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Multimodal Psychophysiological Assessment Reveals Gastric but Not Cardiac Interoception Deficits in Disorders of Gut-Brain Interaction

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ABSTRACT

Disorders of Gut-Brain Interaction (DGBI) are characterized by persistent digestive symptoms in the absence of objectively detectable abnormalities. Visceral hypersensitivity and interoceptive dysfunction are central features of DGBI, yet the specific interoceptive impairments associated with these conditions remain underexplored. This study aimed to characterize interoceptive processing in patients with DGBI by comparing gastric and cardiac interoceptive accuracy, interoceptive beliefs, and related affective responses with those of healthy controls. Thirty patients with DGBIs and 30 matched healthy controls completed the Water Load Test-II (WLT-II) and the Heartbeat Counting Task (HCT) to assess gastric and cardiac interoception, respectively. Participants completed self-report measures of interoceptive beliefs (MAIA-II), visceral sensitivity (VSI), and somatic symptom burden (SSD-12). Resting electrogastrographic signal (EGG) was also recorded. Results revealed that patients suffering from DGBIs exhibited significantly reduced gastric interoception compared to controls ($p < 0.001$), despite no differences in cardiac interoception ($p = 0.893$), supporting a modality-specific impairment. Patients also showed altered drinking behavior during WLT-II, requiring less water to reach satiety but more to reach fullness. Despite interoceptive beliefs not differing between groups, patients reported greater visceral sensitivity and somatic distress. Notably, WLT interoceptive measure in patients correlated positively with the "Trusting" MAIA-II subscale ($r = 0.423$, $p = 0.020$), and EGG peak frequency correlated with affective symptom distress ($r = 0.496$, $p = 0.024$). These findings suggest that impaired gastric interoception in DGBIs is associated with dysregulated physiological and affective responses, independent of subjective interoceptive beliefs. Our results highlight the importance of using modality-specific interoceptive assessments and suggest the potential for interoceptive training interventions to improve symptom management in DGBI populations.

1 | Introduction

Gastrointestinal symptoms often include abdominal pain, diarrhea, constipation, bloating, nausea, and fullness. In the absence of objective organic damage, this symptomatology defines Functional Gastrointestinal Disorders (FGIDs), often referred to as Disorders of Gut-Brain Interaction (DGBIs) (Drossman 2016; Black et al. 2020). Gut-Brain axis refers to a complex communication system responsible for maintaining gastric homeostasis and influences cognitive and affective aspects (Rhee et al. 2009). This fundamental network includes the central nervous system (CNS), the enteric nervous system (ENS), and the autonomic nervous system (ANS). The autonomic nervous system, including sympathetic and parasympathetic branches,

regulates bidirectional communication between the gut and the central nervous system. Specifically, it conveys afferent signals originating from the intestinal lumen via enteric, spinal, and vagal pathways to the CNS, while simultaneously transmitting efferent signals from the CNS back to the intestinal wall. Enteric microbiota, distributed along the gastric intestinal wall, seems to have a role in disruption and deficits in gut-brain communication, influencing both gastric and cognitive/affective symptomatology (Koloski et al. 2012; Carabotti et al. 2015). Since DGBIs are not linked to gastrointestinal structural abnormalities, they are classified according to the symptom-based Rome IV Criteria (Drossman 2016; Drossman et al. 1999; Drossman and Dumitrascu 2006). An estimated 40% of adults worldwide meet the diagnostic criteria for DGBIs, with a higher prevalence in women than men and a worsening of overall quality of life (Sperber et al. 2021). In addition to this, DGBIs have a huge economic impact: for example, the annual expenses per patient with Irritable Bowel Syndrome (IBS) in Europe are in a range between €1421.7 and €2487.1 (Tack et al. 2019). According to other estimates, yearly IBS expenses in Italy, which is our frame of reference, amount to € 2800 per patient, for a total of EUR 6–8 billion (Flacco et al. 2019).

The etiology of Disorders of Gut-Brain Interaction is still unclear, although it is thought that they arise due to an interaction between environmental, psychosocial, genetic, and physiological factors (Mayer et al. 2014). For example, psychological stressors, abuse history, or pre-existing anxiety or depression could be predictors of DGBI development (Collins et al. 2012; Drossman 2016). Furthermore, impairment of gut–brain axis communication has been implicated in the pathogenesis of DGBIs. This dysregulation is associated with alterations in intestinal motility and secretion, as well as the development of visceral hypersensitivity (Mayer et al. 2015; Carabotti et al. 2015). The most commonly encountered DGBIs are Functional Dyspepsia (FD) and Irritable Bowel Syndrome (IBS), with a prevalence between 1.1% and 45.0% for IBS (Lovell and Ford 2012) and 1.8%–57.0% for FD (Ford et al. 2015). FD is a chronic disorder characterized by persistent or recurrent upper abdominal symptoms, including epigastric pain, burning, early satiety, or postprandial fullness, without any identifiable structural disease. IBS is a chronic disorder characterized by recurrent abdominal pain associated with altered bowel habits, in the absence of identifiable structural or biochemical abnormalities. These patients suffer from visceral hypersensitivity (i.e., the increased sensibility to pain originating from viscera) and chronic abdominal pain (Drossman 2016; Mayer and Gebhart 1994).

Visceral Hypersensitivity is considered a pathophysiological mechanism linked to chronic abdominal pain and increased sensitivity in the gastrointestinal tract (Simrén et al. 2018). Neuroimaging studies demonstrate that this core feature of DGBI is characterized by elevated activation of areas involved in visceral and pain processing, such as the insula, anterior cingulate, and somatosensory cortices (Derbyshire 2003; Tillisch et al. 2011). Generally, people who experience visceral hypersensitivity show abnormalities in interoceptive abilities (Bonaz et al. 2021).

Interoception is defined as the constant sensing, integration, and interpretation of visceral signals and states at a conscious level (Ceunen et al. 2016; Craig 2002; Khalsa et al. 2018). This construct can be divided into different dimensions as postulated by Suksasilp and Garfinkel in their multi-dimensional interoceptive framework (Suksasilp and Garfinkel 2022). Interoceptive accuracy refers to the degree of accordance between objectively measured physiological signals and an individual's reported perception of those signals, typically assessed through behavioral tasks. Interoceptive beliefs encompass both consciously accessible and unconscious beliefs about one's internal bodily sensations and experiences. These can be measured through self-report questionnaires and confidence ratings, as well as task-based methods that infer implicit prior beliefs thought to shape interoceptive perception. Interoceptive insight describes the metacognitive ability to evaluate one's own interoceptive performance, for example, how well an individual's confidence or perceived accuracy during a task matches their actual accuracy (Suksasilp and Garfinkel 2022).

Interoception has a key role in homeostasis, and its alteration is implicated in several physical and psychological disorders, such as psychiatric, neurological, structural, and functional disorders (Bonaz et al. 2021; Quadt et al. 2018). For example, studies indicate that people with hypertension (Yoris et al. 2018), depression and anxiety (Paulus and Stein 2010; Stephan et al. 2016), anorexia nervosa (Pollatos et al. 2008), autism (Garfinkel et al. 2016), alexithymia (Shah et al. 2016), chronic pain (Di Lernia et al. 2016), and endometriosis (Cantoni et al. 2025) show altered interoception when compared to healthy subjects. However, it is only over the past 10 years that the study of interoception in patients with Disorders of Gut-Brain Interaction has started to attract the interest of scholars. For example, Fournier et al. (2020) found that difficulty in interoceptive awareness, measured through the Toronto Alexithymia Scale (TAS-20, Taylor et al. 2003), predicted the presence of IBS. This corroborates previous findings by Longarzo et al. (2017), who found that the stronger the functional connectivity between the left anterior ventral insula and two clusters situated in the supramarginal gyrus, the higher the IBS patient scores on the Self-Awareness Questionnaire (Longarzo et al. 2015). Moreover, Gajdos et al. (2020) found differences in interoceptive beliefs measured via the Multidimensional Assessment of Interoceptive Awareness (MAIA-II) questionnaire (Mehling et al. 2018) between subjects with high and low frequency of functional gastrointestinal symptoms. Specifically, patients with low frequency of DGBI symptoms report perceiving more somatic sensations, have reduced confidence in their body signals, and a negative attitude towards bodily processes. However, in the same study, there were no differences in performance at the level of interoceptive accuracy measured through the Heartbeat Counting Task. Finally, Schulz et al. (2023) reported a significant difference among different types of patients and controls in drinking behavior but not in gastric sensitivity measured through Water Load Test II (Van Dyck et al. 2016). In particular, patients suffering from inflammatory bowel disorder drank significantly more water to reach satiety compared to patients with IBS, but no differences emerged when the two experimental groups were compared to healthy samples.

One of the most used non-invasive techniques to assess the psychophysiology of gastric signals is Electrogastrography (EGG) (Koch and Stern 2004). Specifically, EGG measures gastric

myoelectrical activity via cutaneous electrodes positioned on the abdominal surface directly above the stomach (Yin and Chen 2013). Alterations in gastric activity were assessed in patients who suffered from FD (Lin et al. 1998, 1999), while considering DGBIs in general, Leahy et al. (1999) found abnormal EGG signals in 36% of patients with FD and in 25% of those with IBS who reported concurrent dyspeptic symptoms. In contrast, normal EGG signals were found in 93% of asymptomatic controls and 92% of patients with IBS without dyspeptic complaints. Overall, results are rather unclear, and past research has not found any differences in gastric myoelectrical activity between patients with DGBIs and controls (Schulz et al. 2023; Van der Voort et al. 2003).

Within this framework characterized by contrasting results, the present study aims to gauge interoceptive abilities in patients with DGBIs, by focusing on gastric interoception, assessed using the Water Load Test II (Van Dyck et al. 2016). DGBI patients' performance in this task was compared to that of age- and sex-matched healthy controls. In addition, interoceptive cardiac abilities were evaluated using the Heartbeat Counting Task (Schandry 1981) in order to compare interoception at the level of the heart and the gut. We expected lower gastric, but not cardiac, interoception in DGBI patients compared to healthy controls, reflecting the notion that interoceptive deficits map onto the organ system affected by the disorder, rather than extending across all bodily domains (Horsburgh et al. 2024; Cantoni et al. 2025). Moreover, we were interested in exploring differences in resting gastric myoelectrical activity between groups, as well as investigating whether potential interoceptive abnormalities in patients suffering from DGBIs are associated with gastric psychophysiological markers and self-reported psychological symptomatology. Furthermore, self-report questionnaires were used to assess interoceptive beliefs, attention to visceral signals, and psychosomatic symptoms, providing a multidimensional profile of interoceptive processing in patients with DGBIs.

2 | Materials and Methods

2.1 | Participants

We recruited thirty patients diagnosed with irritable bowel syndrome (IBS; $n = 18$), functional dyspepsia (FD; $n = 9$), and 3 with both syndromes (IBS + FD; $n = 3$) (mean age = 37.8 years, range = 22–72; 5 males, 25 females), along with thirty healthy controls individually matched for sex and age (mean age = 37.7 years, range = 23–65; 5 males, 25 females). Four patients with IBS were diarrhea-type, 4 constipation-type, and the remaining were mixed-type.

The recruitment of the control group was carried out through a word-of-mouth procedure and university classes. Patients in the experimental group were diagnosed with a DGBI and recruited from the Gastroenterology Outpatient Clinic of the Department of Integrated Activity of Internal Medicine and Medical Specialties at Policlinico Umberto I, Rome. Diagnoses were made by specialized clinicians based on standard clinical criteria and included the exclusion of *Helicobacter pylori* infection or any other organic cause. To support classification, participants completed the Rome IV Diagnostic Questionnaire (Drossman and Hasler 2016), a validated self-report tool widely used in clinical and research contexts to identify DGBIs. All participants were also screened by a gastroenterologist to ensure the absence of recent pharmacological interference. Specifically, individuals who had taken medications known to affect gastrointestinal motility within 24 h before the experimental session were excluded.

The control group consisted of healthy individuals individually matched to the clinical group for sex and age. Exclusion criteria for both groups included a Body Mass Index > 24, the presence of cardiovascular, metabolic, neurological, or psychiatric disorders, as well as the chronic use of medications (except for those taken to treat DGBI symptoms in the patient group). All participants were free to withdraw from the study at any time; in such cases, they were replaced with individuals with similar demographic and health characteristics.

The experimental protocol was reviewed and approved by the Ethics Committee of Policlinico Umberto I (protocol number: 0354/2022) and complied with the ethical standards of the 2013 Declaration of Helsinki. All participants provided written informed consent and were naïve to the purpose of the study.

An a priori power analysis was conducted using G*Power 3.1.9.4 (Faul et al. 2007), based on effect sizes reported in previous studies (Di Lernia et al. 2020; Salamone et al. 2021) to detect differences in interoceptive sensations between groups. The analysis was set to detect a large effect ($f = 0.4$, corresponding to $\eta^2 = 0.14$) using a one-way ANOVA with two groups, an alpha level of 0.05, and a statistical power of 0.80. The resulting critical F-value was 4.03. Based on these parameters, the required sample size was estimated at 26 participants per group.

2.2 | Procedure

Participants arrived at the lab after refraining from food for 3 h and from water for 2 h. This is considered standard procedure for assessing gastric interoceptive sensations (Van Dyck et al. 2016). They provided written informed consent and began the experimental session with a resting electrogastrogram (EGG) recording, which lasted 15 min.

Following the EGG acquisition, participants completed two tasks: (i) the Heartbeat Counting Task that assessed cardiac interoception (Schandry 1981), lasting approximately 5 min; and (ii) the Two-Step Water Load Test (Van Dyck et al. 2016), which assessed gastric interoception, lasting approximately 15 min. Self-report questionnaires were completed at home after the experimental session. Participants received a personalized link via email to access the survey platform SurveyMonkey (Momentive Inc., San Mateo, CA), a secure online tool for data collection that complies with standard privacy and data protection regulations. The platform allowed participants to complete the questionnaires at their convenience, using either a computer or a mobile device. At the end of the experimental tasks, participants were debriefed regarding the purpose of the experimental procedure and the study. The entire session (Figure 1) lasted approximately 1 h.

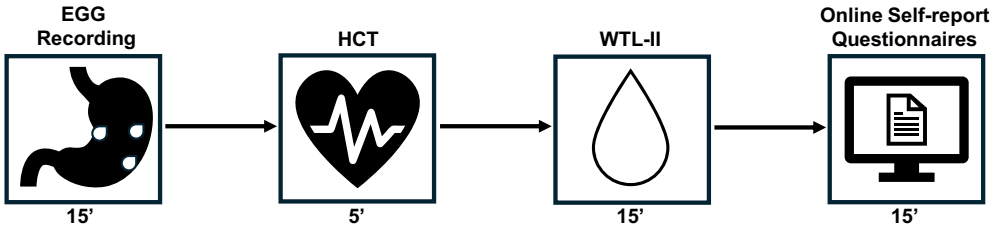

FIGURE 1 | Experimental procedure.

2.3 | EGG Acquisition

EGG captures two key components: (i) the slow-wave gastric rhythm, occurring at approximately 0.05 Hz, which originates from a specialized pacemaker region located along the greater curvature of the stomach's mid-to-upper corpus; and (ii) transient myoelectrical signals associated with smooth muscle activity that underlie gastric peristaltic contractions (see Wolpert et al. 2020, for a comprehensive review). In the present study, we employed a one-channel bipolar EGG configuration using three pre-gelled, disposable Ag/AgCl electrodes, following the standardized placement protocol described by Yin and Chen (2013). The first recording electrode was positioned midway between the participant's xiphoid process and umbilicus. The second electrode was located 5 cm above and 5 cm to the left of the first electrode, using the participant's left side as a reference point. A ground electrode was affixed along the left costal margin. Data were acquired via a PowerLab system (ADInstruments Ltd).

2.4 | Interoceptive Tasks

2.4.1 | Cardiac Task—Heartbeat Counting Task (HCT, Schandry 1981)

Participants were asked to silently count their perceived heartbeats and not to guess them over four time intervals (25 s, 35 s, 45 s, and 100 s), presented in a randomized order. After each trial, they reported the number of perceived heartbeats. During the task, cardiac activity was continuously monitored via a three-electrode ECG setup using pre-gelled Ag/AgCl electrodes in a standard bipolar lead II configuration. Interoceptive accuracy was quantified using the following formula: $1/4\Sigma(1 - |\text{actual\_heartbeats} - \text{reported\_heartbeats}|/\text{actual\_heartbeats})$, where higher values indicate greater accuracy (Schandry 1981). ECG signals were acquired with three pre-gelled, disposable Ag/AgCl electrodes (50 mm) placed in a bipolar lead II configuration and connected to a PowerLab 8/30 system with a BioAmp amplifier (ADInstruments). Data were processed in LabChart 7.3.8 (ADInstruments) to identify QRS complexes and calculate heart rates for each interval. Subjective heartbeat counts were collected using E-Prime 2.0 (Psychology Software Tools Inc.).

2.4.2 | Gastric Task—Two-Step Water Load Test (WLT-II, Van Dyck et al. 2016)

The task, adapted from van Dyck et al. (2016), consisted of two consecutive phases. In the first phase (maximum duration: 5 min), participants were instructed to drink water with a straw until they reached a subjective feeling of satiety (sat_mL). Immediately afterwards, participants were asked to drink (maximum duration: 5 min) until they experienced a sensation of maximum gastric fullness (Δfull_mL). The ratio of the volume consumed in the first phase to the total volume ingested across both phases was then used to compute a gastric interoception index: $\text{sat\%} = (\text{sat\_mL}/\text{total\_mL}) \times 100$. This dimensionless value ranges from 0 to 100 and provides a standardized estimate of gastric sensitivity. A higher index indicates the individual's subjective perception of how closely the sensation of satiation approaches that of fullness, independent of their actual gastric volume. The two 1.5 L water bottles (one for each drinking session) were placed inside a box that concealed both the bottle and the liquid level, preventing participants from seeing the amount of water they were drinking. At baseline and following each phase, participants rated their internal gastric sensations (see Table 1).

2.5 | Self-Report Questionnaires

Participants completed the Italian versions of the following online self-report questionnaires to assess different aspects of bodily and symptom-related experiences.

2.5.1 | Body Perception Questionnaire—Short Form (BPQ-SF; Porges 1993)

In the present study, only the *Body Awareness* subscale was used. This subscale consists of 45 items and measures

TABLE 1 | WLT-II questionnaire assessing gastric sensations.

Q1: How satiated do you feel right now?	1	2	3	4	5	6	7
Q2: How full do you feel right now?	1	2	3	4	5	6	7
Q3: How much discomfort do you feel right now?	1	2	3	4	5	6	7
Q4: How much guilt do you feel right now?	1	2	3	4	5	6	7
Q5: How sluggish do you feel right now?	1	2	3	4	5	6	7
Q6: How much nausea do you have right now?	1	2	3	4	5	6	7
Q7: How aroused do you feel right now?	1	2	3	4	5	6	7

individual differences in the conscious perception of internal bodily signals. Each item is rated on a 5-point Likert scale. Higher total scores indicate greater self-reported interoceptive awareness.

2.5.2 | Visceral Sensitivity Index (VSI; Labus et al. 2004)

This 15-item self-report measure, structured on a Likert response format, is specifically developed to assess cognitive and emotional reactions, such as fear, heightened alertness, and anxiety, associated with the misinterpretation of internal visceral sensations. It is particularly suited to capture the psychological component of gastrointestinal symptom perception. The total scores range from 0, indicating no gastrointestinal-specific anxiety (GSA), to 75, reflecting high levels of GSA.

2.5.3 | Somatic Symptom Scale—12 (SSS-12; Toussaint et al. 2017)

This 12-item self-report questionnaire was developed to assess the psychological characteristics defined in Criterion B of Somatic Symptom Disorder (SSD) (DSM-5; Guha 2014). The scale captures maladaptive cognitive, emotional, and behavioral responses to somatic symptoms. Responses are rated on a 5-point scale and summed to yield a total score, with higher values reflecting greater psychological distress associated with physical symptoms.

2.5.4 | Multidimensional Assessment of Interoceptive Awareness—2 (MAIA-2; Mehling et al. 2018)

This 37-item self-report questionnaire aims to measure interoceptive beliefs. It consists of 8 different subscales, each reflecting a specific aspect of the subjective experience of bodily sensations (Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body Listening, Trusting). Responses to each item are rated on a 6-point Likert scale and summed for every subscale separately.

2.6 | Data Analysis

All the analyzes were performed with Jamovi software (The jamovi project, 2023) and R Studio software (RStudio Team 2023).

2.6.1 | Interoceptive Measures

To test if cardiac and gastric interoception scores were different between patients with Disorders of Gut–Brain Interaction and healthy controls, we ran a series of *t*-tests: for the gastric interoceptive measure, satiety scores, fullness scores measured through the WLT-II, and total volumes of ingested water scores, we ran four Mann–Whitney U tests, as the data did not meet the assumptions of normality, while for cardiac interoceptive accuracy, measured through the HCT, we ran a Student's *t*-test, as the data were normally distributed.

2.6.2 | Self-Reports in the WLT-II

To assess changes in participants' ratings of satiation, fullness, and negative affect across the three phases of the Water Load Test-II (i.e., baseline, satiety, fullness), we conducted a 3 (Phase: baseline, satiety, fullness) × 2 (Group: DGBI, Control) mixed-design ANOVA, with Phase as a within-subjects factor and Group as a between-subjects factor. Where significant main effects or interactions were found, Tukey's HSD post hoc comparisons were performed.

2.6.3 | Interoceptive Beliefs and Other Self-Report Questionnaires

To test the group differences in interoceptive beliefs, we run a series of independent samples Student's *t*-tests on each subscale of the Multidimensional Assessment of Interoceptive Awareness II (MAIA-II; Mehling et al. 2018). To control for multiple comparisons, *p*-values were adjusted using False Discovery Rate (FDR) correction (Benjamini and Hochberg 1995). An additional independent samples *t*-test was used to compare Body Perception Questionnaire (BPQ; Porges 1993) scores between groups. Group differences on the Visceral Sensitivity Index (VSI; Labus et al. 2004) and on the affective and behavioral subscales of the Somatic Symptom Disorder questionnaire (SSD-12; Toussaint et al. 2017) that violated normality assumptions were assessed using Mann–Whitney *U* tests. For the cognitive SSD-12 subscale and the SSD-12 total score, two independent samples Student's *t*-tests were used, as data met the assumptions for parametric tests.

2.6.4 | Electrogastrogram Preprocessing and Analysis

The 15-min baseline raw electrogastrography (EGG) data were processed in MATLAB using the FieldTrip toolbox (Oostenveld et al. 2011). After visual inspection, movement and technical artifacts were manually excluded, and clean data were recombined into continuous traces. Signals were band-pass filtered between 0.016 and 0.15 Hz (≈1–9 cpm) to capture gastric slow waves and segmented into 150 s epochs with 75% overlap. Power spectra were computed via fast Fourier transform (FFT) with a Hanning taper, yielding a frequency resolution of 0.001 Hz. For each participant, we extracted the dominant normogastric frequency, corresponding to maximal power within the 0.033–0.066 Hz range (≈2–4 cpm) in line with Monti et al. (2022). In order to determine power spectral density (as in Schulz et al. 2023), EGG band specific power was calculated as the percentage of power in the respective frequency band relative to bradygastria (1.0–2.5 cpm), normogastria (2.6–3.7 cpm), tachygastria (3.8–10.0 cpm), and the duodenal power band (10.1–15.0 cpm).

To test the group differences in peak normogastric frequency of EGG, we ran independent samples Student's *t*-tests between patients with DGBI and healthy controls, since data were normally distributed. Shapiro Wilk tests show deviations from normal distribution in bradygastria ($W = 0.885$; $p < 0.001$), tachygastria ($W = 0.956$; $p = 0.029$), and duodenal ($W = 0.851$; $p < 0.001$), while tests revealed normal distribution for normogastria ($W = 0.966$, $p = 0.09$). We ran independent Mann Whitney *t*-tests

for bradygastria, tachygastria, and duodenal power band, while Student's *t*-test was performed for normogastria.

2.6.5 | Exploratory Analyzes

To explore associations between physiological and self-report measures within the patients with DGBI's group, we conducted Pearson correlation analyzes using an R Studio correlation package (v0.6.0; Makowski et al. 2020). Specifically, we examined the relationship between peak gastric contraction frequency, derived from the electrogastrogram (EGG), and the Somatic Symptom Disorder (SSD-12, Toussaint et al. 2017) questionnaire. Additionally, we tested the association between gastric interoceptive accuracy and interoceptive beliefs measured through the Multidimensional Assessment of Interoceptive Awareness (MAIA-II; Mehling et al. 2018).

3 | Results

3.1 | Interoceptive Measures

Four independent *t*-tests were carried out to explore the differences in cardiac and gastric interoceptive measures between patients with Disorders of Gut-Brain Interaction and healthy controls. Shapiro–Wilk tests indicated significant deviations from normality for satiety scores ($W = 0.957$, $p = 0.033$), fullness scores ($W = 0.925$, $p = 0.001$), total volume of ingested water ($W = 0.959$, $p = 0.04$), and gastric interoception scores ($W = 0.918$, $p < 0.001$). In contrast, cardiac interoceptive accuracy scores did not significantly deviate from a normal distribution ($W = 0.962$, $p = 0.060$). Accordingly, Mann–Whitney *U* tests were applied to non-normally distributed variables, while the normally distributed variable was analyzed using an independent samples Student's *t*-test. No significant difference emerged between the two groups in cardiac interoceptive accuracy measured through the Heartbeat Counting Task (Schandry 1981) ($t(58) = -0.134$; $p = 0.893$) and in the total volume of ingested water ($U = 403$, $p = 0.492$). In contrast, a significant difference was observed in gastric interoception, assessed via the Two-step Water Load Test (Van Dyck et al. 2016) ($U = 200$; $p < 0.001$) (Figure 2c), indicating that healthy participants exhibited higher scores than patients with DGBI. Additionally, healthy controls reported significantly higher satiety scores than patients with DGBI ($U = 305$; $p = 0.033$) (Figure 2a), suggesting that the latter required significantly less water to reach the sensation of satiety. Finally, patients with DGBI consumed significantly more water than healthy controls to reach the sensation of maximum gastric fullness ($U = 312$; $p = 0.042$) (Figure 2b).

3.2 | Self-Reports in the WLT-II

A significant main effect of water-load phase (i.e., baseline vs. satiety vs. fullness) on satiation ratings was observed (F [2,174] = 62.3571; $p < 0.001$; $\eta^2 = 0.417$). Post hoc comparisons revealed significant increases in satiation from baseline to satiety ($t = -8.56$; $p < 0.001$) and from baseline to fullness ($t = -10.49$; $p < 0.001$), but not from satiety to fullness ($t = -1.93$; $p = 0.134$). Similarly, a significant effect of phase was found for fullness ratings (F [2,174] = 157.194; $p < 0.001$; $\eta^2 = 0.642$), with significant increases from baseline to satiety ($t = -12.25$; $p < 0.001$), satiety to fullness ($t = -4.97$; $p < 0.001$), and baseline to fullness ($t = -17.23$; $p < 0.001$). No significant group differences emerged for average satiation or fullness ratings.

A significant main effect of water-load phase was also found for negative affect ratings (F [2, 174] = 11.74; $p < 0.001$; $\eta^2 = 0.106$). Post hoc comparisons showed significant increases in negative affect from baseline to fullness ($t = -4.83$; $p < 0.001$) and from satiety to fullness ($t = -2.79$; $p = 0.016$), but not from baseline to satiety ($t = -2.04$; $p = 0.107$). Additionally, a significant main effect of group was found for negative affect (F [1, 174] = 22.944; $p < 0.001$; $\eta^2 = 0.103$), with patients reporting significantly higher negative affect than healthy controls across all phases ($t = -4.79$; $p < 0.001$). No significant interaction was found between group and water load phase for negative affect (F [1, 174] = 0.707; $p = 0.495$; $\eta^2 = 0.006$).

3.3 | Interoceptive Beliefs and Other Self-Report Questionnaires

To test differences in interoceptive beliefs between the two samples, we conducted a series of *t*-tests, one for each MAIA-II

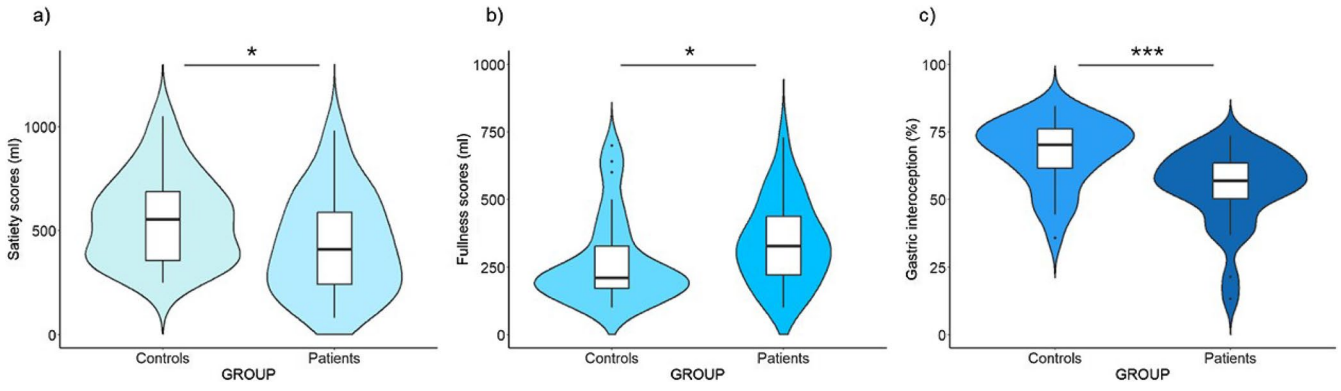

FIGURE 2 | Gastric interoceptive measure. *T*-test to explore differences in (a) satiety scores during the Two-step Waterload Test between patients with DGBIs and healthy controls; (b) fullness scores during the Two-steps Waterload Test between patients with DGBIs and healthy controls; (c) gastric interoception measured via the Two-step Waterload Test between patients with DGBIs and healthy controls. Higher scores indicate greater ml of water needed to achieve satiety (a) and fullness (b) and greater ability to detect gastric interoceptive signals (c). Statistical significance: $^*p \leq 0.05$; $^{***}p \leq 0.001$.

subscale: after FDR correction, none of these revealed a statistically significant difference between the two groups (all p's > 0.05), indicating no across-group differences in interoceptive beliefs. Additionally, no difference emerged between patients and healthy controls in Body Perception Questionnaire scores (all p's > 0.05). Internal consistency of MAIA-II in the present sample was satisfactory for each subscale (Cronbach α range: 0.72–0.836) and also for BPQ (Cronbach α: 0.954).

Shapiro–Wilk tests revealed deviation from the normal distribution in the visceral sensitivity index scores (W = 0.953, $p = 0.021$), Somatic Symptom Disorder (SSD-12) affective (W = 0.949, $p = 0.015$), and behavioral (W = 0.956, $p = 0.029$) subscales, whereas the SSD-12 affective subscale (W = 0.987, $p = 0.781$) and total score (W = 0.985, $p = 0.659$) were normally distributed. Group comparisons on the Visceral Sensitivity Index revealed that patients reported significantly greater concern regarding their visceral sensations compared to healthy controls ($U = 107$; $p < 0.001$) (Figure 3a). Furthermore, analyzes of the Somatic Symptom Disorder (SSD-12) subscales indicated that patients exhibited significantly stronger negative emotional responses to their symptoms ($U = 226$; $p < 0.001$) (Figure 3c), higher dysfunctional thoughts about their bodily symptoms ($t[58] = -5.09$; $p < 0.001$) (Figure 3d), and more maladaptive behavior in response to symptom perception ($U = 127$; $p < 0.001$) (Figure 3e). Overall, patients scored significantly higher on the SSD-12 total score, reflecting elevated levels of health-related anxiety, catastrophizing, emotional distress, and dysfunctional behaviors associated with somatic symptoms ($t[58] = -5.61$; $p < 0.001$) (Figure 3b). Internal consistency was good also for SSD-12 with subscales (Cronbach α range: 0.7–0.922) and VSI (Cronbach α: 0.942).

3.4 | Electrogastrogram

The independent sample t-test showed no difference between patients and controls in EGG peak frequency ($t = 0.544$; $p = 0.58$). Considering frequency band percentage power, no differences emerged between patients with DGBI and controls in bradygastria ($U = 320$; $p = 0.055$), normogastria ($t = 0.236$; $p = 0.814$), tachygastria ($U = 425$; $p = 0.712$), and duodenal band power ($U = 431$; $p = 0.779$).

3.5 | Exploratory Analyzes

In DGBI patients, peak frequency in the electrogastrogram was positively correlated with the affective subscale of the somatic symptom disorder (SSD-12) questionnaire (R [27] = 0.496; $p_{fdr} = 0.024$) (Figure 4a), suggesting an association between gastric contraction frequency and patients' negative emotional responses to their symptoms. All correlations with other SSD-12 subscales did not reach the statistical threshold.

Additionally, patients' gastric interoception measured through WLT-II was positively correlated with the "Trusting" subscale of the Multidimensional Assessment of Interoceptive Awareness questionnaire (MAIA-II) (R [28] = 0.423; $p_{fdr} = 0.020$) (Figure 4b), indicating that greater accuracy in detecting gastric sensations was associated with a higher

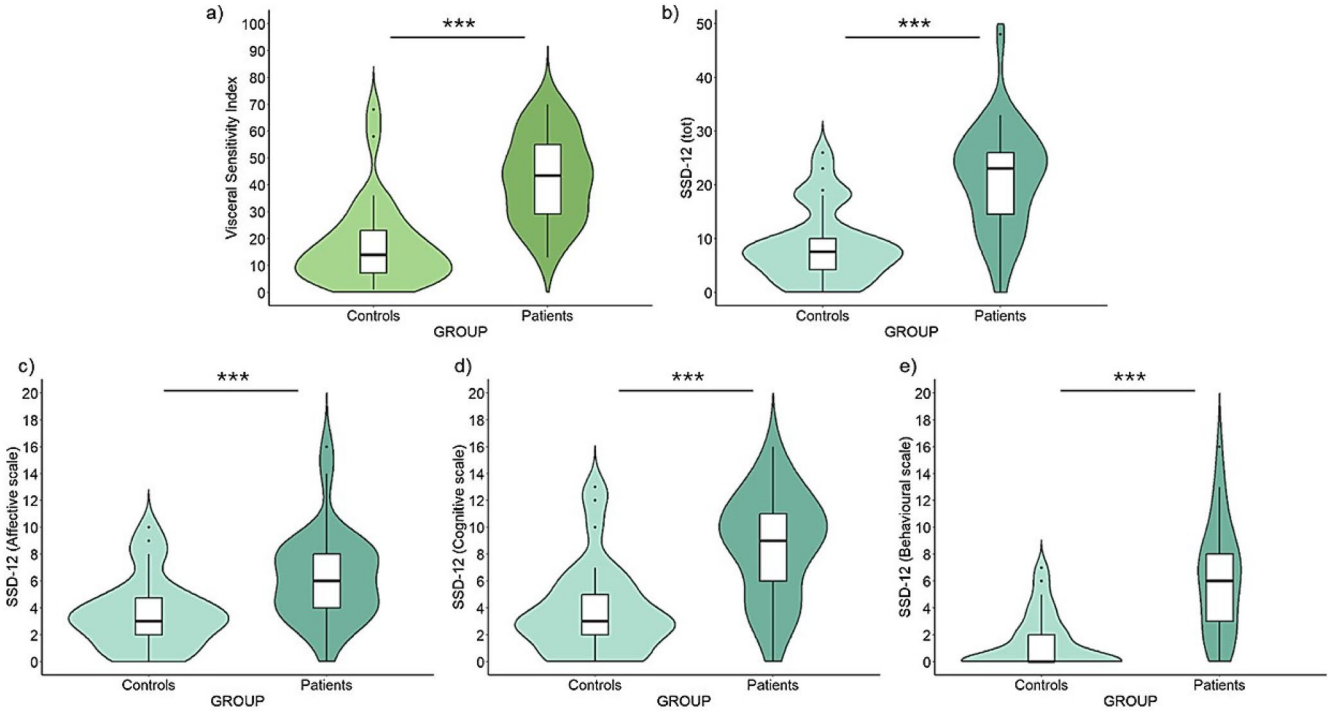

FIGURE 3 | Significant differences in self-report questionnaires between patients with DGBI and healthy controls. T-test to explore differences in the (a) Visceral sensitivity index scores; (b) Somatic Symptoms Disorder total score; (c) Somatic Symptoms Disorder affective subscale; (d) Somatic Symptoms Disorder cognitive subscale; (e) Somatic Symptoms Disorder behavioral subscale. Higher scores indicate greater concern regarding visceral sensations (a), higher levels of health-related anxiety, catastrophizing, emotional distress, and dysfunctional behaviors (b), stronger negative emotional responses to our own symptoms (c), higher dysfunctional thoughts about our own bodily symptoms (d), and more maladaptive behaviors in response to symptom perception (e). Significance: ***$p \leq 0.001$.

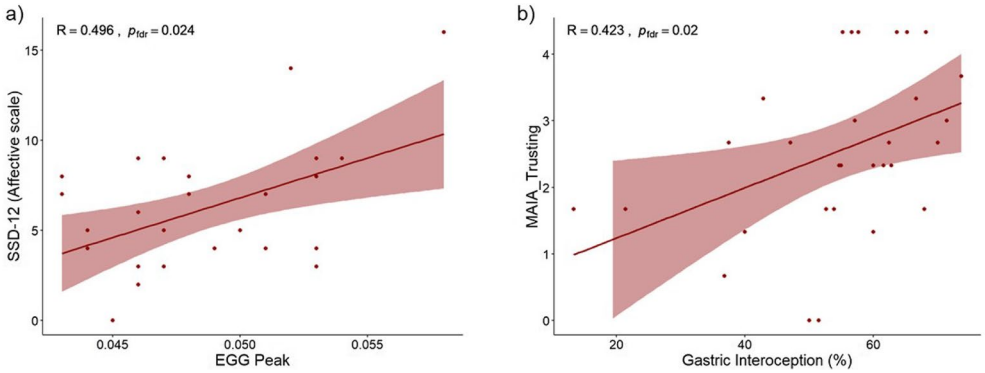

FIGURE 4 | (a) Correlation between EGG peak and SSD-12 Affective subscale: the higher the participants' gastric contraction frequency, the higher the patients' negative emotional responses to their symptoms. (b) Correlation between patients' gastric interoceptive measure and the "Trusting" subscale of the Multidimensional Assessment of Interoceptive Awareness questionnaire: the higher the patients' scores in the Waterload Test (indicating higher ability to perceive gastric signals), the higher the patients' degree of trust in visceral sensations. All *p*-values were FDR corrected.

degree of trust in visceral sensations. All correlations with other MAIA-II subscales did not reach the statistical threshold. In the HC group, none of the correlations reached statistical significance.

4 | Discussion

The present study explored interoceptive processing in individuals with Disorders of Gut-Brain Interaction, focusing on gastric interoception using the Water Load Test II (WLT-II, Van Dyck et al. 2016), and cardiac interoception, measured via the Heartbeat counting task (Schandry 1981). Over the years, several water load versions have been developed for clinical trials in patients with upper gastrointestinal symptoms and DGBIs (Chen et al. 2006; Jones et al. 2003), but to date, the most widely used (Desmedt et al. 2023) is the one developed by van Dyck et al. (2016). This task has been used both for patients with gastrointestinal and eating disorders (Schulz et al. 2023; van Dyck et al. 2021) and for healthy subjects under transcutaneous auricular vagus nerve stimulation (taVNS) (Salaris and Azevedo 2025). Our results show that patients with DGBIs exhibit altered gastric sensitivity compared to matched healthy controls, whereas cardiac interoception appears preserved. These findings fit into a broader debate in the literature discussing whether interoceptive abilities align across different body modalities or remain organ-specific (see Desmedt et al. 2023; Ferentzi et al. 2018; Gajdos et al. 2020; Schulz et al. 2023 for results supporting the organ-specific perspective, and Füstös et al. 2013; Garfinkel et al. 2017; Herbert et al. 2012; Whitehead and Drescher 1980 supporting the generalized interoceptive ability perspective). Specifically, the selective impairment in gastric but not cardiac interoception highlights the need for modality-specific interoceptive assessment in clinical populations, rather than assuming interoceptive deficits generalize across domains (Bonaz et al. 2021; Garfinkel et al. 2015).

Concerning drinking behavior during the water load test, patients with DGBI were found to drink significantly less water than controls to achieve the feeling of satiety, whereas they drank more water than controls to achieve the feeling of fullness. These results are in contrast with Schulz et al. (2023), who did not find any difference in the drinking behavior between patients with IBS and healthy controls (Schulz et al. 2023). This difference might be due to the fact that our sample included a broader range of patients with DGBIs (i.e., IBS and FD), while Schulz et al. (2023) focused specifically on patients with IBS. Indeed, patients with FD often exhibit early satiety and gastric hypersensitivity, which may explain why they drink less water to feel satiated and more to feel full, reflecting a dysregulated perception of gastric signals (Van Oudenhove et al. 2004). In addition, these results can also be explained by the dysfunction in gastric accommodation detectable in these patients (Talley 2017). Lastly, a possible interpretation for the gastric interoceptive measure in these patients could be linked to the roles of affective factors. Indeed, taking into consideration results about the negative affect on WLT questionnaires, anxiety underlying early satiety (i.e., fear of bloating) could have influenced the results, as it has been demonstrated how this affective symptom is related to gastric symptomatology (Pohl et al. 2018; Khalsa et al. 2018; Mazaheri et al. 2016). Future studies on the topic need a more accurate and objective way to measure gastric interoception.

The self-report data from the WLT-II questionnaire provide additional insight into the subjective experience of gastric interoception and affective responses during the task. As expected, there were significant main effects of water-load phase on both satiation and fullness ratings, with substantial increases observed from baseline to satiety and from baseline to fullness. These findings confirm the WLT-II as a physiologically and subjectively sensitive paradigm, capable of inducing graded interoceptive sensations related to gastric distension (Van Dyck et al. 2016).

Interestingly, while participants reported significantly increased satiation from baseline to satiety phase and from baseline to fullness phase, no significant increase in satiation was found from the satiety to fullness phase. This pattern may reflect a perceptual threshold: above a certain level, the perception of satiation may reduce its degree of correlation with gastric distension and possibly become more variable across individuals. In contrast, fullness ratings increased significantly across all phases, suggesting that participants consistently perceived

and differentiated the increasing intensity of gastric distension. These results indicate that fullness may be a more finely tuned or linear interoceptive signal compared to satiation, which could involve a more categorical or homeostatically anchored judgment (Berthoud 2011).

Furthermore, no group differences were found in either satiation or fullness ratings, suggesting that both patients with DGBIs and healthy controls experienced similar subjective gastric beliefs during the task. This is in contrast with the differences in gastric interoceptive measures and may indicate a dissociation between perceived intensity and interoceptive accuracy (Suksasilp and Garfinkel 2022). In other words, while patients with DGBIs may report their gastric sensations similarly to controls, their ability to accurately discriminate or interpret these signals remains impaired.

Additionally, results showed that negative affect increased significantly during the WLT-II phases (from baseline to fullness and from satiety to fullness, but not from baseline to satiety). This suggests that the escalation in gastric distension was associated with increased emotional discomfort only at the higher end of the sensation spectrum.

Finally, results showed that patients with DGBIs reported higher negative affect ratings compared to healthy controls. This aligns with previous literature showing elevated affective distress and somatosensory amplification in DGBI populations (Drossman 2016). Taken together, these findings support the idea that affective dysregulation and negative appraisal of interoceptive signals are key components of DGBI symptomatology (Khalsa et al. 2018; Mazaheri et al. 2016).

Focusing on interoceptive beliefs, namely the subjective tendency to focus on one's internal body signals, no significant difference emerged between patients with DGBIs and healthy controls in the MAIA-II and BPQ questionnaire scores. This supports the notion that individuals with DGBIs may not consciously perceive their altered visceral signaling or may have difficulties integrating bodily cues into conscious awareness (Karaivazoglou et al. 2024). In addition, the lack of differences between patients and controls in interoceptive beliefs may reflect the fact that MAIA-II does not distinguish between bodily systems. Since patients with DGBIs are likely to be more attuned to gastric signals, a GI-specific assessment may be better suited to detect differences in this population. The present study extends previous literature demonstrating that interoceptive deficits detected through interoceptive tasks (i.e., WLT-II) are not necessarily reflected in self-report assessments of interoceptive beliefs or attention (e.g., MAIA-II, BPQ). This dissociation may reflect a discrepancy between objective interoceptive performance and interoceptive beliefs, consistent with recent results on patients with chronic pain conditions (Cantoni et al. 2025; Horsburgh et al. 2024) and theoretical frameworks that distinguish interoceptive accuracy, awareness, and beliefs (Garfinkel et al. 2015; Suksasilp and Garfinkel 2022). This finding contrasts with the results of Fournier et al. (2020), who reported that patients with IBS experienced lower interoceptive beliefs compared to healthy controls. However, their assessment of interoceptive beliefs relied on the Difficulties in Interoceptive Abilities (DIA) subscale of the TAS-20, rather than the MAIA-II used in the current study. Moreover, our results also differ somewhat from those of Gajdos et al. (2020), who found that individuals reporting high levels of functional gastrointestinal symptoms had lower trust in their internal bodily signals compared to those with fewer symptoms. It is important to highlight that our sample consisted of patients with a formal diagnosis of DGBI, whereas Gajdos et al.'s (2020) was composed of healthy subjects reporting gastrointestinal symptoms.

Despite the potential psychophysiological relevance of gastric signals, the present study did not show significant electrogastrography (EGG) differences between patients with DGBIs and healthy controls, a result consistent with recent findings (Schulz et al. 2023). This absence of group differences may be attributable to the specific electrogastrography (EGG) montage employed (Yin and Chen 2013). Future research is encouraged to investigate gastric psychophysiological differences using more refined montages and different electrogastrographic markers, such as the updated methodology proposed by Wolpert et al. (2020). An additional limitation concerns the absence of a post-WLT EGG recording. While our focus was on baseline gastric myoelectrical activity to capture tonic rhythms, including post-WLT recordings—employed in previous studies on eating disorders (Kerr et al. 2022; van Dyck et al. 2021)—would have allowed us to also examine meal-related changes, which are highly relevant in IBS and functional dyspepsia. Future studies should therefore combine baseline and post-ingestive EGG measures to provide a more comprehensive characterization of gastric physiology in DGBIs.

Moreover, patients suffering from DGBIs reported higher levels of visceral sensitivity and greater symptom-related emotional distress, maladaptive cognitions, and maladaptive behavior, as measured by the Somatic Symptom Disorder-12 (SSD-12), than healthy controls. These results replicate and expand upon prior research emphasizing the interplay between affective dysregulation and symptom amplification in DGBIs (Drossman 2016; Ma et al. 2025; Mazaheri et al. 2016). Furthermore, our exploratory correlation analyzes revealed that, exclusively in the patients' group, a higher gastric interoceptive measure was associated with greater trust in visceral sensations, whereas increased gastric myoelectrical activity (i.e., EGG peak frequency) was linked to more intense affective responses to bodily symptoms. No such associations were observed in the healthy control group, highlighting a potential clinical specificity of the psychophysiological connection between visceral signal detection and emotional reactivity, aligning with models of affective interoception and embodied cognition (Craig 2002; Quadt et al. 2018; Stephan et al. 2016). In addition to this, a recent study by Porciello et al. (2024) revealed that, in a healthy sample, the acidity level of the stomach, assessed using an ingestible pill to record gastrointestinal physiology, correlates with basic feelings of disgust and fear, confirming the association between gastrointestinal physiology and affective states (Porciello et al. 2024). Moreover, using the same technology, Monti et al. (2022) found that physiological signals from the stomach change with different facets of bodily self-consciousness measured throughout a virtual reality embodiment paradigm—the so-called "Embreathment Illusion" (Cantoni et al. 2024; Monti et al. 2020, 2022)—in a non-clinical sample. Together with these findings, our results further confirm the relationship between emotions, bodily awareness, and gastric physiology.

Despite the significance of these findings, it is important to acknowledge limitations in the procedures we adopted. First, we did not collect data for Body Mass Index (BMI), preventing us from making sure that BMI was similar for the two groups. Also, this study included the use of the Heartbeat Counting Task (HBCT) alone to assess cardiac interoceptive accuracy. Although this tool remains one of the most widely employed methods within the cardiac interoception literature, it is recognized that performance on the HBCT may be influenced by a range of individual physiological and psychological variables, including personal beliefs (Zamariola et al. 2018), resting heart rate and heart rate variability (Knapp-Kline and Kline 2005), body fat percentage (Rouse et al. 1988), and systolic blood pressure (O'Brien et al. 1998). Thus, to better understand the specific contribution of cardiac interoception, future studies should include complementary tasks, such as the Heartbeat Discrimination Task (Brener and Kluvitse 1988), that can help disentangle perceptual accuracy from potential confounds. Additionally, the use of the WLT-II to assess gastric interoceptive measures represents a limitation of the current study. This task depends on subjective reports of fullness, which can be shaped by individual cognitive biases, emotional states, and previous experiences (Ahlich et al. 2023). This introduces a risk of misinterpreting patients' responses, as exaggerated or diminished sensations might reflect cognitive factors related to their functional disorder rather than genuine interoceptive ability. Another concern is the task's limited ecological validity, as it measures satiety using water instead of typical solid foods, reducing its applicability to everyday eating contexts. Moreover, variability in how individuals interpret the concept of "maximum fullness" further complicates the reliability of this measure (Van Dyck et al. 2016). Finally, it is worth noting that WLT-II, differently from HCT and resting heart rate, does not involve an objective physiological measure; thus, it is difficult to define it as a method to assess interoceptive accuracy, as it does not include an objective measure of actual stomach volume. Indeed, in recent years, more advanced methods for examining the physiology of the stomach and the perception of gastric sensations have been developed. For instance, the glucose test involves participants reporting their feelings of satiety while their blood glucose levels are continuously tracked (Young et al. 2021). Another approach, the gastrointestinal mechanosensory stimulation task, requires participants to swallow a vibrating capsule and press a button each time they perceive the vibrations in their stomach (Smith et al. 2021). However, while these tasks and new tools offer promising insights, practical challenges such as the invasiveness of the procedure, cost, and required testing environments pose significant barriers to their widespread implementation (Desmedt et al. 2023). Lastly, although we made sure to recruit only patients and control subjects who were not diagnosed with neurological or psychiatric disorders, we did not screen participants with specific tests. Thus, we cannot rule out the possibility that patients/controls suffered from subclinical psychiatric symptoms. We acknowledge this as a limitation of the study.

Besides making a pioneering contribution to a largely unexplored research field, this project aimed to pave the way for future gastrointestinal rehabilitation therapies. Indeed, these findings may have implications for interventions aimed at recalibrating interoceptive processes in patients with DGBIs by establishing interoception training protocols (Sugawara et al. 2020). Another tool used for improving interoceptive accuracy and functional gastric symptomatology is taVNS. Firstly, it has been demonstrated that taVNS enhances cardiac interoceptive accuracy in healthy subjects (Villani et al. 2019). Secondly, it has been shown that taVNS improved gastric pain and general quality of life in patients with IBS (Shi et al. 2021). Thirdly, it also diminishes dyspeptic symptoms in patients with FD (Zhu et al. 2021). Taken together, these findings confirm the promising role of taVNS as a complementary tool for the non-invasive treatment of DGBIs (Veldman et al. 2025).

Future research should focus on refining additive protocols to the pharmacological ones for DGBI, evaluating their long-term efficacy, and identifying predictors of treatment efficacy. Ultimately, this work adds to the recent literature by laying the foundations for a new generation of neuro-gastroenterological interventions based on interoception.

Author Contributions

A. Salaris: conceptualization, investigation, writing – original draft, methodology, visualization, formal analysis, data curation, project administration. **C. Cantoni:** conceptualization, investigation, writing – review and editing, methodology, visualization, formal analysis, data curation. **S. Ciccarone:** conceptualization, investigation, visualization, writing – review and editing, formal analysis, data curation. **C. Mocci:** investigation, data curation, resources, writing – review and editing. **V. Cardinale:** investigation, writing – review and editing, resources, conceptualization. **C. Severi:** conceptualization, methodology, investigation, visualization, writing – review and editing. **A. Monti:** conceptualization, methodology, software, visualization, writing – review and editing. **D. Alvaro:** resources, conceptualization, writing – review and editing. **S. M. Aglioti:** conceptualization, funding acquisition, writing – review and editing, methodology, visualization, project administration, supervision, resources, data curation, software.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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