive eating. The German version showed a Cronbach's alpha of .91 (vs. present study .92) for the total IES-2, while subscale alphas ranged from .72 to .91 (vs. .71 to .89 in the present study), indicating comparable reliability.

3.5 ED symptoms

3.5.1 Eating Disorder Examination Questionnaire (EDE-Q8; Kliem et al., 2016)

Global ED psychopathology was measured using the 8-item short version of the Eating Disorder Examination Questionnaire (EDE-Q8), which was originally validated in German by Kliem et al. (2016). This short form includes two items from each of the four core subscales: Eating Concern, Weight Concern, Shape Concern, and Restraint. Participants rated their experiences over the past 28 days on a 7-point Likert scale (0 = "*no day*", 6 = "*every day*"). The total score, ranging from 0 to 6, is calculated by averaging the subscale means, with higher scores reflecting greater severity of ED psychopathology. The EDE-Q8 has demonstrated strong psychometric properties, including a high correlation with the original 36-item version of the Eating Disorder Examination Questionnaire (EDE-Q; Fairburn & Cooper, 1993) and an excellent internal consistency ($\alpha = .93$), which was comparable in the present study with $\alpha = .90$.

3.6 Covariates

3.6.1 Sex

Participants' self-reported sex was included as a covariate.

3.6.2 Body Mass Index (BMI)

Participants' height and weight were measured during the laboratory sessions to calculate their BMI using the formula: weight (kg) divided by height squared (m²). Measurements were taken using calibrated scales.

3.6.2 Depressive Symptoms

The German version of the DASS-21 (Depression, Anxiety, and Stress Scale-21; Nilges & Essau, 2015) is a self-report questionnaire designed to assess psychological distress across three dimensions: depression, anxiety, and stress. In the present study, we used the depression subscale, consisting of seven items. Participants are asked to rate how frequently they experience symptoms of depression over the past week. An example item is: "*I felt downhearted and blue*". Responses range from 0 ("*did not apply to me at all*") to 3 ("*applied to me very much or most of the time*") on a four-point Likert-scale. Higher scores reflect higher intensity of depressive symptoms. Internal consistency across for the depression subscale excellent ($\alpha = .91$; Nilges & Essau, 2015) which was comparable in the present study with $\alpha = .90$.

3.7 Data Analysis

Statistical analyses were conducted using IBM SPSS Statistics (version 26, SPSS Inc., Chicago, IL) and R (version 4.3.2; R Core Team, 2022). Data analysis and visualization were performed with the lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), emmeans (Lenth, 2025), and ggplot2 (Wickham, 2016) R packages.

For *hypothesis 1*, we calculated mixed-effects models with random intercepts for participants (to account for repeated measures) and fixed effects for group (VR, 2D and CG), session (sessions 1, 2, 3 and 4) and their interaction for the following variables: Mean HR, HRV (RMSDD), HRV (HFnu), WLT-II indices and WLT-II questionnaire data. For the EDIP-Q, the HBCT (HBCT scores, HBCT confidence ratings and cardiac interoceptive insight) and the MAIA-2 (and its subscales), we calculated mixed-effects models with a random intercept for participants and fixed effects for group (VR, 2D and CG), timepoint (pre-training and post-training) and their interaction. For *hypothesis 2* and *3*, we carried out mixed-effects models with random intercepts for participants and fixed effects for group (VR, 2D and CG), timepoint (pre-training and post-training) and their interaction for the DEBQ, IES-2 and EDE-Q8.

The significance of effects was evaluated using F-tests with a significance threshold set at $\alpha = .05$. For follow-up analyses and condition comparisons, pairwise post-hoc tests were performed using estimated marginal means (EMM) with Tukey's HSD correction applied to p-values. Effect sizes were computed as Cohen's d using the *effsize* package (Torchiano, 2020). Before conducting the analyses, all dependent variables were centered and standardized. We controlled for depression scores, BMI and Sex.

4 Results

4.1 Demographic characteristics

Sociodemographic characteristics of participants can be found in Table 1.

Table 1

Socio-demographic characteristics of participants

	VR (<i>n</i> = 30)	2D (<i>n</i> = 32)	CG (<i>n</i> = 32)	Total (<i>N</i> = 94)
Female	26 (86.7%)	21 (65.6%)	26 (81.3%)	73 (77.7%)
Age	22.83	26.13	24.34	24.47
<i>M (SD)</i>	(3.53)	(12.38)	(7.05)	(8.57)
BMI	21.78	22.74	22.75	22.44
<i>M (SD)</i>	(2.37)	(3.01)	(2.79)	(2.75)
DASS	4.59	3.42	4.89	4.27
Depression	(4.70)	(3.25)	(4.72)	(4.28)
<i>M (SD)</i>				

Note. **2D** = 2D Group (television). **BMI** = Body Mass Index. **VR** = Virtual Reality Group. **CG** = Control Group. *M* = Mean. *SD* = Standard Deviation.

4.2 Descriptives

Descriptive statistics of the variables included in the analyses can be found in Table A1 in the appendix A. At T1, no significant group differences were found for the outcome variables, except for RMSSD (2D > VR > CG). Compared to community samples, scores were slightly higher for intuitive eating (Tylka & Kroon Van Diest, 2013; van Dyck, Herbert, et al., 2016), and slightly lower for DEBQ values (Nagl et al., 2016; Wardle, 1987). EDE-Q8 scores aligned with previous non-clinical studies (Crawford & Henry, 2003). Values for measures of heartbeat perception (Herbert, Muth, et al., 2012; van Dyck, Vögele, et al., 2016), ECG (Brinth et al., 2024), and WLT-II (Davey et al., 2022; van Dyck et al., 2021; van Dyck, Vögele, et al., 2016) were also consistent with prior research. Model statistics for the covariates can be found in Table B1 in appendix B.

4.3 Hypothesis 1: Interoception

4.3.1 Gastric interoceptive sensitivity (WLT-II indices)

For the *additional water volume until maximum fullness*, there was a significant main effect of Session, with participants drinking significantly more water until fullness in Session 1 compared to Sessions 3 ($p = .032$, $d = 0.40$, 95% CI [0.11,.070]) and Session 4 ($p < .001$, $d = 0.62$, 95% CI [0.33,0.91]), as well as significantly more in Session 2 compared to Session 4 ($p = .005$, $d = 0.49$, 95% CI [0.20,0.78]; see Figure 3a). For the *percentage of satiation to maximum fullness*, there was a significant main effect of Session, with participants reporting a significantly higher ratio of satiation to fullness in Session 4 compared to Session 1 ($p < .001$, $d = 0.58$, 95% CI [-0.88,-0.29]) and Session 2 ($p < .001$, $d = 0.68$, 95% CI [-0.97,-0.39]). There was also a significant increase between Sessions 2 and 3 ($p = .023$, $d = 0.42$, 95% CI [-0.71, -0.13]; see Figure 3b). There were no Group $\times$ Time effects and no other significant effects for gastric interoceptive sensitivity (WLT-II indices; all $ps > .05$, see Table 2 and Figure 4a and 4b in the supplement).

4.3.2 Gastric interoceptive self-report and attribution of interoceptive sensations (WLT-II Questionnaire)

For *Satiation*, there was a significant main effect of Group, with the 2D group showing significantly higher satiation values after the WLT-II than the CG ($p = .002$, $d = 1.00$, 95% CI [0.42, 1.58]; see figure 3c). For *Fullness*, there was a significant main effect of Group with the VR group showing significantly lower levels of fullness after the WLT-II than the 2D group ($p = .031$, $d = -0.60$, 95% CI [-1.06, -0.14]; see figure 3d). There were no Group $\times$ Time effects or other significant effects for gastric interoceptive self-report (*Satiation* and *Fullness*), or for *Negative Affect* (*Attribution of interoceptive sensations*; all $ps > .05$, see Table 2 and Figure 4c in the supplement).

4.3.3 Gastric interoceptive self-report: EDIP-Q

For *EDIP-Q Satiety*, there was a significant main effect of Timepoint with higher values after the training ($p = .029$, $d = 0.33$, 95% CI [-0.63, -0.32]; see Figure 5b in the supplement). There were neither Group or Group $\times$ Time effects nor were there other significant effects for *EDIP-Q Satiety* or for *EDIP-Q Emotion*, *EDIP-Q Hunger* or *EDIP-Q Discrimination* (all $ps > .05$, see Table 2 and Figures 5a, 5b, 5c and 5d in the supplement).

4.3.4 Cardiac objective physiological state: ECG

For *Mean HR*, there was a significant main effect of Session, with significantly lower mean HR in Session 2 ($p = .039$, $d = -0.41$, 95% CI [-0.71, -0.11]) and Session 3 ($p = .048$, $d = -0.40$, 95% CI [-0.70, -0.10]) compared to Session 1 (see figure 4d in the supplement). For *HFnu*, there was a significant main effect of Group, with the VR group ($p < .001$, $d = -1.65$, 95% CI [-2.43, -0.86]) showing significantly lower HFnu than the CG and the difference between the 2D and CG being marginally significant ($p = .071$, $d = -0.87$, 95% CI [-1.65, -0.10]; see Figure 4f in the supplement). There were no Group $\times$ Time effects and no other significant effects for cardiac objective physiological state (ECG measures; all $ps > .05$, see Table 2 and Figure 4e in the supplement).

4.3.5 Cardiac interoceptive accuracy and self-report: HBCT

For *cardiac interoceptive self-report (confidence)*, there was a significant main effect of Timepoint, with significantly higher values of confidence on the HBCT after the training ($p = .001$, $d = 0.50$, 95% CI [-0.80, -0.20]; Figure 6b in the supplement). There were no Group or Group $\times$ Time effects and there were no significant effects for *cardiac interoceptive accuracy, self-report or insight* (all $ps > .05$, see Table 2 and Figures 6a and 6c in the supplement).

4.3.6 General interoceptive self-report: MAIA-2

For the *MAIA-2 total*, the *Self-Regulation*, *Trusting* and *Body Listening* subscale, there were significant main effects for Timepoint, with significantly higher values after the training (MAIA-2 total: $p = .017$, $d = 0.36$, 95% CI [-0.66, -0.07]; see Figure 6d in the supplement); *Self-Regulation*: $p = .005$, $d = 0.43$, 95% CI [-0.72, -0.14]; *Trusting*: $p = .023$, $d = 0.34$, 95% CI [-0.64, -0.05]; *Body Listening* $p = .016$, $d = 0.37$, 95% CI [-0.66, -0.07]). For *Body Listening*, there was also a significant Group effect in the VR group ($p = .020$, $d = 0.96$, 95% CI [0.26, 1.65]) and the 2D group ($p = .041$, $d = 0.85$, 95% CI [0.16, 1.55]) showing significantly higher values than the CG (see Figure 3e). There were no other significant effects for the *MAIA-2* or its subscales, with no Group $\times$ Time effects (all $ps > .05$, see Table 2).

4.4 Hypothesis 2: Eating Behavior

4.4.1 DEBQ

For restrained eating, there was a significant main effect of Timepoint with higher values after the training ($p = .029$, $d = 0.33$, 95% CI [-0.62, -0.04]; Figure 7b in the supplement). The Timepoint $\times$ Group interaction was significant, but post-hoc analyses did not yield significance.

All other effect for the *DEBQ* subscales were non-significant, all $ps > .05$ (see Table 2 and Figures 7a and 4c in the supplement).

4.4.2 *IES-2*

For the *IES-2* total, there was a significant Timepoint $\times$ Group interaction with the 2D group showing significantly higher values after the training ($p = .048$, $d = 0.73$, 95% CI [-1.23, -0.24]; see Figure 3f). For *Eating Physical Rather than Emotional Reasons* there was a significant Timepoint $\times$ Group interaction with the 2D group showing marginally significantly higher levels of eating for physical rather than emotional reasons after the training ($p = .086$, $d = 0.68$, 95% CI [-1.17, -0.18]). For *Reliance on Hunger Satiety Cues*, there was a significant main effect of Timepoint with higher values after the training ($p = .026$, $d = 0.33$, 95% CI [-0.63, -0.04]). The Timepoint $\times$ Group interaction was significant, with the 2D group showing marginally significantly higher values after the training ($p = .099$, $d = 0.66$, 95% CI [-1.16, -0.16]). There were no other significant effects for the *IES-2*, all $ps > .05$ (see Table 2).

4.5 Hypothesis 3: *ED symptoms*

4.5.1 *EDE-Q8*

The main effect of Group and the interaction Timepoint $\times$ Group were marginally significant, while the Timepoint effect was not significant (see Table 2 and Figure 7d in the supplement).

Figure 3

(a) Amount of water consumed until fullness on the WLT-II (in mL), (b) percentage of water consumed from satiation in ratio to fullness on the WLT-II, (c) satiation and (d) fullness ratings on the WLT-II questionnaire, (e) Body Listening (MAIA-2) and (f) total intuitive eating (IES-2) for the VR, 2D and CG group along the four experimental the VR, 2D and CG group along the four experimental

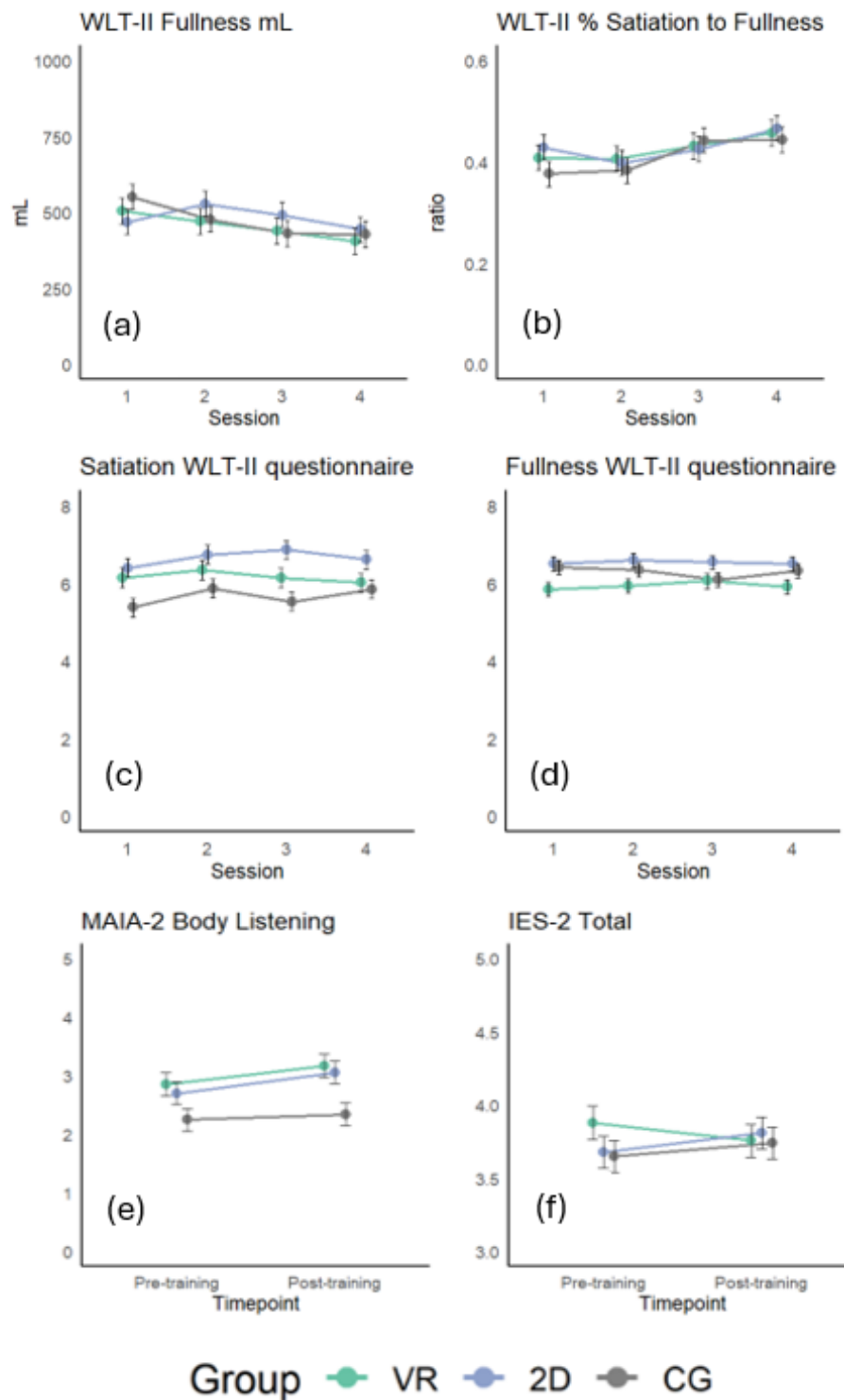


Table 2*Mixed-model ANOVA results for interoception, eating behavior and eating disorder symptoms*

	Group		Time		Group × Time	
	<i>F</i> (df1,df2)	<i>p</i>	<i>F</i> (df1,df2)	<i>p</i>	<i>F</i> (df1,df2)	<i>p</i>
WLT-II						
Sat ml	0.43(2, 10.71)	.653	2.56(3, 269.26)	.055	0.24(6, 269.22)	.964
Full ml	0.07(2, 96.47)	.928	7.18(3, 269.46)	<.001	1.96(6, 269.47)	.071
Total ml	0.02(2, 99.82)	.983	2.08(3, 269.61)	.103	1.17(6, 269.56)	.322
% sat to full	0.58(2, 94.95)	.561	9.02(3, 269.08)	<.001	0.92(6, 269.14)	.482
WLT-II-Q						
Satiation	5.82(2, 94.00)	.004	2.17(3, 271.33)	.092	0.98(6, 271.47)	.441
Fullness	3.49(2, 91.52)	.035	0.10(3, 271.27)	.962	0.63(6, 271.57)	.703
Negative Affect	0.76(2, 96.65)	.469	0.77(3, 271.39)	.514	1.65(6, 271.44)	.135
EDIP-Q						
Satiety	0.20(2, 87.15)	.821	0.14(1, 85.90)	.713	0.47(2, 86.08)	.629
Emotion	0.01(2, 89.29)	.987	4.91(1, 87.79)	.029	1.15(2, 87.95)	.321
Discrimination	1.38(2, 87.59)	.258	0.00(1, 86.62)	.949	0.27(2, 86.81)	.766
Hunger	0.57(2, 88.21)	.566	0.61(1, 87.83)	.436	0.32(2, 88.01)	.727
ECG						
Mean HR	0.64(2, 92.23)	.530	3.11(3, 246.14)	.027	1.89(6, 246.08)	.083
HRV (RMSSD)	0.56(2, 88.48)	.576	1.75(3, 245.89)	.157	0.86(6, 245.90)	.524
HRV (HFnu)	8.76(2, 88.08)	< .001	1.49(3, 246.13)	.217	1.49(6, 246.15)	.182
HBCT						
Score	1.88(2, 88.43)	.159	0.86(1, 86.69)	.356	1.86(2, 86.87)	.162
Confidence	1.09(2, 89.97)	.340	11.09(1, 88.31)	.001	0.36(2, 88.49)	.700
Insight	0.45(2, 84.23)	.639	0.39(1, 83.09)	.536	2.00(2, 83.26)	.142
MAIA-2 total	1.09(2, 87.16)	.340	5.96(1, 86.06)	.017	0.36(2, 86.24)	.697
Eating behavior						
DEBQ EE	0.02(2, 87.90)	.978	0.01(1, 86.27)	.933	1.88(2, 86.40)	.159
DEBQ EX	0.18(2, 89.58)	.837	0.56(1, 88.35)	.458	2.47(2, 88.53)	.091
DEBQ RE	0.88(2, 87.76)	.419	4.93(1, 86.36)	.029	3.64(2, 86.53)	.030

Table 2 (continued)

	Group		Time		Group × Time	
	<i>F</i> (df1,df2)	<i>p</i>	<i>F</i> (df1,df2)	<i>p</i>	<i>F</i> (df1,df2)	<i>p</i>
IES-2 total	0.21(2, 89.18)	.815	1.37(1, 87.56)	.245	7.63(2, 87.71)	<.001
IES-2 UPE	0.21(2, 89.29)	.808	0.72(1, 88.22)	.399	1.96(2, 88.41)	.147
IES-2 EPR	0.13(2, 89.09)	.878	1.24(1, 87.56)	.268	4.20(2, 87.72)	.018
IES-2 RHSC	0.09(2, 89.41)	.916	5.12(1, 87.94)	.026	4.10(2, 88.10)	.020
IES-2 B-FCC	0.58(2, 88.18)	.562	0.00(1, 87.16)	.999	2.50(2, 87.35)	.088
ED symptoms						
EDE-Q8	2.69(2, 87.44)	.073	0.09(1, 85.87)	.762	2.67(2, 86.02)	.075

Note. **2D** = 2D Group (television). **B-FCC** = Body-Food Choice Congruency IES-2. **CG** = Control Group. **DASS** = Depression, Anxiety, Stress Scale – 21 (Nilges & Essau, 2015). **DEBQ** = Dutch Eating Behaviour Questionnaire (Nagl et al., 2016). **EE** = Emotional Eating DEBQ. **EDE-Q8** = Eating Disorder Examine Questionnaire short 8 item version (Kliem et al., 2016). **EDIP** = Eating disorder-specific interoceptive perception questionnaire (Ortmann et al., 2024). **EPR** = Eating for Physical rather than Emotional Reasons IES-2. **EX** = External Eating DEBQ. **Full ml** = additional water volume until maximum fullness (ml). **HBCT** = heart beat counting task (Legrand et al., 2022). **HFnu** = high frequency normalized units. **HR** = heart rate. **HRV** = heart rate variability. **IES-2** = Intuitive Eating Scale 2 (van Dyck, Herbert, et al., 2016). **M** = Mean. **MAIA-2** = Multidimensional Assessment of Interoceptive Awareness questionnaire 2 (Mehling et al., 2018). **RE** = Restrained Eating DEBQ. **RHSC** = Reliance on Hunger Satiety Cues IES-2. **RMSSD** = root mean square of successive differences. **% sat to full** = percentage of satiation to maximum fullness. **Sat ml** = Ingested water volume until satiety (ml). **SD** = Standard Deviation. **Total ml** = total ingested water volume (ml). **UPE** = Unconditional Permission to Eat IES-2. **VR** = Virtual Reality Group. **WLT-II** = two-step water load test (van Dyck, Vögele, et al., 2016).

5 Discussion

In the present study, our goal was to assess the effects of a novel gastric biofeedback paradigm on interoception, eating behavior and ED symptoms in a healthy student sample. Our findings suggest that gastric biofeedback training, particularly in the 2D condition, may enhance *intuitive eating*, the *perception of satiation*, *fullness* and *body listening*.

In the WLT-II (van Dyck et al., 2016), participants drank less to reach fullness over time, increasing the satiation-to-fullness ratio, without differences between groups. Our findings align with Davey et al. (2023), who conducted eight weeks of attention training on either cardiac or gastrointestinal signals in healthy participants and found no significant group differences in WLT-II water intake. Similarly, no differences were found in WLT-II indices between a mindfulness intervention and a CG (Palascha et al., 2021). Our results also align with research showing that repeated WLT-II performance leads to decreased water intake until fullness, increased intake until satiation, and a higher satiation-to-fullness ratio in healthy female participants (Davey et al., 2022). This effect, independent of intervention, likely reflects improved satiation perception through task repetition. This is supported by the observation that, while the total amount of water ingested remains constant, participants drink more water until satiation and less until fullness, leading to an increased satiation-to-fullness ratio (rising from an overall mean of 40% in the first session to 46% in the final session). These findings are consistent with our EDIP-Q results, which showed that participants in all groups reported a better ability to perceive satiety over time (Ortmann et al., 2024).

Another possibility is that our control condition may not have been neutral but acted as an intervention. Participants focused on their stomach signals and imagined regular stomach contractions. Davey et al. (2023) showed that training attention to gastrointestinal signals can enhance self-reported bodily awareness, body listening, and self-regulation. This raises the possibility that our strict control condition may have produced similar effects to the gastric biofeedback intervention, effectively serving as a form of training.

Regarding the WLT-II questionnaire (*gastric interoceptive self-report*), participants in the 2D group reported feeling more satiated than the CG and fuller than the VR group after the WLT-II. Although we expected the strongest effect in VR, the 2D group proved the most promising for enhancing self-reported satiety and fullness. We can rule out water intake differences as a cause, as there were no group differences. The VR condition may have been more stimulating than anticipated, limiting relaxation, while 2D participants may have better relaxed and focused on gastric sensations. The hypothesized mechanism underlying gastric biofeedback is increased parasympathetic activity through relaxation (McCorry, 2007), subsequently enhancing interoception (H. Y. Weng et al., 2021). The vagus nerve, which is part of the parasympathetic system, transmits signals between the brain and internal organs, including the heart and stomach (Craig, 2002; Critchley & Harrison, 2013). The perception of satiation is largely controlled by stomach mechanoreceptors that detect stretch and transmit

signals via the vagus nerve to the nucleus of the solitary tract (NTS) in the hindbrain, where they contribute to the regulation of food intake (Janssen et al., 2011). Consequently, gastric biofeedback, especially in the 2D condition, may engage this process by promoting relaxation and focused attention on gastric sensations, thereby facilitating signal transmission of gastric signals to the brain.

Participants showed increased *interoceptive self-report* (MAIA-2; Mehling et al., 2018), with improvements in overall self-reported interoception and in the subscales *self-regulation* and *trusting*, independent of group. *Body listening* improved especially in the gastric biofeedback groups (VR and 2D). Body listening improvements partially supported our hypothesis: both intervention groups outperformed controls, without significant differences between VR and 2D. These results align with prior studies reporting HRV biofeedback improvements in *noticing*, *attention regulation*, and *self-regulation* (Mensing et al., 2024) and enhanced *body listening* with gastrointestinal signal training (Davey et al., 2023).

Overall intuitive eating significantly increased in the 2D group. Improvements in the subscales *eating for physical rather than emotional reasons* and *hunger and satiety reliance* were marginally significant. These results align with hunger and HRV biofeedback studies, which also reported increases in intuitive eating (Ledoux et al., 2014; Mensinger et al., 2024). An explanation may be that greater *attention to* and *trust in* internal signals may enhance their use in food-related decisions. The lack of change in emotional or external eating likely reflects floor effect, whereas intuitive eating may still improve even at low baseline levels of emotional or external eating. Our results indicate that the 2D condition significantly improved intuitive eating overall, while specific subscale improvements should be interpreted with more care.

Participants showed reduced HR over time. No significant changes were observed for HRV time domain (RMSSD), while in the frequency domain (HFnu), the VR group had lower values than controls, but this difference existed at baseline. Heartbeat counting performance and cardiac metacognitive insight did not improve, though participants across groups reported increased confidence. These findings do not support the hypothesized effects on cardiac interoception. This is consistent with recent research showing that cardiac biofeedback (VR vs. 2D) did not lead to modality-specific improvements in heartbeat perception ability (Ali et al., 2023). Confidence increase aligns with previous work showing body scan practices enhance confidence in heartbeat detection (D. Fischer et al., 2017), possibly due to HBCT repetition training effects (Murphy & Bird, 2025). Another possibility is that instructions in our control

condition trained participants (see above) and increased confidence, making it difficult to separate the effects of the target and control interventions.

Contrary to our hypothesis, neither did emotional and external eating scores change, over time nor were there group differences (2D, VR, CG). Restrained eating increased significantly, with a group-by-time interaction. Although post-hoc tests were non-significant, descriptively restraint increased in VR and CG, and decreased in 2D. This may reflect our normo-typical sample, where increased restraint could signal improved body awareness and satiety recognition, typically impaired in EDs such as BN or BED (Ortmann et al., 2024). These results align with mixed findings on eating behaviors following biofeedback or short interventions (Alberts et al., 2012; Atkinson & Wade, 2015, 2016; Ledoux et al., 2014). Our normo-typical, mixed-gender sample likely introduced a floor effect. It is also possible that gastric biofeedback requires clearer instruction on *why* and *how* to influence e.g. restraint via interoception to enhance effects.

For ED symptoms (EDE-Q8; Kliem et al., 2016), we found a marginally significant group-by-time interaction. ED symptoms decreased descriptively in both biofeedback groups (VR and 2D) but increased in the CG. Prior findings are mixed, with mindfulness and biofeedback interventions (electrodermal, HRV, EEG) showing either reductions in certain ED symptoms or no effects (Atkinson & Wade, 2015, 2016; Beccia et al., 2018; Imperatori et al., 2018; Meule et al., 2012). Notably, most required longer training (six to twelve weeks), raising the question of whether gastric biofeedback similarly needs an extended duration for significant effects on ED symptoms.

Our intervention, particularly the 2D condition, appears promising for individuals with difficulties perceiving and relying on satiation, fullness, and bodily signals related to eating. As gastric biofeedback directly targets stomach-related cues, it is plausible that the most pronounced effects occurred in hunger, satiety, and fullness sensing. Despite our sample's low baseline levels of emotional, external, and restrained eating, high intuitive eating scores, and minimal ED symptoms, we still observed meaningful improvements. This suggests that even in a normo-typical population, gastric biofeedback may enhance responsiveness to internal bodily cues and promote more adaptive eating behaviors. Increased attention to and confidence in bodily signals may improve the ability to sense and act on satiety and fullness cues, facilitating eating based on physiological needs rather than emotional triggers. Participants also reported greater trust in their bodily signals, more self-regulated eating, and reduced tendencies to eat or drink until uncomfortably full. These patterns indicate a strengthened capacity to use internal

cues for food-related decisions. Future research should examine gastric biofeedback in populations with greater interoceptive impairments or ED symptoms to assess its therapeutic potential.

5.1 Strengths and limitations

This study is the first to investigate the effects of gastric biofeedback on interoception, eating behavior, and ED symptoms in university students. A key strength is the comprehensive assessment of interoception using a variety of measures across cardiac and gastric domains. The study design required four testing sessions per participant, ensuring thorough data collection but also introducing a considerable testing burden. Fatigue may have influenced participant engagement, suggesting future studies should reduce testing demands while preserving data variety. As the sample consisted mainly of healthy individuals with low emotional, external, restrained eating, and ED symptoms, potential floor effects cannot be excluded. Our results are less conclusive for a broader range of ED symptoms, such as binge-eating or purging. Eating behaviors and EDs are complex and multifaceted, involving bio-psycho-social factors (Esbenshade & Venegas, 2024; Frank, 2016), which necessitate multifaceted interventions. The generalizability of our finding is also limited by the predominantly female sample. While prior research suggests minimal sex differences in gastric interoception and inconsistent findings in cardiac interoception (Prentice & Murphy, 2022), more balanced samples are needed to determine whether the observed effects generalize across sexes or reflect sex-specific interoceptive differences. The study may also have benefited from extended training periods with additional sessions, as in other biofeedback paradigms ranging from six to twelve sessions (Imperator et al., 2018). Additionally, including an additional CG without breath-based training could have helped to isolate the specific effects of gastric biofeedback. A key limitation concerns the timing of the WLT-II, administered post-training in each session for feasibility reasons, preventing definitive assessment of baseline differences across groups. However, the EDIP-Q (Ortmann et al., 2024), which was administered pre-intervention, showed no initial group differences in self-reported sensations of satiety and hunger. Future studies should incorporate true baseline assessments of the WLT-II, to clarify whether the observed effects, particularly in the 2D condition, persist when accounting for pre-existing differences. Nonetheless, the findings indicate that further investigation of the 2D condition as a promising and easily applicable intervention approach is warranted.

5.2 Future research directions and clinical implications

Future research should explore additional dimensions of interoception to better understand its role in gastric biofeedback interventions. Interoception extends beyond accuracy, sensitivity, self-report, attribution of interoceptive sensations, and physiological states to include neuronal representations, the preconscious impact of afferent signals, and attention to interoceptive sensations (Suksasilp & Garfinkel, 2022). Incorporating measures such as gastric evoked potentials (Mayeli et al., 2023) and models of active inference applied to gastric interoception could provide valuable insights into individual differences in gastrointestinal signal processing and further elucidate the complex body-brain interactions (Smith et al., 2021). Further research is needed to determine whether behavioral changes, such as adjustments in water intake until satiation and fullness, can be achieved through gastric biofeedback or similar training. While participants in all groups drank less until full and more until satiation, it remains unclear whether this resulted from an unintended training effect of the WLT-II or because the CG also engaged in a form of training. Future studies should isolate these effects by incorporating a waitlist CG, modifying the WLT-II to prevent unintentional training, or using alternative behavioral measures of gastric interoception that minimize learning effects. Previous research indicates that mindfulness interventions may support healthier dietary habits in individuals with high blood pressure (Loucks et al., 2023). It would be valuable to examine whether gastric biofeedback yields comparable benefits by enhancing dietary adherence through improved interoceptive abilities. Future research should explore gastric biofeedback as a targeted intervention for interoception and eating behaviors, particularly in individuals with EDs, where interoceptive impairments may be more pronounced. The 2D condition may especially benefit those struggling with satiation sensing, fullness, body listening, and hunger-satiety reliance. Investigating its long-term stability and real-life applicability, including effects on food intake, will be essential. Importantly, the 2D version has the potential to be displayed on a smartphone, making home-based training feasible if patients can access the required EGG equipment on loan. While stomach signal sensing plays a key role, hunger, satiety, and fullness also involve hormonal and neural processes (Janssen et al., 2011), which future studies should consider. Biofeedback is thought to enhance stress tolerance and coping with food-related situations by modulating both top-down control and bottom-up processing of food stimuli, reducing attention or motivational value assigned to such stimuli (Imperator et al., 2018). This may involve dampening activity in brain regions like the amygdala in response to food cues (Imperator et

al., 2018). Examining its potential to regulate arousal and neural responses to food cues could further clarify its clinical relevance (Imperator et al., 2018).

5.3 Conclusion

In conclusion, our study examined the effects of a novel gastric biofeedback paradigm (in a VR group, a 2D group and a CG) on interoception, eating behavior and ED symptoms. We found that particularly the 2D condition shows promising results to improve interoceptive self-report (satiation sensing, fullness sensing and body listening) as well as overall intuitive eating. Given its low-threshold, scalable format, the 2D version may offer a clinically relevant, accessible tool for enhancing interoceptive functioning, particularly in settings where immersive VR is not feasible, and could potentially be used in home settings. These findings underscore the potential of 2D gastric biofeedback for early intervention and prevention efforts, and future research should evaluate its efficacy in clinical ED populations to further determine its therapeutic potential.

4 GENERAL DISCUSSION

This thesis aimed to address key gaps in the literature regarding the relevance and trainability of gastric interoceptive processes underlying eating behavior. Across three studies, it investigated: (1) whether multidimensional gastric interoception was more relevant for maladaptive eating behavior than multidimensional cardiac interoception (2) if targeting the gastric rhythm through gastric biofeedback paradigm was feasible, efficacious and well-accepted by participants and (3) if the gastric biofeedback had beneficial effects on gastric, cardiac and general interoception as well as on eating behaviors and ED symptoms. By focusing on the modulation of gastric rhythms - a central mechanism in the perception of hunger, satiation, and fullness - this work introduced an understudied psychophysiological approach with potential clinical applicability.

4.1 Summary of findings

4.1.1 The relevance of cardiac and gastric interoception for disordered eating behavior (Study 1)

The main aim of Study 1 was to examine whether gastric interoception is more relevant to maladaptive eating behaviors than cardiac interoception. This study addressed an important research gap concerning the multidimensional assessment of cardiac and gastric interoception in relation to maladaptive eating behaviors. Rather than focusing on a single interoceptive dimension (such as self-report), we assessed multiple dimensions using behavioral tasks, self-report measures, and physiological recordings. Specifically, we measured *interoceptive accuracy*, *cardiac interoceptive self-report*, *interoceptive insight*, and *objective physiological state* in the cardiac domain. In the gastric domain, we measured *gastric interoceptive sensitivity*, *attribution of interoceptive sensations*, *gastric interoceptive self-report*, *interoceptive insight*, and *objective physiological state*. Maladaptive eating behaviors (emotional, external and restrained eating) were assessed in a sample of healthy individuals ($n = 87$) and individuals with an ED ($n = 41$). Using LASSO regression, we found that gastric interoception was a stronger predictor of maladaptive eating behaviors than cardiac interoception, with the *attribution of interoceptive sensations* (i.e., negative affect after ingesting water) emerging as the most important predictor. These findings underscore the importance of the gastric system in both the assessment and targeted intervention of maladaptive eating behaviors.

4.1.2 Gastric Biofeedback in Virtual Reality: Feasibility, Efficacy and Self-reported Experience (Study 2)

Building on the findings of Study 1, which highlighted the relevance of gastric interoception for maladaptive eating behaviors, the aim of Study 2 was to develop and evaluate a training protocol that directly targets gastric interoception through EGG biofeedback in healthy adults. This study addressed an important research gap, as gastric biofeedback, while promising for training gastric interoception and regulating gastric rhythm, has so far only been tested in a single small-scale study ($N = 26$; Stern et al., 2004). In the present study, we examined the feasibility and efficacy of the intervention regarding how well participants were able to modulate their gastric rhythm. In addition, we assessed participants' subjective experience and acceptance of the training through self-report measures. The study employed a randomized controlled design with three groups: a VR biofeedback group ($n = 30$), a 2D biofeedback group ($n = 32$), and a relaxation-based CG ($n = 32$). Our findings indicated that the paradigm was technically feasible and well-received by participants. Results showed an expected peak in normogastria and a nadir in dysrhythmic activity during training. Contrary to expectations, the three groups all showed a decrease in gastric dysrhythmia over time. Further studies are required to clarify whether and how training success translates into beneficial outcomes in populations with altered gastric motility patterns.

4.1.3 Listening to your stomach: Effects of gastric biofeedback training on interoception, eating behavior and eating disorder symptoms (Study 3)

After examining the technical feasibility and user acceptance of the gastric biofeedback paradigm, the aim of Study 3 was to examine whether the training might be promising to improve interoception and eating behaviors. More specifically, we investigated its effects on gastric, cardiac, and general interoception, as well as on eating behavior (emotional, external, restrained, and intuitive eating) and ED symptoms. This publication addressed an important research gap in the field of gastric biofeedback, as the only prior study conducted to date (Stern et al., 2004) did not assess the effects of the training on any psychological outcomes. Moreover, assessments of how interoceptive trainings influence interoception across multiple dimensions and organ systems remain scarce. Mixed model analyses ($N = 94$) indicated that the 2D gastric biofeedback condition yielded the most promising improvements, particularly in *gastric and general self-reported interoception* (including satiation and fullness perception, as well as body listening), and in intuitive eating. These results point to the potential of 2D gastric biofeedback as an effective and accessible method for enhancing interoception and supporting healthier

eating behaviors, with possible applicability in home-based settings. Future studies should investigate its clinical relevance in populations with EDs.

4.2 Integration with existing literature

This thesis contributes to the existing literature in several important ways. First, Studies 1 and 3 are among the few studies to assess multidimensional interoception across multiple organ systems (cardiac and gastric), addressing a significant gap in the field. Despite growing consensus that interoception should be assessed across both multiple dimensions and organ systems, much of the existing research remains limited to single-domain or unidimensional approaches (Martin et al., 2019; Nord & Garfinkel, 2022; Suksasilp & Garfinkel, 2022). Second, with Studies 2 and 3, this project includes the first empirical evaluation of gastric biofeedback since the pioneering study by Stern et al. (2004). Additionally, our studies examined effects not only on gastric myoelectric activity, but also on broader variables such as interoception, eating behavior, and ED symptoms, which has not been done before. Third, the gastric biofeedback was implemented in a relaxing, nature-based virtual environment for the first time. Importantly, Study 2 provided one of the few direct comparisons between VR-based and 2D biofeedback formats using identical biofeedback visualizations. Consistent with recent findings, no substantial advantage of VR over a well-designed 2D condition was observed (Pratviel et al., 2024; Weibel et al., 2023). This suggests that immersive formats may not always be necessary when comparable 2D screen alternatives are available. This has important practical implications, as 2D solutions tend to be advantageous over VR in terms scalability and accessibility.

Findings from Study 1 align with a growing body of literature emphasizing the role of the gastric system in eating behavior (Cusack et al., 2022; Janssen et al., 2011; Khalsa et al., 2022; Martin et al., 2019; Poovey et al., 2022; Smith et al., 2021; van Dyck, Vögele, et al., 2016). However, our results provide a more detailed understanding of how different dimensions of gastric interoception relate to specific maladaptive eating behaviors (emotional, external, and restrained eating) which remain understudied in this context. These behaviors are important to examine because they are common in the general population and even more prevalent among individuals with EDs, where they are known to contribute to patterns such as overeating and binge-eating (Nagl et al., 2016; van Strien et al., 2005). Notably, our results suggest that the *attribution of gastric interoceptive sensations* (i.e., negative affect following water ingestion), as the strongest predictor of emotional, external and restrained eating.

This highlights it as an additional promising target for future interventions aiming to improve gastric interoceptive processing in the context of maladaptive eating behaviors.

In Study 1 we also found that higher levels of emotional eating were linked to greater water intake until satiation, higher self-reported satiation, fullness and lower percentages of normogastria. A possible explanation might be that individuals with high emotional eating scores may lack a fine-tuned perception regarding satiety and fullness thresholds and might become aware of gastric sensations “too late”. This might potentially contribute to overeating. These individuals also showed lower levels of normogastric activity. This supports the hypothesis outlined in Study 3, namely that regulating gastric rhythm may be an effective strategy to improve the perception of gastric signals, which in turn could facilitate more adaptive eating decisions based on more accurately perceived internal cues. It may be particularly promising to combine both the training of gastric signal perception and their attribution (see section 4.3). For emotional eating, cardiac interoception was also relevant, which is consistent with prior research linking cardiac interoception to emotional processing (Greenwood & Garfinkel, 2025). In our study, emotional eating was associated with lower HRV (HFnu), reduced mean HR, and heartbeat detection accuracy, in line with previous findings (Ahlich & Rancourt, 2022; Lovan et al., 2022; Young et al., 2017). In the case of restrained eating, additional contributions from HRV and HR were observed, supporting earlier studies showing heightened HRV following fasting (Herbert, Herbert, et al., 2012; Vögele et al., 2009).

In Study 2, contrary to our hypotheses, normogastria did not significantly change and dysrhythmic activity decreased in all groups, not only in the active biofeedback groups. This may be explained by a potential ceiling effect for normogastria improvements, as our healthy sample with low ED symptoms and high intuitive eating scores exhibited considerably higher baseline normogastria than the small sample ($N = 26$) in Stern et al. (2004). The tachygastria reduction across all groups contrasted with the findings by Stern et al., (2004), who did not find a change in tachygastria via gastric biofeedback. Possibly, the training by Stern et al., (2004) had more effect on normogastria, while ours acted more on tachygastria. Nevertheless, descriptive trends in the 2D group suggest that even individuals with high normogastria may be capable of reducing gastric dysrhythmias and increasing normogastria through biofeedback training. Future studies should re-examine the intervention in individuals with more pronounced gastric motility issues, such as those with lower normogastria. It remains to be tested whether, in such populations, a relaxation-based control condition that involves focused attention on gastric signals (such as our CG), may be sufficient to reduce tachygastria.

Regarding the results of Studies 2 and 3, contrary to our expectations, the VR group did not outperform the 2D group, suggesting that VR may have been more arousing than expected. This was mirrored in results of the self-report measures in Study 2. The proposed mechanism of our intervention was that slow, regular breathing promotes relaxation by increasing parasympathetic activity (McCorry, 2007), thereby producing downstream effects on interoception and eating behavior (H. Y. Weng et al., 2021). We found evidence of this relaxation effect through decreases in tachygastria and mean HR across groups. This process is most likely mediated by the vagus nerve, which transmits afferent signals from internal organs, including the stomach, to the brain (Craig, 2002; Critchley & Harrison, 2013). Mechanoreceptors in the stomach wall detect stretch and send signals via the vagus nerve to the nucleus of the NTS, where they help regulate satiation and food intake (Janssen et al., 2011). This is consistent with findings from mindfulness-based interventions, which have shown increased insular activation during focused breathing, a region implicated in interoceptive processing (Nord & Garfinkel, 2022). Additionally, to improve signal transmission, increased attention to internal signals may play a role. Attention naturally shifts between internal and external signals. When external cues dominate, interoceptive signals are less likely to reach conscious awareness (Garfinkel & Eccleston, 2025). Increasing attention to internal stimuli may improve recognition of bodily signals and decrease reactivity to external stimuli (Garfinkel & Eccleston, 2025). Beyond relaxation, it has been suggested that controlled respiration enhances the signal-to-noise ratio between interoceptive and exteroceptive cues, thereby facilitating interoceptive processing (Saltafossi et al., 2025). Taken together, gastric biofeedback, particularly in the 2D condition, may facilitate more efficient stomach–brain communication by promoting relaxation and directing attention toward gastric sensations. In the 2D group, this is reflected in improved perception of satiation, fullness, and body listening, which likely contributed to the observed increase in intuitive eating. Given the association between intuitive eating and interoception (DeVille, Erchull, et al., 2021; Herbert et al., 2013; Joshi et al., 2024a), these findings suggest that participants may not only have become more attuned to internal cues, but also have begun to use them more effectively to guide their eating behavior.

As certain effects of the training (reduction in tachygastria, mean HR and improvements in various interoceptive dimensions) were not limited to the intervention groups, we suggest that our CG may have functioned as an active condition. Participants were instructed to focus on their stomach sensations and to mentally simulate regular gastric contractions. Prior research has shown that directing attention towards gastrointestinal signals can itself enhance bodily awareness, body listening, and self-regulatory capacities (Davey et al., 2023). This suggests

that our control condition may have elicited similar effects to the active intervention, effectively operating as a form of interoceptive training. To better isolate the specific effects of gastric biofeedback, future studies should consider including an alternative control condition, such as one focused solely on regular breathing or a waitlist group without any bodily focus. Nevertheless, our results suggest that receiving real-time feedback on physiological signals may provide added benefits beyond general bodily attention and relaxation. This is in line with findings from a brief mindfulness exercise that enhanced sensitivity to hunger cues, though it did not influence the perception of satiation (Palascha et al., 2021). Participants using these mindfulness exercises detected hunger earlier than controls, suggesting that even short interventions can improve sensitivity to hunger, while modulating satiation perception may require more extensive training or different approaches (Palascha et al., 2021).

4.3 Clinical implications

The findings of this research project have implications for the prevention and treatment of maladaptive eating behaviors and EDs, as well as for the promotion of adaptive eating behaviors. Results from Study 1 underscore the relevance of the gastric domain in maladaptive eating, suggesting that gastric interoception should be systematically incorporated into individualized assessment and intervention approaches. This may be beneficial not only for individuals with EDs but also for those with subclinical symptoms or difficulties in recognizing and responding to internal hunger and satiety cues.

In the context of EDs, gastric biofeedback may enhance stress tolerance and promote adaptive coping during stress-inducing eating situations by reducing arousal (Imperatori et al., 2018; Weerdmeester et al., 2020). Since stress is thought to disrupt gut-brain communication and diminish attention to internal cues, interventions that facilitate relaxation may help restore this balance and reduce maladaptive eating behaviors (Imperatori et al., 2018; Vujic et al., 2020). Altered or diminished visceral input can impair the ability to interpret internal bodily signals in relation to past experiences and present cues, potentially contributing to disordered eating (Jacquemot & Park, 2020; Smith et al., 2021). Enhancing the accuracy and trust in gastric signals may support more effective regulation of food intake (van Dyck et al., 2021) by improving individuals' capacity to reflect on current sensations of hunger, satiety, and fullness, and to use previous eating experiences to better predict future satiation. For example, during a meal, an individual might assess their present level of satiety, recall how they felt after finishing a similar portion previously, and anticipate how they are likely to feel if they continue eating.

In ED populations, interventions targeting gastric interoceptive processes may offer valuable insights into bodily states that are otherwise difficult to assess. For example, in AN it remains unclear whether individuals truly lack hunger or whether their reports reflect cognitive control. Similarly, in BN and BED, patients often describe reduced satiety, though the underlying mechanisms remain poorly understood (Ortmann et al., 2024; van Dyck et al., 2021). Just as insomnia treatments help patients reinterpret ambiguous bodily cues, interoceptive training could help ED patients tolerate discomfort associated with satiety or gastric sensations. Such approaches may bypass explicit cognitive control and instead focus on recalibrating the body's physiological responses, potentially reducing symptom burden in this difficult-to-treat population by addressing maladaptive hunger and fullness signaling. Such an approach may help alleviate uncomfortable stomach sensations while enhancing the perception of gastric signals, by combining targeted regulation of gastric activity with the promotion of techniques to reach a general state of relaxation.

Study 1 also highlighted the importance of *attribution of interoceptive sensations* for maladaptive eating behaviors. Although our intervention in Study 3 (in the 2D group) improved internal signal perception (satiation perception, fullness perception and body listening), it did not alter the negative affect associated with gastric sensations, suggesting this may require explicit targeting. Prior research has shown that individuals with EDs often experience gastric signals as aversive, contributing to distress and avoidance (Boswell et al., 2019; Plasencia et al., 2019). Building on this, interoceptive exposure approaches for EDs (such as gulping water or drinking milkshakes) have shown initial promise in reducing anxiety toward gastric sensations through repeated exposure to these aversive gastric sensations (Boswell et al., 2019; Plasencia et al., 2019). However, due to their distressing nature, such paradigms often face compliance challenges (Hildebrandt et al., 2021). Gastric biofeedback may offer a valuable addition as its relaxing properties, absence of adverse effects, and positive reception in our healthy sample suggest potential for clinical use. Integrating gastric biofeedback with elements of interoceptive exposure could, therefore, address both gastric signal perception and its emotional appraisal. As found by Heim et al., (2023), interventions that target both the physiological signal and its interpretation tend to yield stronger symptom improvements. This supports the view that effective change in eating behavior may require not only enhanced internal signal perception but also more adaptive emotional reactions and interpretations of these internal states. Importantly, it may be easier to modify maladaptive attributions when bodily signals are more accurately perceived, as clearer interoceptive input may facilitate more adaptive interpretations. In this sense, gastric interoceptive training may help patients build trust

in their bodily signals by fostering a more coherent relationship between sensation, thought, and emotional regulation.

As we have seen in section 4.2, our intervention appears beneficial in increasing attention to internal signals. In EDs, it has been proposed that there is an imbalance between exteroceptive and interoceptive processing, often characterized by an externalized focus on the body (Herbert & Pollatos, 2018); gastric biofeedback might be of particular interest to address this. Importantly, the intervention should be tailored to individual interoceptive profiles, addressing the most disrupted dimension (Nord & Garfinkel, 2022). However, its effectiveness will most likely depend on targeting the right mechanism for the right person (Nord & Garfinkel, 2022). As interoceptive disturbances vary both within and across diagnoses, biofeedback and related interoception-based treatments may be most beneficial when integrated into personalized therapeutic frameworks that match intervention strategies to individual patterns of dysfunction (Nord & Garfinkel, 2022).

Gastric biofeedback may also have a relevance beyond eating behavior and EDs. Conditions such as depression, anxiety, schizophrenia, and diabetes are frequently accompanied by gastric dysrhythmia and symptoms like nausea, bloating, or abdominal discomfort (Ly et al., 2015; Mathur et al., 2001; Ogawa et al., 2004; Peupelmann et al., 2009; Ruhland et al., 2008; Simpson & Stakes, 1987). In populations where gastric symptoms are mainly driven by stress-related physiological dysregulation, rather than by maladaptive emotional attributions, gastric biofeedback may offer a useful tool to help individuals identify and regulate these bodily sensations. These overlaps suggest its potential as a cross-diagnostic intervention for populations with disturbed gastric function.

Additionally, given the necessary paradigm shift in current treatment approaches towards prevention, early detection and the treatment of subclinical symptoms (Leichsenring et al., 2022), our intervention may offer particular value for individuals who do not (yet) meet clinical thresholds. By enhancing interoception and intuitive eating, it shows promise for addressing early signs of maladaptive eating behaviors and subclinical ED symptoms, thereby potentially contributing to a reduction of long-term mental health burden.

4.4 Strength, Limitations and future research directions

This research project has several notable strengths. First, it applied a dimensional approach to eating behavior by including both healthy and clinical participants in Study 1, and a healthy sample in the intervention experiment (Studies 2 and 3). A major methodological strength lies

in the comprehensive, multidimensional assessment of interoception across two organ systems, cardiac and gastric, using behavioral tasks, self-report, and physiological measures. Including both clinical and non-clinical populations enabled us to examine a broad spectrum of eating behavior. Studies 2 and 3 employed a two-week intervention period, allowing for the investigation of potential mechanisms of change beyond cross-sectional associations and providing preliminary causal insights into gastric interoception and eating behavior. The project also represents the first replication of gastric biofeedback since the pioneer study by Stern et al. (2004), and is the first to implement it in a nature-based VR environment. Due to their restorative and stress-reducing qualities, as well as their potential to counteract the monotony and potential boredom of simpler visualizations, (virtual) nature environments are well-suited to provide both relaxation and sustained engagement (Gaume et al., 2016; Rockstroh et al., 2019; Yoon & Jeon, 2025). Finally, the gastric biofeedback training was well accepted by all participants, who reported positive experiences and no notable adverse effects. The design included a carefully designed 2D condition and a rigorous CG.

While this research project provides valuable insights, several limitations have to be acknowledged. In Study 1, although both clinical and healthy participants were included, the clinical sample was limited to individuals with BN and BED, and the assessment of disordered/maladaptive eating relied solely on the DEBQ (van Strien et al., 1986). As such, the scope of eating behaviors examined was restricted. The DEBQ captures only selected dimensions of maladaptive eating behavior and does not fully reflect the broader spectrum of disordered eating, such as purging or loss of control eating. Furthermore, individuals with AN, avoidant/restrictive food intake disorder (ARFID), or other feeding and EDs were not included. This is a notable limitation, especially given emerging evidence that different ED subtypes show distinct profiles of gastric interoceptive impairment (Ortmann et al., 2024). For example, while AN is associated with heightened satiety sensitivity and blunted hunger perception, individuals with BN and BED tend to report reduced satiety sensitivity and difficulty distinguishing hunger from emotional cues (Ortmann et al., 2024). Additionally, Studies 2 and 3 were conducted exclusively in a healthy sample, limiting generalizability to clinical groups. Future research should expand both the range of disordered eating behaviors assessed and the diversity of clinical populations examined to tailor interventions to specific interoceptive profiles. A factor that may have contributed to the limited range of maladaptive eating behaviors and ED symptoms in Studies 2 and 3 is the way the intervention was advertised. Our recruitment strategy emphasized training hunger and satiety perception, which may have unintentionally deterred individuals with maladaptive eating behaviors and ED symptoms, possibly due to

avoidance of these topics. Future studies should consider adapting the advertisement to make the intervention more approachable and relevant for these populations.

Another limitation concerns the gender composition of our sample, which consisted predominantly of female participants. This limits the generalizability of our findings to males and other gender groups. Although some studies suggest minimal sex differences in gastric interoception and mixed results in cardiac interoception (Prentice & Murphy, 2022), disordered eating behaviors and ED symptoms are known to manifest differently across genders. Especially young men remain underrepresented in ED research despite significant prevalence (Brown & Keel, 2023; Gorrell & Murray, 2019; Limbers et al., 2018; Reilly et al., 2017; Sweeting et al., 2015). As gender influences the development and expression of disordered eating (Gorrell & Murray, 2019; Limbers et al., 2018), future studies should include more balanced samples to clarify potential sex-specific interoceptive patterns and responses to intervention.

Moreover, while the two-step water load test (WLT-II; van Dyck, Vögele, et al., 2016) provides a valuable method for assessing gastric sensations, particularly in clinical contexts, it is based on subjective thresholds of satiation and fullness, which may be influenced by motivational factors such as the willingness to drink. Complementary methods that assess the ability to detect specific gastric signals, such as vibration-based stimulation via ingestible capsules, may offer additional insights into gastric interoceptive sensitivity (Smith et al., 2021). Although we aimed to assess interoception in a comprehensive manner, additional dimensions remain unexamined. These include neural representations, preconscious impact of afferent signals, and interoceptive attention (Suksasilp & Garfinkel, 2022). Future research on gastric interoception should consider incorporating measures of neural activity related to gastric signals, such as those used in recent studies by Haruki and Ogawa (2023) and Todd et al. (2021) and investigate whether these neural indices are modifiable through gastric biofeedback interventions.

In Studies 2 and 3, the length and intensity of the laboratory sessions may have contributed to participant burden. Future studies, particularly those involving clinical populations, should consider reducing the testing load to increase feasibility and avoid drop-outs. Another limitation concerns the duration of the intervention. While participants completed two weeks of training, other biofeedback protocols, such as HRV training for gastrointestinal disorders, recommend extended use over at least six weeks to achieve stronger effects (Pereira et al., 2025). This underscores the potential value of extending gastric biofeedback beyond the

laboratory. Given that the 2D version performed comparably to the VR format, it may be feasible to adapt it into a smartphone-based application, allowing individuals to continue the training independently at home or in structured settings such as inpatient or rehabilitation facilities. Future studies should explore the effectiveness and usability of such formats and directly compare app-based and TV-screen based delivery methods.

Moreover, participants in the intervention were shown their EGG signals, which correlate with gastric contractions but are not identical to them (Whitehead & Drescher, 1980). It would be valuable to explore ways of visualizing stomach fullness more directly, to make the feedback more concrete. For example, visual representations of the stomach itself, along with an estimate of its fullness, could help participants connect the feedback to their bodily sensations.

One possible reason why ED symptoms did not significantly decrease in our intervention is that hunger, satiation, and fullness are shaped by more than gastric myoelectric activity alone. Gastric functioning involves complex gut–brain interactions, including processes such as gastric accommodation, emptying, and hormonal signaling (Engelen et al., 2023; Hunt et al., 2015; K. L. Koch & Stern, 2004; Soybel, 2005). For instance, hormones like glucagon-like peptide-1 (GLP-1) are released in response to stomach distension and act on the brainstem to enhance satiety, emphasizing that central hormonal pathways play a key role in gastric satiation beyond purely mechanical cues (Janssen et al., 2011). These mechanisms highlight the physiological complexity underlying satiety and fullness perception and should be taken into account when studying gastric interoception.

In addition, while we asked participants which strategies they used to modulate their gastric activity during the training, we did not provide specific instructions, as no established guidelines are currently available. Future studies should investigate whether certain strategies are more effective in enhancing gastric motility and, based on these findings, consider standardizing or recommending specific approaches during the intervention.

4.5 Conclusion

This thesis examined the relevance and trainability of gastric interoception in the context of eating behavior and ED symptoms. Gastric interoception emerged as a stronger predictor of maladaptive eating than cardiac interoception. To investigate its modifiability, an EGG-based gastric biofeedback intervention was developed and evaluated. This intervention targeted the regulation of gastric rhythms, which are central to the perception of hunger, satiation, and

fullness. Its effects were assessed across cardiac and gastric interoception (measured via physiological signals, behavioral tasks, and self-report), eating behaviors, and ED symptoms. The intervention proved technically feasible and was well accepted by participants. Notably, the findings suggest that certain aspects of gastric interoception, particularly the perception of satiation and fullness, are trainable. Improvements were also observed in general self-reported interoception (i.e., body listening) and intuitive eating. The training may support individuals in reconnecting with internal hunger and satiety cues in food-related decision-making—signals that are often overridden in modern Western societies by efforts to conform to sociocultural ideals (e.g., thinness norms) and by constant exposure to environments saturated with highly palatable, energy-dense foods. Such foods, particularly when highly processed, can activate the brain’s reward system and further disrupt sensitivity to internal signals of hunger and fullness (Calcaterra et al., 2023; Kelly et al., 2022; Rego et al., 2023). As such, the intervention may be promising not only for clinical populations but also for individuals with subclinical symptoms, by fostering intuitive eating before the onset of a full ED. Future studies should test the intervention's applicability in clinical ED populations and further investigate whether additional aspects of gastric interoception can be improved, particularly those related to emotional responses to gastric sensations, which may be especially relevant for disordered and maladaptive eating behaviors. The training may also be beneficial for subclinical disordered eating behaviors or other conditions in which gastric symptoms (such as nausea or epigastric discomfort) play a role, and where regulating gastric rhythms could offer therapeutic benefits. Together, the three studies advance our theoretical understanding of gastric interoception in the context of eating behavior. Additionally, our findings suggest the pre-/clinical application of gastric biofeedback as a promising tool to improve the perception of stomach-derived signals and its use in guiding more adaptive food-related behaviors.

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6 APPENDICES

Appendix A: Supplementary material Study 1

Table 7

Spearman correlations of dimensions of cardiac and gastric interoception

Gastric intero-												
Total					Negative affect			ceptive insight		Brady-gastria	Normo-gastria	Tachy-gastria
		Sat_ml	Full_ml	_ml	Sat_%	Satiation	Fullness					
Cardiac interoceptive accuracy	r _s	.122	.144	.167	-.045	-.053	-.074	-.034	.157	-.033	-.010	.176
	p	.216	.144	.090	.651	.584	.440	.724	.114	.736	.918	.073
Cardiac interoceptive self-report	r _s	-.078	.237*	.074	-.255**	-.076	-.040	-.109	-.030	-.080	-.030	.110
	p	.424	.014	.449	.008	.422	.672	.245	.758	.415	.760	.259
Cardiac interoceptive insight	r _s	.112	.258**	.200*	-.156	.161	.065	.087	-.023	.055	-.099	.015
	p	.260	.009	.043	.117	.093	.499	.368	.820	.581	.319	.879
Mean HR	r _s	-.126	-.064	-.107	-.036	.002	-.020	-.023	-.017	.178	.050	-.117
	p	.197	.515	.275	.718	.983	.836	.808	.865	.067	.607	.232
HRV(RMSSD)	r _s	-.058	.023	-.043	-.052	-.069	.001	.034	-.030	-.197*	.034	.125
	p	.552	.818	.659	.596	.466	.989	.718	.759	.042	.727	.201
HRV (HFnu)	r _s	-.142	-.019	-.103	-.065	-.129	-.035	.094	-.119	-.025	.053	.000
	p	.145	.843	.293	.509	.170	.713	.319	.225	.795	.587	.997

Note. **Full_ml** = additional water volumes ingested until maximum fullness. **HFnu** = high frequency normalised units. **Mean HR** = Mean Heart Rate. **RMSSD** = root mean square of successive differences. **Sat_%** = percentage of satiation to maximum fullness. **Sat_ml** = mean volume of water ingested until satiation. **Total_ml** = total water volumes ingested.

Table 8

Spearman correlations of dimensions of gastric interoception with disordered eating and BMI

		Gastric										
		Sat_ml (n = 106)	Full_ml (n = 106)	Total_ml (n = 106)	Sat_% (n = 106)	Satiation (n = 114)	Fullness (n = 114)	Negative affect (n = 114)	interocept ive insight (n = 105)	Brady- gastria (n = 106)	Normo- gastria (n = 106)	Tachy- gastria (n = 106)
DEBQ	r _s	.192*	0.101	.181	.064	.315**	.299**	.350**	.061	.157	-.237*	.052
emotional	p	.049	.305	.064	.517	.001	.001	.000	.539	.108	.015	.598
DEBQ	r _s	.193*	.009	.121	.136	.093	.197*	.314**	.057	.116	.049	-.187
external	p	.048	.930	.216	.165	.324	.036	.001	.567	.238	.617	.055
DEBQ	r _s	.112	.066	.110	.019	.093	.100	.301**	.104	.025	.008	.040
restrained	p	.255	.500	.262	.849	.323	.289	.001	.293	.802	.937	.686
BMI	r _s	.072	.075	.079	.038	.066	.191*	.110	-.173	.086	-.229*	.107
	p	.460	.442	.422	.699	.485	.042	.248	.077	.386	.019	.277

Note. **BMI** = Body Mass Index. **DEBQ** = Dutch Eating Behaviour Questionnaire (van Strien et al., 1986). **Full_ml** = additional water volumes

ingested until maximum fullness. **Total_ml** = total water volumes ingested, **Sat_%** = percentage of satiation to maximum fullness. **Sat_ml** = mean volume of water ingested until satiation.

Table 9

Spearman correlations of dimensions of cardiac interoception with disordered eating and BMI

		Cardiac		Cardiac		Mean HR (n = 113)	HRV (RMSSD) (n = 113)	HRV (HFnu) (n = 113)	DEBQ		DEBQ	
		interoceptive accuracy (n = 110)	interoceptive self-report (n = 114)	interoceptive insight (n = 109)	Cardiac insight (n = 109)				emotional (n = 120)	external (n = 120)	restrained (n = 120)	restrained
DEBQ emotional	r _s	-.047	.054	.125	.125	-.136	.080	-.125	1			
	p	.623	.569	.194	.194	.151	.397	.188				
DEBQ external	r _s	.039	.071	.096	.096	.020	.000	-.085	.507**	1		
	p	.684	.453	.321	.321	.834	.999	.371	.000			
DEBQ restrained	r _s	.150	.049	.100	.100	-.193*	.226*	.104	.353**	.206*	1	
	p	.118	.602	.300	.300	.040	.016	.272	.000	.024		
BMI	r _s	-.136	.034	-.007	-.007	.020	-.103	.016	.346**	.200*	.196*	
	p	.159	.722	.943	.943	.831	.281	.863	.000	.032	.035	

Note. **DEBQ** = Dutch Eating Behaviour Questionnaire (van Strien et al., 1986). **HFnu** = high frequency normalised units. **Mean HR** = Mean Heart Rate. **RMSSD** = root mean square of successive differences.

Appendix B: Supplementary material Study 2

Supplement S1

Instructions for the VR Biofeedback condition and 2D condition (German)

« Das Wahrnehmen von körpereigenen Signalen hängt mit gesundem Essverhalten, gesundem Körpergewicht und Gesundheit im Allgemeinen zusammen. Haben Sie daher im Alltag ruhig Vertrauen, dass Ihre Körpersignale (wie z.B. Magensignale) vertrauenswürdige und nützliche Informationen liefern können.

Wir können nun zur nächsten Aufgabe übergehen. In dieser Aufgabe geht es darum zu untersuchen, in welchem Ausmass Personen in der Lage sind, ihre Magenaktivität durch Entspannung und geistige Anstrengung zu beeinflussen.

Normale Magenaktivität besteht aus drei Kontraktionen die Minute und das Ziel ist es, dass Sie versuchen, Ihren Anteil an normaler Magenaktivität zu erhöhen. Sie werden nun Ihre eigene Magenaktivität in einer virtuellen Naturumgebung über das *Virtual-Reality-Headset* / den *Fernseher* sehen. Es gibt zwei durchsichtige Kugeln, die sich rhythmisch mit Wasser füllen und wieder entleeren: die Linke zeigt eine Aktivität von dreimal die Minute an, die als "Schrittmacher" fungiert, und die Rechte zeigt Ihre eigene Magenaktivität an.

Ihr Ziel ist es, Ihre eigene Aktivität an den Schrittmacher anzupassen. Dies können Sie durch Entspannung und regelmässiges, ruhiges Atmen schaffen. Die Umgebung (Wolken, Wasserfarbe und Windgeräusche) ist nach 6-7 min proportional zu wie sehr sie sich entspannen und ihre Magenaktivität sich dem Beispiel anpasst (je schöner das Wetter, desto mehr passen sich ihre Aktivität an das Beispiel an). Lassen Sie sich bei der Aufgabe nicht stressen, wenn sich die Kugeln nicht perfekt angleichen (z.B. kann es sein, dass das Wasser in der Kugel nicht ganz hoch oder ganz runter geht). Es ist normal, dass sie nicht ganz gleich sind und perfekt

übereinstimmen, wir sind ja auch nur Menschen. Es geht nur darum, dass sie sich annähern und ähnlicher werden. Denken Sie auch wieder dran, sich so wenig wie möglich zu bewegen, da wir die physiologischen Daten sonst nicht benutzen können.»

«Ist alles klar oder gibt es noch Fragen?» «Können Sie mir bitte kurz zusammenfassen, was Sie verstanden haben, was sie tun sollen?» «Können Sie mir kurz sagen, was die 2 Kugeln Abbilden?» «Können Sie mir kurz zusammenfassen, was Sie machen sollen? Und was das Wetter zeigt nach 6-7 min?»

Instructions for the control condition (German)

«Das Wahrnehmen von körpereigenen Signalen hängt mit gesundem Essverhalten, gesundem Körpergewicht und Gesundheit im Allgemeinen zusammen. Haben Sie daher im Alltag ruhig Vertrauen, dass Ihre Körpersignale (wie z.B. Magensignale) vertrauenswürdige und nützliche Informationen liefern können.

Wir können nun zur nächsten Aufgabe übergehen. In dieser Aufgabe geht es darum zu untersuchen, in welchem Ausmass Personen in der Lage sind, ihre Magenaktivität durch Entspannung und geistige Anstrengung zu beeinflussen.

Normale Magenaktivität besteht aus drei Kontraktionen die Minute und das Ziel ist es, dass Sie versuchen, Ihren Anteil an normaler Magenaktivität zu erhöhen. Dies können Sie erreichen, indem Sie sich entspannen, regelmässig und ruhig atmen, und an schöne Dinge denken, wie beispielsweise an einem schönen Tag am Strand zu liegen. Stellen Sie sich ebenfalls vor, dass Ihr Magen sich 3-mal die Minute zusammenzieht, wie ein Luftballon der sich dreimal pro Minute aufbläst und wieder entleert, oder wie ein mit Wasser gefüllter Ball, der sich dreimal pro Minute füllt und entleert. Bitte versuchen Sie auch hier, sich möglichst wenig zu bewegen, die Kontraktionen der Bauchmuskeln zu minimieren und nicht zu sprechen.»

«Ist alles klar oder gibt es noch Fragen?» «Können Sie mir bitte kurz zusammenfassen, was Sie verstanden haben, was sie tun sollen?»

Supplement S2

Table 2

Descriptive statistics of gastric data and self-reported experience measures

	VR						2D						CG						Total					
	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max				
Bradygastria pre-training	114	22.49	13.42	1.59	61.76	118	26.40	14.98	2.76	65.48	121	25.39	13.64	2.08	63.55	353	24.79	14.09	1.59	65.48				
Normogastria pre-training	114	56.09	17.07	18.72	92.58	118	53.21	14.98	23.77	84.14	121	52.18	15.12	18.18	94.75	353	53.79	15.77	18.18	94.75				
Tachygastria pre-training	114	21.42	11.25	5.39	62.70	118	20.38	10.49	4.55	53.65	121	22.44	12.06	3.17	77.96	353	21.42	11.29	3.17	77.96				
Bradygastria training	119	9.25	6.80	0.98	35.84	125	10.40	5.84	1.74	32.99	104	11.40	6.52	3.04	33.46	358	10.31	6.42	0.98	35.84				
Normogastria training	119	64.83	18.99	7.32	92.96	125	69.97	13.76	20.22	94.04	104	68.55	14.14	28.83	91.62	358	67.79	15.95	7.32	94.04				
Tachygastria training	119	25.92	19.33	5.06	91.40	125	19.63	12.63	3.50	72.84	104	20.05	13.06	3.96	64.43	358	21.91	15.59	3.50	91.40				
Bradygastria post-training	116	19.00	10.60	2.34	53.11	121	20.56	11.35	2.71	56.77	122	19.12	11.60	1.77	56.96	359	19.57	11.19	1.77	56.96				
Normogastria post-training	116	60.85	15.34	26.61	93.67	121	58.41	14.03	24.58	90.93	122	61.11	15.90	29.15	94.33	359	60.12	15.12	24.58	94.33				
Tachygastria post-training	116	20.15	9.73	2.77	48.71	121	21.03	9.76	4.96	46.27	122	19.77	11.88	1.96	66.91	359	20.32	10.51	1.96	66.91				
Scene relaxing	119	7.88	1.64	2.00	10	127	7.84	1.66	3.00	10	/	/	/	/	/	246	7.86	1.65	2.00	10				
Sphere intuitive visualization	119	7.10	1.93	2.00	10	127	6.54	2.09	1.00	10	/	/	/	/	/	246	6.81	2.03	1.00	10				
Environment helpful	119	6.07	2.55	0.00	10	127	5.82	2.60	1.00	10	/	/	/	/	/	246	5.94	2.57	0.00	10				

Note. **2D** = 2D Group (television). **VR** = Virtual Reality Group. **CG** = Control Group. **M** = Mean. **SD** = Standard Deviation.

Supplement S2 (continued)

Table 2

Descriptive statistics of gastric data and self-reported experience measures

	VR					2D					CG					Total				
	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max
Liking	119	7.10	1.94	1.00	10	128	7.21	1.91	1.00	10	128	6.59	2.64	0.00	10	375	6.96	2.20	0.00	10
Intention to use	119	4.55	2.62	0.00	10	128	4.38	2.88	0.00	10	128	4.67	2.77	0.00	10	375	4.53	2.76	0.00	10
Recommendation to use	119	5.27	2.38	0.00	10	128	5.80	2.16	1.00	10	128	5.67	2.67	0.00	10	375	5.59	4.42	0.00	10
Time perception	119	6.81	2.18	1.00	10	128	6.88	2.12	1.00	10	128	5.84	2.67	0.00	10	375	6.50	2.38	0.00	10
Concentration	119	8.03	1.91	1.00	10	128	8.00	1.62	3.00	10	128	7.23	2.01	1.00	10	375	7.75	1.89	1.00	10
Distraction	119	2.50	2.41	0.00	9.00	128	3.07	2.49	0.00	10	128	3.62	2.61	0.00	10	375	3.08	2.54	0.00	10
MBDF good mood	119	2.62	0.28	2.00	3.50	128	2.63	0.35	1.75	3.50	128	2.64	0.29	1.50	3.25	375	2.63	0.31	1.50	3.50
MBDF alert tired	119	2.80	0.59	1.80	4.67	128	2.94	0.66	1.60	4.67	128	2.83	0.54	1.80	4.33	375	2.86	0.60	1.60	4.67
MBDF rest unrest	119	2.78	0.37	2.00	3.75	128	2.83	0.38	1.75	4.00	128	2.75	0.38	1.50	3.50	375	2.79	0.38	1.50	4.00
IPQ realism	107	2.30	0.90	0.33	4.67	103	2.26	1.08	0.33	5.00	/	/	/	/	/	210	2.28	0.99	0.33	5.00
IPQ spatial presence	107	3.2	1.29	0.40	6.00	103	2.25	1.20	0.40	6.00	/	/	/	/	/	210	2.73	1.33	0.40	6.00
IPQ involvement	107	3.17	1.28	0.50	6.00	103	2.86	1.24	0.50	5.25	/	/	/	/	/	210	3.02	1.27	0.50	6.00
VRSQ mean	119	1.64	0.44	1.00	2.78	128	1.60	0.42	1.00	2.89	94	1.62	0.42	1.00	3.00	341	1.62	0.43	1.00	3.00
UAQ mean	119	3.05	0.64	1.43	4.14	128	3.01	0.74	1.57	4.71	128	2.97	0.64	1.71	4.43	375	3.01	0.67	1.43	4.71

Note. **2D** = 2D Group (television). **VR** = Virtual Reality Group. **CG** = Control Group. **M** = Mean. **SD** = Standard Deviation.

Supplement S3

Table 3

Significant Post Hoc Comparisons for Timepoint $\times$ Group Interaction of Hypothesis 1:

Normogastria Timepoint and Group Analysis

Contrast	<i>p</i>	<i>d</i>	95% CI for <i>d</i>
Baseline VR < Training VR	< .001	-0.63	[-0.89, -0.37]
Baseline VR < Training 2D	< .001	-1.06	[-1.42, -0.70]
Baseline VR < Training CG	< .001	-0.86	[-1.23, -0.49]
Training VR > Baseline 2D	< .001	0.80	[0.44, 1.16]
Training VR > Baseline CG	< .001	0.91	[0.55, 1.27]
Post VR < Training 2D	.004	-0.71	[-1.07, -0.35]
Post VR > Baseline CG	.020	0.63	[0.27, 0.99]
Baseline 2D < Training 2D	< .001	-1.23	[-1.48, -0.97]
Baseline 2D < Training CG	< .001	-1.03	[-1.40, -0.66]
Training 2D > Post 2D	< .001	0.85	[0.60, 1.11]
Training 2D > Baseline CG	< .001	1.34	[0.99, 1.70]
Training 2D > Post CG	.005	0.69	[0.34, 1.05]
Post 2D > Training CG	.016	-0.65	[-1.02, -0.29]
Baseline CG < Training CG	< .001	-1.14	[-1.41, -0.87]
Baseline CG < Post CG	< .001	-0.65	[-0.90, -0.40]
Training CG > Post CG	.009	0.49	[0.22, 0.76]

Supplement S4

Table 4

Mixed-Model ANOVA results for self-reported variables.

	Session / Timepoint			Group			Session / Timepoint x Group		
	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>
Scene relaxing	3,178.45	0.59	.622	1,67.40	0.01	.931	3,178.68	0.62	.600
Sphere intuitive visualization	3,178.53	1.89	.132	1,67.73	1.85	.179	3,178.75	1.80	.149
Environment helpful	3,178.01	4.92	.003	1,72.80	0.08	.784	3,178.05	0.27	.848
Liking	3,272.06	3.71	.012	2,101.52	1.10	.338	6,272.07	0.95	.458
Intention to use	3,272.12	0.36	.779	2,104.12	0.07	.936	6,272.08	0.82	.554
Recommendation to use	3,272.22	0.26	.854	2,102.64	0.69	.506	6,272.21	0.90	.494
Time perception	3,272.07	2.47	.062	2,94.93	3.59	.031	6,272.33	0.83	.545
Concentration	3,272.13	7.30	< .001	2,95.98	3.21	.045	6,272.31	1.36	.233
Distraction	3,272.23	1.60	.190	2,96.43	2.43	.093	6,272.40	0.67	.672
MBDF good mood	3,272.42	1.06	.369	2,93.68	0.06	.944	6,272.87	0.77	.597
MBDF alert tired	3,272.36	4.28	.006	2,93.53	0.93	.397	6,272.83	0.90	.496
MBDF rest unrest	3,272.53	1.41	.240	2,93.45	0.82	.445	6,273.06	1.28	.266
IPQ realism	3,151.26	0.73	.533	1,66.33	0.01	.963	3,151.25	2.30	.079
IPQ spatial presence	3,150.93	0.87	.457	1,66.56	8.44	.005	3,150.90	1.34	.263
IPQ involvement	3,151.29	1.92	.129	1,57.90	0.74	.392	3,151.52	1.34	.265
VRSQ mean	3,242.12	2.11	.099	2,86.39	0.17	.843	6,242.12	2.57	.020
UAQ1 Physical symptom improvement	3,272.11	8.43	< .001	2,98.59	0.65	.523	6,272.19	0.94	.464

Table 4 (continued)

	Session / Timepoint			Group			Session / Timepoint x Group		
	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>
UAQ2 physical well-being improvement	3,271.86	1.46	.226	2,97.05	0.79	.455	6,271.98	0.95	.461
UAQ3 positive impact on mood	3,271.93	0.39	.757	2,98.45	0.03	.966	6,272.00	0.98	.441
UAQ4 positive impact on experience of stress	3,271.31	0.85	.466	2,97.01	0.00	.998	6,271.41	0.42	.864
UAQ5 overall training satisfaction	3,272.11	1.57	.198	2,98.73	0.67	.515	6,272.18	0.81	.565
UAQ6 applying of strategies in everyday life	3,271.64	0.54	.658	2,98.13	0.02	.979	6,271.71	0.85	.530
UAQ7 side effects	3,271.81	0.87	.455	2,94.10	0.39	.679	6,272.12	1.64	.136
Scene relaxing	3,178.45	0.59	.622	1,67.40	0.01	.931	3,178.68	0.62	.600
Sphere intuitive visualization	3,178.53	1.89	.132	1,67.73	1.85	.179	3,178.75	1.80	.149
Environment helpful	3,178.01	4.92	.003	1,72.80	0.08	.784	3,178.05	0.27	.848
Liking	3,272.06	3.71	.012	2,101.52	1.10	.338	6,272.07	0.95	.458
Intention to use	3,272.12	0.36	.779	2,104.12	0.07	.936	6,272.08	0.82	.554
Recommendation to use	3,272.22	0.26	.854	2,102.64	0.69	.506	6,272.21	0.90	.494
Time perception	3,272.07	2.47	.062	2,94.93	3.59	.031	6,272.33	0.83	.545
Concentration	3,272.13	7.30	< .001	2,95.98	3.21	.045	6,272.31	1.36	.233

Table 4 (continued)

	Session / Timepoint			Group			Session / Timepoint x Group		
	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>
Distraction	3,272.23	1.60	.190	2,96.43	2.43	.093	6,272.40	0.67	.672
MBDF good mood	3,272.42	1.06	.369	2,93.68	0.06	.944	6,272.87	0.77	.597
MBDF alert tired	3,272.36	4.28	.006	2,93.53	0.93	.397	6,272.83	0.90	.496
MBDF rest unrest	3,272.53	1.41	.240	2,93.45	0.82	.445	6,273.06	1.28	.266
IPQ realism	3,151.26	0.73	.533	1,66.33	0.01	.963	3,151.25	2.30	.079
IPQ spatial presence	3,150.93	0.87	.457	1,66.56	8.44	.005	3,150.90	1.34	.263
IPQ involvement	3,151.29	1.92	.129	1,57.90	0.74	.392	3,151.52	1.34	.265
VRSQ mean	3,242.12	2.11	.099	2,86.39	0.17	.843	6,242.12	2.57	.020
UAQ1 Physical symptom improvement	3,272.11	8.43	< .001	2,98.59	0.65	.523	6,272.19	0.94	.464
UAQ2 physical well-being improvement	3,271.86	1.46	.226	2,97.05	0.79	.455	6,271.98	0.95	.461
UAQ3 positive impact on mood	3,271.93	0.39	.757	2,98.45	0.03	.966	6,272.00	0.98	.441
UAQ4 positive impact on experience of stress	3,271.31	0.85	.466	2,97.01	0.00	.998	6,271.41	0.42	.864

Note. **BMI** = Body Mass Index. **DASS** = Depression-Anxiety-Stress Scale – 21 (Nilges & Essau,2021). **EDIP** = Eating disorder-specific interoceptive perception questionnaire (Ortmann et al.,2024). **HBCT** = heart beat counting task (Legrand et al.,2022). **HFnu** = high frequency normalized units. **HR** = heart rate. **HRV** = heart rate variability. **MAIA-2** = Multidimensional Assessment of Interoceptive Awareness questionnaire 2 (Mehling et al.,2018b). **RMSSD** = root mean square of successive differences. **WLT-II** = two-step water load test (van Dyck,Vögele,et al.,2016)

Appendix C: Supplementary material Study 3

Appendix A

Table A1

Descriptive statistics of interoception, eating behavior and eating disorder symptoms at T1

	VR (n = 30)	2D (n = 32)	CG (n = 32)	Total (N = 94)
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
WLT-II				
Sat ml	333.83 (198.51)	362.90 (193.50)	320.50 (143.71)	338.67 (178.45)
Full ml	489.03 (274.14)	484.13 (223.66)	551.75 (243.48)	508.98 (246.88)
Total ml	822.87 (379.51)	835.32 (335.52)	872.25 (287.18)	844.01 (332.18)
% sat to full	0.41 (0.16)	0.42 (0.14)	0.38 (0.15)	0.40 (0.15)
WLT-II-Q				
Satiation	6.10 (1.45)	6.41 (1.32)	5.38 (2.17)	5.96 (1.73)
Fullness	5.83 (1.54)	6.50 (1.11)	6.41 (1.01)	6.26 (1.25)
Negative Affect	3.01 (0.66)	3.08 (0.76)	3.33 (0.79)	3.14 (0.75)
EDIP-Q				
Satiety	4.91 (1.18)	4.73 (1.23)	4.64 (1.65)	4.76 (1.36)
Emotion	5.34 (0.90)	5.10 (1.08)	5.06 (1.22)	5.16 (1.07)
Discrimination	5.93 (1.03)	6.09 (0.93)	5.93 (1.26)	5.98 (1.07)
Hunger	5.17 (1.05)	5.59 (0.86)	5.3 (0.99)	5.36 (0.98)
ECG				
Mean HR	65.48 (10.06)	62.93 (8.94)	62.40 (7.03)	63.59 (8.77)
HRV (RMSSD)	67.12 (26.17)	86.09 (51.28)	78.63 (44.40)	77.38 (42.33)
HRV (HFnu)	28.15 (19.18)	36.99 (21.87)	47.36 (26.47)	37.50 (23.76)
HBCT				
Score	0.53 (0.24)	0.65 (0.25)	0.62 (0.27)	0.60 (0.25)
Confidence	3.56 (1.17)	3.74 (1.23)	3.41 (1.04)	3.57 (1.15)
Insight	0.11 (0.49)	0.16 (0.60)	0.32 (0.56)	0.20 (0.56)
MAIA-2 total	2.98 (0.53)	2.95 (0.66)	2.76 (0.64)	2.89 (0.62)

Table A1 (continued)

	VR (<i>n</i> = 30)	2D (<i>n</i> = 32)	CG (<i>n</i> = 32)	Total (<i>N</i> = 94)
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
Eating behavior				
DEBQ EE	1.93 (0.87)	2.01 (0.79)	2.06 (1.08)	2.00 (0.91)
DEBQ EX	3.18 (0.48)	3.13 (0.58)	3.23 (0.57)	3.18 (0.54)
DEBQ RE	2.01 (0.47)	2.34 (0.72)	2.20 (0.75)	2.19 (0.67)
IES-2 total	3.88 (0.47)	3.68 (0.54)	3.65 (0.83)	3.73 (0.64)
IES-2 UPE	3.91 (0.54)	3.72 (0.71)	3.79 (0.84)	3.80 (0.70)
IES-2 EPR	3.84 (0.72)	3.66 (0.68)	3.64 (1.07)	3.71 (0.84)
IES-2 RHSC	3.80 (0.79)	3.59 (0.83)	3.51 (1.05)	3.63 (0.90)
IES-2 B-FCC	4.08(0.73)	3.80 (0.74)	3.71 (0.78)	3.86 (0.76)
ED symptoms				
EDE-Q8	0.83 (0.63)	1.13 (0.92)	1.40 (1.24)	1.13 (0.99)

Note. **2D** = 2D Group (television). **B-FCC** = Body-Food Choice Congruency IES-2. **CG** = Control Group. **DASS** = Depression, Anxiety, Stress Scale – 21 (Nilges & Essau, 2015). **DEBQ** = Dutch Eating Behaviour Questionnaire (Nagl et al., 2016). **EE** = Emotional Eating DEBQ. **EDE-Q8** = Eating Disorder Examine Questionnaire short 8 item version (Kliem et al., 2016). **EDIP** = Eating disorder-specific interoceptive perception questionnaire (Ortmann et al., 2024). **EPR** = Eating for Physical rather than Emotional Reasons IES-2. **EX** = External Eating DEBQ. **Full ml** = additional water volume until maximum fullness (ml). **HBCT** = heart beat counting task (Legrand et al., 2022). **HFnu** = high frequency normalized units. **HR** = heart rate. **HRV** = heart rate variability. **IES-2** = Intuitive Eating Scale 2 (van Dyck, Herbert, et al., 2016). **M** = Mean. **MAIA-2** = Multidimensional Assessment of Interoceptive Awareness questionnaire 2 (Mehling et al., 2018). **RE** = Restrained Eating DEBQ. **RHSC** = Reliance on Hunger Satiety Cues IES-2. **RMSSD** = root mean square of successive differences. **% sat to full** = percentage of satiation to maximum fullness. **Sat ml** = Ingested water volume until satiety (ml). **SD** = Standard Deviation. **Total ml** = total ingested water volume (ml). **UPE** = Unconditional Permission to Eat IES-2. **VR** = Virtual Reality Group. **WLT-II** = two-step water load test (van Dyck, Vögele, et al., 2016).

Appendix B

Table B1

Mixed-model ANOVA results for the covariates Depression, Sex, BMI on Interoception, Eating Behavior and ED symptoms variables.

	DASS Depression			Sex			BMI		
	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>
WLT-II									
Sat ml	1,87.78	0.14	.705	1,87.98	0.33	.565	1,87.51	0.89	.349
Full ml	1,86.89	2.54	.114	1,87.07	4.50	.037	1,86.70	0.12	.734
Total ml	1,87.16	1.76	.188	1,87.39	1.33	.252	1,86.92	0.61	.438
% sat to full	1,87.35	0.17	.681	1,87.45	6.04	.016	1,87.16	0.42	.518
WLT-II-Q									
Satiation	1,88.99	0.89	.349	1,88.81	0.01	.910	1,88.12	1.70	.196
Fullness	1,89.00	6.50	.013	1,88.69	0.09	.769	1,87.78	1.17	.282
Negative Affect	1,89.07	0.18	.675	1,88.96	0.14	.705	1,88.35	0.97	.328
EDIP-Q									
Satiety	1,163.24	1.20	.002	1,86.71	0.25	.618	1,87.08	3.68	.058
Emotion	1,148.40	2.05	.154	1,88.90	1.67	.199	1,89.18	8.09	.006
Discrimination	1,173.20	3.55	.061	1,87.14	0.46	.497	1,87.58	0.16	.686
Hunger	1,173.80	1.97	.162	1,87.78	0.15	.703	1,88.34	1.07	.303
ECG									
Mean HR	1,79.53	0.09	.766	1,79.61	0.67	.417	1,79.48	0.03	.856
HRV (RMSSD)	1,79.19	< .01	.996	1,79.25	5.62	.020	1,79.15	0.34	.560
HRV (HFnu)	1,79.41	1.89	.173	1,79.47	7.36	.008	1,79.37	0.22	.638
HBCT									
Score	1,166.66	0.20	.657	1,87.22	0.35	.556	1,88.71	0.04	.849
Confidence	1,165.99	0.27	.605	1,88.75	4.41	.039	1,9.26	0.65	.422
Insight	1,143.69	0.89	.348	1,85.18	3.77	.055	1,86.54	1.82	.181
MAIA-2 total									
MAIA-2 total	1,169.49	24.60	<.001	1,86.71	0.04	.842	1,87.12	1.02	.316
Noticing	1,172.86	14.48	<.001	1,86.48	0.51	.478	1,87.05	0.51	.478
Not-Distracting	1,175.77	9.32	.003	1,88.70	4.10	.046	1,89.18	0.19	.661
Not-Worrying	1,175.97	3.60	.059	1,88.02	1.71	.194	1,88.52	1.61	.208

Attention	1,171.95	19.07	<.001	1,88.48	0.01	.963	1,89.06	0.18	.673
Regulation									
Emotional	1,174.29	5.32	.022	1,87.60	0.01	.926	1,88.15	0.00	.951
Awareness									
Self-Regulation	1,171.75	13.81	<.001	1,87.05	0.21	.646	1,87.63	0.17	.683
Body Listening	1,171.96	3.44	.065	1,86.24	2.60	.110	1,86.82	0.52	.475
Trusting	1,175.98	18.28	<.001	1,88.62	0.31	.580	1,89.12	2.91	.092
Eating behavior									
DEBQ EE	1,135.59	3.9	.050	1,87.55	3.63	.060	1,87.78	9.08	.003
DEBQ EX	1,164.94	0.06	.802	1,89.14	0.01	.956	1,89.51	0.33	.567
DEBQ RE	1,154.39	0.49	.485	1,87.35	5.93	.017	1,87.67	16.97	<.001
IES-2 total	1,138.28	11.56	.001	1,88.82	4.52	.036	1,89.06	14.54	<.001
IES-2 UPE	1,17.89	8.37	.004	1,88.84	0.93	.337	1,89.25	9.97	.002
IES-2 EPR	1,145.41	1.17	.002	1,88.71	9.02	.003	1,88.98	12.38	<.001
IES-2 RHSC	1,15.26	3.48	.064	1,89.01	2.61	.110	1,89.31	8.58	.004
IES-2 B-FCC	1,172.11	0.17	.677	1,87.73	1.35	.249	1,88.15	0.53	.470
ED symptoms									
EDE-Q8	1,141.36	13.39	<.001	1,87.07	9.53	.003	1,87.33	24.8	<.001

Note. **2D** = 2D Group (television). **B-FCC** = Body-Food Choice Congruency IES-2. **CG** = Control Group. **DASS** = Depression, Anxiety, Stress Scale – 21 (Nilges & Essau, 2015). **DEBQ** = Dutch Eating Behaviour Questionnaire (Nagl et al., 2016). **EE** = Emotional Eating DEBQ. **EDE-Q8** = Eating Disorder Examine Questionnaire short 8 item version (Kliem et al., 2016). **EDIP** = Eating disorder-specific interoceptive perception questionnaire (Ortmann et al., 2024). **EPR** = Eating for Physical rather than Emotional Reasons IES-2. **EX** = External Eating DEBQ. **Full ml** = additional water volume until maximum fullness (ml). **HBCT** = heart beat counting task (Legrand et al., 2022). **HFnu** = high frequency normalized units. **HR** = heart rate. **HRV** = heart rate variability. **IES-2** = Intuitive Eating Scale 2 (van Dyck, Herbert, et al., 2016). **M** = Mean. **MAIA-2** = Multidimensional Assessment of Interoceptive Awareness questionnaire 2 (Mehling et al., 2018). **RE** = Restrained Eating DEBQ. **RHSC** = Reliance on Hunger Satiety Cues IES-2. **RMSSD** = root mean square of successive differences. **% sat to full** = percentage of satiation to maximum fullness. **Sat ml** = Ingested water volume until satiety (ml). **SD** = Standard Deviation. **Total ml** = total ingested water volume (ml). **UPE** = Unconditional Permission to Eat IES-2. **VR** = Virtual Reality Group. **WLT-II** = two-step water load test (van Dyck, Vögele, et al., 2016).

Figure 4

(a) Amount of water drunk until satiation on the WLT-II (in mL), (b) Amount of water drunk in total on the WLT-II, (c) Negative Affect on the WLT-II questionnaire (d) Mean HR during the training (e) Mean RMSSD (HRV) during the training and (f) Mean HF nu (HRV) during the training, for the VR, 2D and CG group along the four experimental

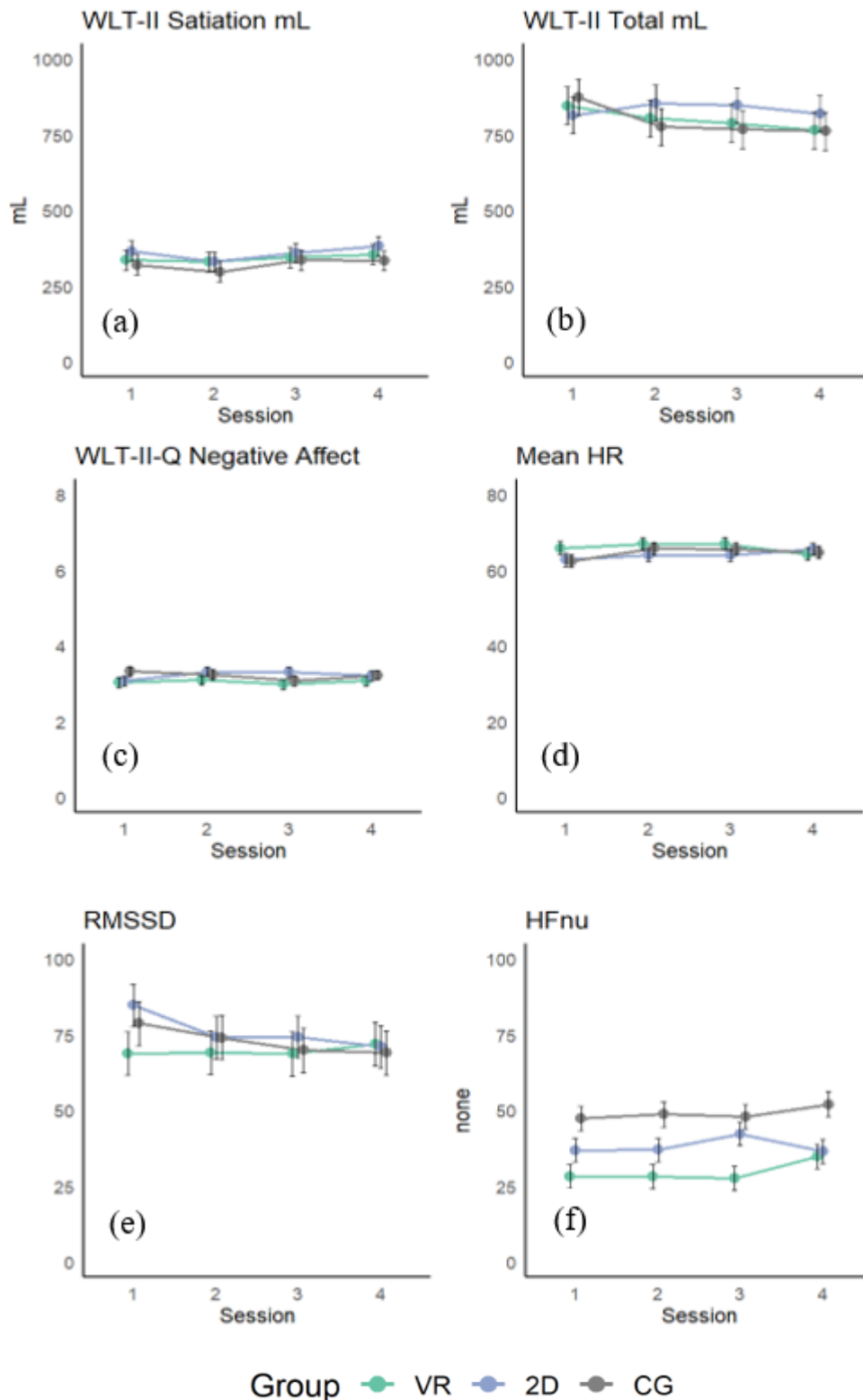


Figure 5

(a) EDIP Emotion (b) EDIP Satiation (c) EDIP Discrimination and (d) EDIP Hunger, pre-training and post-training for the VR, 2D and CG group

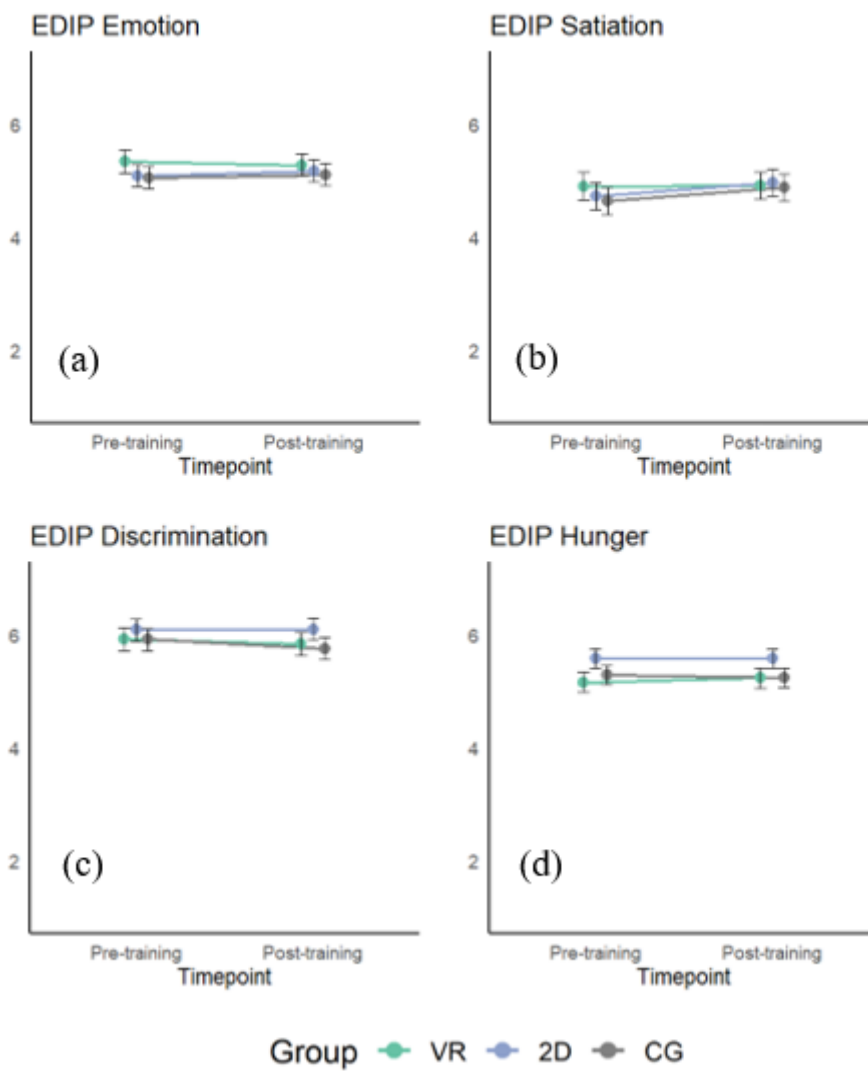


Figure 6

(a) HBCT Score (b) HBCT Confidence (c) HBCT Insight and (d) MAIA total, pre-training and post-training for the VR, 2D and CG group

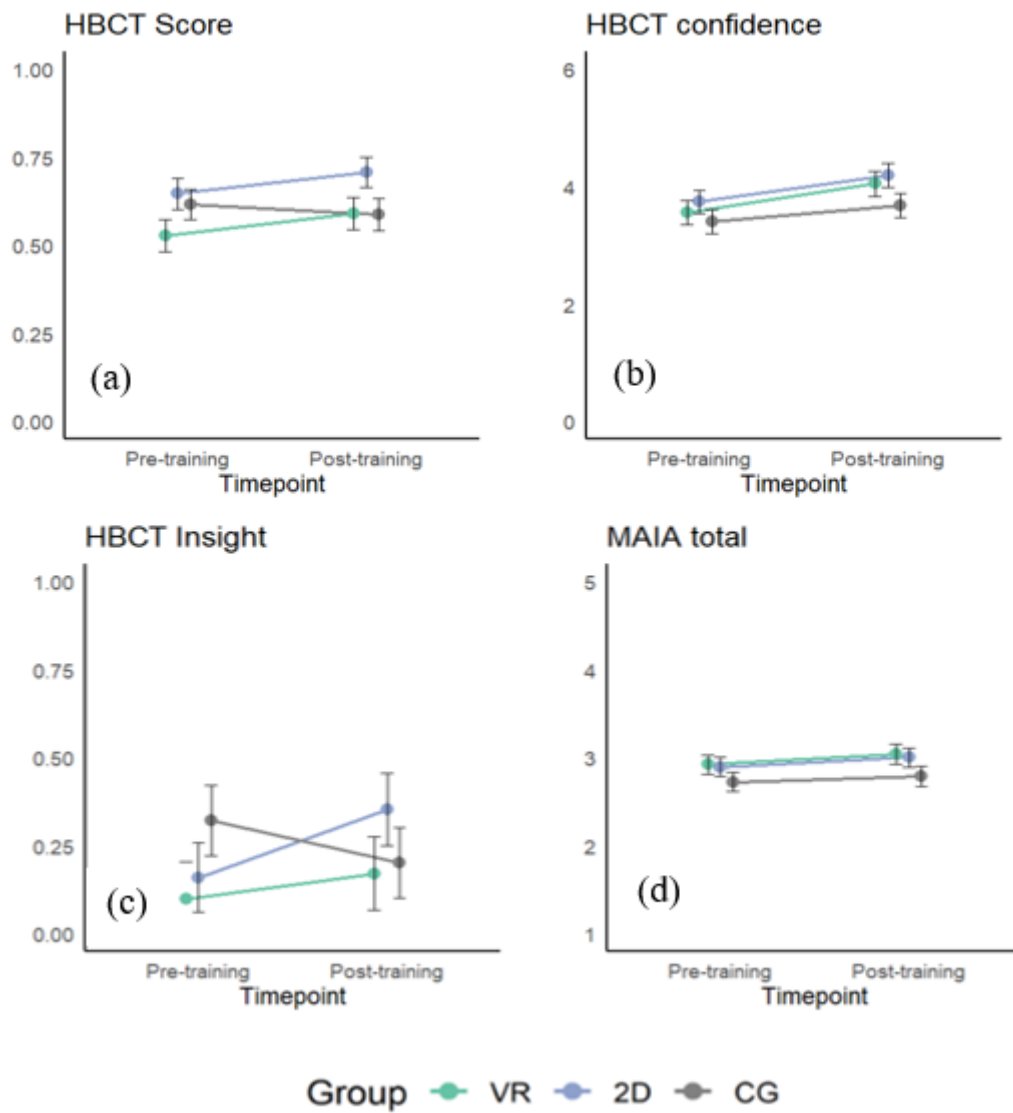
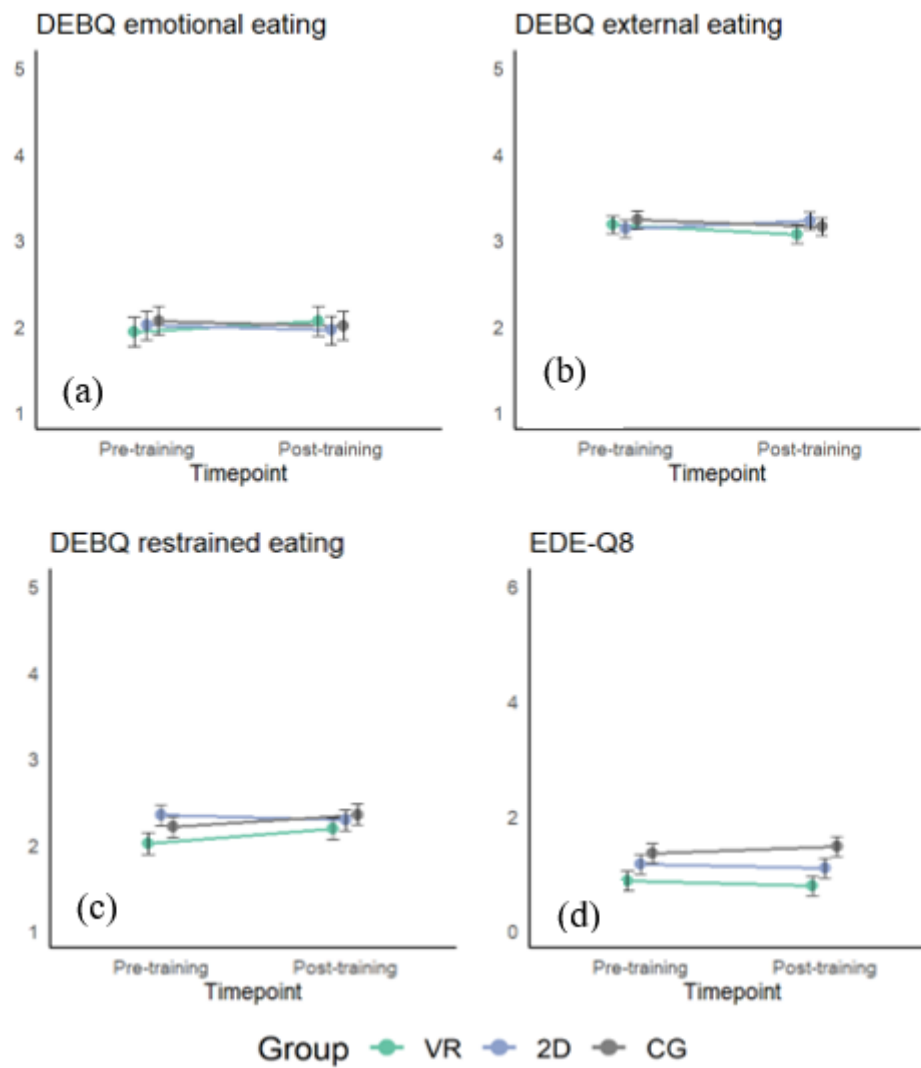
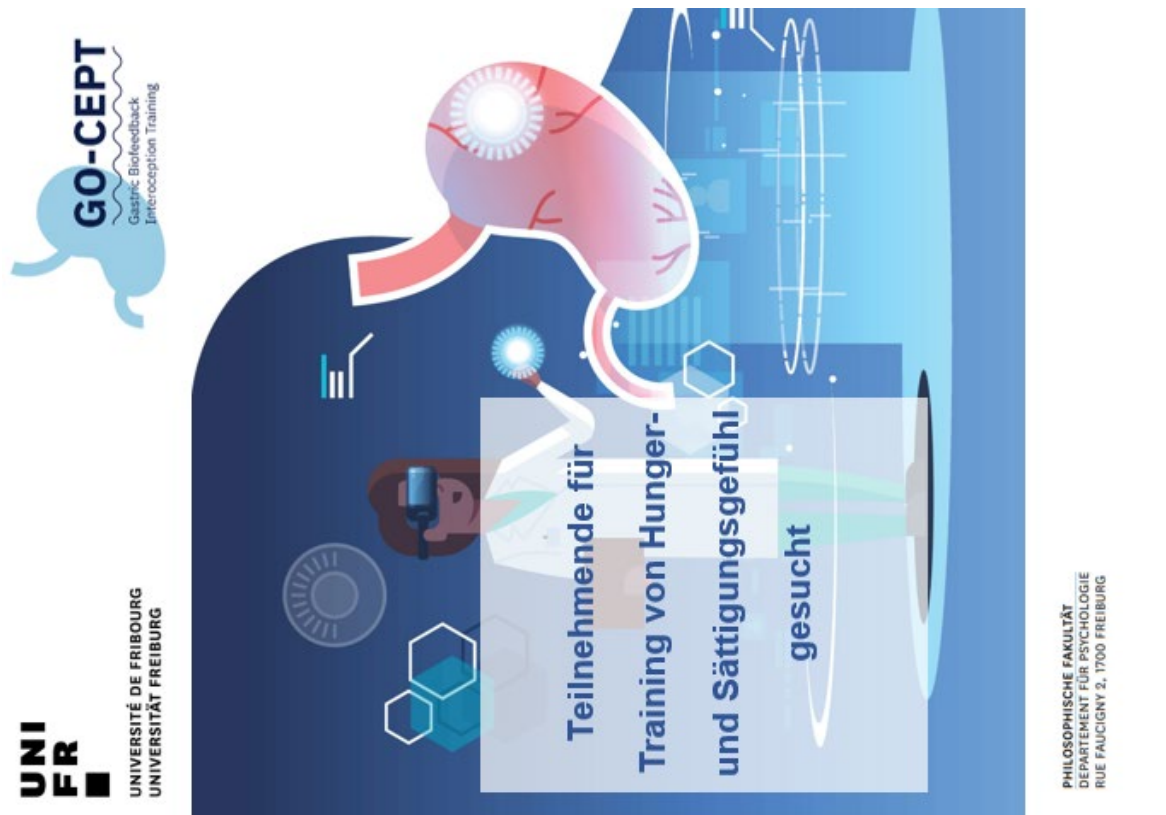


Figure 7

(a) DEBQ emotional eating (b) DEBQ external eating (c) DEBQ restrained eating and (d) EDE-Q8, pre-training and post-training for the VR, 2D and CG group



Appendix D: Go-Cept project flyer (Studies 2 and 3)



Teilnehmende für Training von Hunger- und Sättigungsgefühl «GO-CEPT» gesucht!

Das "Gastrische Biofeedback Interoceptions Training" (Go-Cept) ist ein forschungsbasiertes Trainingsprogramm der Wahrnehmung und Regulierung des Hunger- und Sättigungsgefühl für Erwachsene ab dem Alter von 18 Jahren.

Was ist das Ziel der Go-Cept Studie?

In der Studie wird das Trainingsprogramm hinsichtlich seiner Wirksamkeit evaluiert. Dabei wird ein Training eingesetzt, um die Wahrnehmung von Hunger- und Sättigungssignalen (Interozeption) zu verbessern und zu lernen, diese zu regulieren.

Wer kann am Go-Cept Trainingsprogramm mitmachen?

- Alter: mindestens 18 Jahre alt
- Gute Deutschkenntnisse

Wie läuft das Go-Cept Trainingsprogramm ab?

Die Studie findet am Campus Regina Mundi der Universität Fribourg statt. Du wirst zu 4 Sitzungen eingeladen:

- Termin 1: Labortestung + Training (ca. 2-2:30h)
- Termin 2: Training (ca. 1-1:30h)
- Termin 3: Training (ca. 1-1:30h)
- Termin 4: Labortestung + Training (ca. 2-2:30h)

Meine Vorteile:

- Psychologiestudierende der Universität Fribourg erhalten 9 Versuchsteilnehmendenstunden
- Leistet einen wichtigen Beitrag zur Erforschung von Essstörungen und Adipositas!

Bist Du interessiert oder hast Fragen zur Teilnahme?

Gerne kannst Du eine E-Mail schreiben an go-cept@unifr.ch

Oder scanne den QR-Code oder besuche unsere Website:
<https://www.unifr.ch/psycho/de/go-cept/home/>

Dort kannst Du Dich direkt für die Studie anmelden!



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