frontiers in Signal Processing

TYPE Original Research
PUBLISHED 07 April 2026
DOI 10.3389/frsip.2026.1776807

OPEN ACCESS

EDITED BY
Giuseppe Varone,
Harvard Medical School, United States

REVIEWED BY
Mina Kheirkhah,
University Hospital Jena, Germany
Negar Namdar,
New Jersey Institute of Technology,
United States

*CORRESPONDENCE
Maria Volodina,
mariavolodina@yandex.ru

RECEIVED 28 December 2025
REVISED 24 February 2026
ACCEPTED 09 March 2026
PUBLISHED 07 April 2026

CITATION
Makarova M, Fedosov N, Mikhailova I, Nikolaeva M, Ossadtchi A, Tumyalis A and Volodina M (2026) Self-face viewing attenuates cardiac modulation of corticospinal excitability.
Front. Signal Process. 6:1776807.
doi: 10.3389/frsip.2026.1776807

Self-face viewing attenuates cardiac modulation of corticospinal excitability

Milana Makarova[1,2], Nikita Fedosov[1], Irina Mikhailova[1], Maria Nikolaeva[1], Alexei Ossadtchi[1,3], Alexey Tumyalis[1,2] and Maria Volodina[1,4]*

[1]Centre for Bioelectric Interfaces, HSE University, Moscow, Russia, [2]Federal Center of Brain Research and Neurotechnologies of FMBA of Russia, Moscow, Russia, [3]LLC "Life Improvement by Future Technologies Center", Moscow, Russia, [4]Department of Medical Neurotechnologies, Institute of Neuroscience and Neurotechnologies, Federal State Autonomous Educational Institution of Higher Education «N.I. Pirogov Russian National Research Medical University» Ministry of Health, Moscow, Russia

Introduction: While self-referential attention is thought to enhance interoceptive sensitivity, its effect on cardiac modulation of corticospinal excitability remains unexplored. This pilot study investigated how viewing one's own face (self-face processing) modulates the cardiac-phase coupling of motor output and whether this heart-brain coupling depends on interoceptive accuracy (heartbeat perception).
Methods: In 15 healthy adults, motor-evoked potentials (MEPs) were elicited via transcranial magnetic stimulation (TMS) at three fixed time points following the R-peak (0, 250, and 500 m) during presentation of either self-face or other-face pictures. A Modulation Index was derived from log-transformed MEPs to quantify cardiac-phase modulation strength. Interoceptive accuracy was assessed via a heartbeat-counting task.
Results: Contrary to the hypothesis that self- face viewing would enhance cardiac–motor coupling through inward attentional focus, self-face processing significantly reduced the overall magnitude of cardiac-phase modulation. This attenuation was most pronounced at 0 m and 250 m post-R-peak, corresponding to systolic phase. Across conditions, higher interoceptive accuracy predicted stronger modulation, though this relationship showed a tendency toward attenuation during self-face viewing (interaction $p = 0.059$).
Discussion: The results of this pilot TMS study suggest that, in a task requiring explicit evaluation of facial stimuli, self-face viewing acts as a potent exteroceptive stimulus that diverts attention away from interoceptive signals, thereby weakening the cardiac-cycle influence on motor excitability. These findings highlight the context-dependency of self-processing effects and suggest a possible link between HCT-based interoceptive accuracy and heart-brain- body coupling.

KEYWORDS
cardiac modulation of corticospinal excitability, heart-brain coupling, interoceptive accuracy, motor-evoked potentials (MEPs), self-face processing, transcranial magnetic stimulation

1 Introduction

The sense of self is a core aspect of human experience. A growing body of research suggests it is deeply rooted in the signals coming from inside our bodies. Modern theories propose that interoception (the perception of internal bodily states) is fundamental for self-awareness, emotion, and the feeling of inhabiting one's own body (Craig, 2002; Seth, 2013; Tsakiris, 2017; Seth and Tsakiris, 2018; Park and Blanke, 2019a). According to these views, the brain constantly creates a model of the self by predicting bodily states and comparing these predictions with actual sensory feedback from within (Barrett and Simmons, 2015). Among these internal signals, the rhythmic activity of the cardiovascular system is one of the most persistent and basic, providing a temporal framework that influences brain function and cognition (Garfinkel and Critchley, 2016; Park and Blanke, 2019b; Al et al., 2020).

Strong evidence shows that the cardiac cycle does more than just pump blood; it actively shapes how the brain processes information. With each heartbeat, baroreceptors send signals to the brain changing cortical activity. This rhythm affects the perception of touch and pain (Edwards et al., 2009), emotional responses (Gray et al., 2012; Garfinkel and Critchley, 2016; Legrand et al., 2021), and the baseline cortical excitability (Potts and Li, 1998; Pramme et al., 2014; Rae et al., 2018; Al et al., 2021).

Cardiac phase differentially modulates excitability in sensory versus motor cortical areas: while excitability in the somatosensory cortex appears to be suppressed during systole compared to diastole (Edwards et al., 2009; Wilkinson et al., 2013; Al et al., 2020), motor cortex excitability tends to be heightened during the systolic phase (Konttinen et al., 2003; Galvez-Pol et al., 2020).

An important factor that can change how we process bodily signals is our focus of attention. Shifting attention towards self-relevant information (self-focused attention) activates brain regions involved in self-awareness and interoception, such as the medial prefrontal cortex and the anterior insula (Northoff et al., 2006; Qin and Northoff, 2011). Viewing one's own face is a powerful way to induce this state (Devue and Brédart, 2011). This internal focus is thought to make us more aware of bodily sensations, potentially amplifying the brain's response to interoceptive signals like the heartbeat (Ainley et al., 2013; Farb et al., 2013). Importantly, the motor cortex is not just an output system for movement; it is increasingly recognized as part of a broader network involved in bodily self-awareness and agency - the sense of being the initiator of one's actions. Activity in motor and premotor areas is linked to the subjective experience of body ownership (Gentile et al., 2015) and self-other distinction (Jeannerod, 2003; Legrand, 2006; Galvez-Pol et al., 2020).

However, a key question remains unanswered: can this psychological state of self-focus change the basic physiological dialogue between the heart and the motor cortex? One plausible mechanism is that self-focused attention enhances the precision weighting (or salience) of interoceptive signals within the brain's predictive models (Seth, 2013; Barrett and Simmons, 2015). This increased precision could lead to a stronger top-down amplification of cardiac-afferent signals, making the rhythmic modulation of downstream cortical areas, like the motor cortex, more pronounced.

To address this, we designed an experiment combining single-pulse TMS with electrocardiogram (ECG) gating to probe corticospinal excitability at three precise, time-locked phases of the cardiac cycle (0, 250, and 500 m post-R-wave). Concurrently, we sought to manipulate attentional focus by presenting participants with either a picture of themselves or one of a gender-matched stranger. We measured MEP amplitude from the right first dorsal interosseous (FDI) muscle as our primary index of corticospinal excitability.

We hypothesized that the magnitude of cardiac-phase modulation of MEPs - the fluctuation in excitability across systole and diastole - would be significantly greater when participants viewed their own face compared to when they viewed another's face. We further predicted that this effect of self-focused attention would be more pronounced in individuals with higher interoceptive accuracy, as assessed by a heartbeat perception task.

2 Materials and methods

2.1 Participants

Twenty-two healthy male volunteers were initially recruited for the study. All participants were right-handed according to self-report. For two subjects, the session was not completed due to adverse effects. Due to technical issues, five participants were excluded, resulting in a final sample of fifteen participants for analysis (age 18–31 years old, mean = 22.33, SD = 3.87).

To ensure safety and protocol consistency, we did not include individuals with: a history of neurological or psychiatric disorders, any regular medication intake, and any contraindications for transcranial magnetic stimulation (TMS) or magnetic resonance imaging (MRI) procedures (e.g., history of seizures, epilepsy, stroke, severe head injury, fainting, metal in the head, implanted devices, frequent headaches, or possible pregnancy to prevent potential health risks) (Rossi et al., 2021).

Participants were instructed to refrain from caffeine consumption for at least 4 h prior to the experiment, as well as from sleep deprivation and strenuous physical activity for at least 24 h beforehand. Nine participants were entirely TMS-naïve.

After the stimulation was completed, to assess the unintended sensations and adverse effects, the subjects were asked to answer questions from the TMSense_Q questionnaire (Section IV-Stimulation related sensations) (Giustiniani et al., 2022) (see Supplementary Material S1). The questions were adapted for the Russian-speaking sample.

The study was approved by the HSE University Committee for Interuniversity Surveys and Ethical Assessment of Empirical Research (Protocol No. 80, dated 07.02.2022). All participants provided written informed consent after being fully informed about the nature and purpose of the study.

2.2 Stimuli

A total of 70 pictures were used as stimuli. Thirty-five images depicting a neutral facial expression were selected from the Karolinska Directed Emotional Faces (KDEF) database (publicly available at: https://www.kaggle.com/datasets/tom99763/testtt). The remaining 35 pictures were taken of the participants by the researchers prior to the experiment.

For the participant photos, individuals were seated against a neutral white background. Images were captured from a distance of 50 cm under controlled laboratory lighting conditions using a standard smartphone digital camera. Participants were instructed to maintain a neutral facial expression and to look directly at the camera (frontal pose). Each photographic session yielded 35 images, all capturing the participant's neutral state with slight variations in head tilt.

All images, both from the KDEF database and those of the participants, underwent identical post-processing. The background was digitally removed, and the images were cropped to a uniform size of 562 × 762 pixels. To ensure visual consistency, the color balance and luminance of the KDEF images were digitally adjusted to match the lighting conditions of the laboratory-acquired participant photographs.

2.3 Overall experimental procedure

At the beginning of the experiment, each participant completed an informed consent form, after which his pictures were taken. While the pictures were being processed and uploaded to the presentation computer, the setup phase was conducted. This included the placement of ECG and EMG electrodes, participant registration within the neuronavigation system, and other necessary preparatory steps.

Subsequently, the experiment was initiated on the presentation computer using PsychoPy 3 version 2022.2.4. Following introductory instructions, participants were required to complete an interoceptive assessment test. Three training trials were provided, after which the experimental trials commenced.

Then, the main part of the experiment, involving ECG-triggered TMS stimulation, began. At the start of each trial, a white fixation cross was presented in the center of a gray screen. The duration of this presentation was randomly selected from a range of values 2.0, 2.2, 2.4, 2.6, 2.8, 3.0 s. Next, a picture displaying either the participant's own face or the face of another person was presented; these stimuli were presented in a randomized order. The picture remained on screen until the TMS pulse was delivered.

To maintain attentional focus, following the presentation of each picture, a question regarding a personality trait of the person in the picture was displayed (e.g., "Rate how sociable the person in the photograph is"). These trait descriptors were generated in advance and presented in random order. Participants were required to provide a rating on a Likert scale from 0 to 5. The personality-rating task was included primarily to maintain participants' attention on the photographs throughout the experimental session; no priori hypotheses were formulated regarding a relationship between self-evaluation ratings and the physiological effects of interest. Nonetheless, the rating data were analyzed and the results are reported in Supplementary Material S2.

Once the participant provided their rating, an inter-trial interval ensued, randomly selected from the same range of durations 2.0, 2.2, 2.4, 2.6, 2.8, 3.0 s. This cycle was then repeated until all 210 stimuli had been delivered.

In total, 70 pictures were presented: 35 of the participant's own face and 35 of an unfamiliar one. This set of stimuli was presented under three different timing conditions relative to the R-peak of the cardiac cycle: at 0 m, 250 m, and 500 m following the R-peak, capturing early, mid-, and late phases of the cardiac cycle based on previous work on cardiac-phase modulation of corticospinal excitability (Otsuru et al., 2020).

2.4 Structural MRI for TMS navigation

In a separate session preceding the experimental procedure, individual anatomical T1-weighted magnetic resonance images were obtained for use in neuronavigated TMS (nTMS). The structural images were acquired on a 1.5 T MR scanner (Optima CT 660, GE Medical Systems) with a high-resolution protocol (1 mm isotropic voxel size).

2.5 ECG and EMG recordings

Electrophysiological signals were recorded using the NVX-52 amplifier (LLC "Medical Computer Systems", Russia, https://mks.ru) with a sampling frequency of 1,000 Hz.

To monitor heart rate and blood flow parameters, an electrocardiogram (ECG) and an impedance cardiogram (ICG) were recorded using surface Ag/AgCl electrodes (d = 26 mm, Medico). Electrodes were placed to form a standard V6 lead: the current and impedance electrodes were positioned on the ribs at the V6 level and on both sides of the neck, respectively.

Motor-evoked potentials (MEPs) from the right first dorsal interosseous (FDI) muscle were recorded using surface Ag/AgCl electrodes (0.6-cm^2, 3 M Red Dot) in a belly-tendon montage. The active electrode was placed over the muscle belly of the FDI, the reference electrode was positioned on the tendon of the index finger, and the ground electrode was secured on the ipsilateral wrist.

This configuration ensured reliable MEP detection while minimizing electrical noise. Data quality was controlled offline; trials were excluded from analysis if the pre-stimulus EMG activity (peak-to-peak amplitude during the 1-s window preceding the TMS pulse) exceeded 20 μV, which is considered the threshold for reliable separation of MEPs from background EMG noise (Machetanz et al., 2020; Memarian Sorkhabi et al., 2022).

2.6 TMS setup

Stimulation was delivered using a figure-eight C-B60 coil connected to a MagVenture R30 + M stimulator (MagVenture, Denmark) for biphasic pulse generation. MRI-guided neuronavigation system (Localite GmbH, Germany) was used for optimization, recording, and consistent targeting of the cortical stimulation site. The entire procedure was performed in accordance with established international safety guidelines (Rossi et al., 2021).

The procedure began with identifying the cortical representation and searching for the "hotspot" of the target muscle through "rough mapping" (Krieg et al., 2017; Nazarova et al., 2021). The coil was systematically moved over the contralateral primary motor cortex (M1) hand area while delivering single TMS pulses until a site was found that consistently elicited motor-evoked potentials (MEPs) of 500–800 μV in the first dorsal interosseous (FDI) muscle. Following hotspot localization, the resting motor threshold (RMT) for the FDI muscle was determined using the automated Stochastic Approximation Motor Threshold (SAMT) algorithm (v1.8.0, https://tms-samt.github.io/, Wang et al., 2023). The stimulation intensity for the main experiment was set to 110% of the individual's RMT.

During the experimental session, single-pulse cardiac-triggered TMS was delivered using the HarPULL system for real-time ECG-tracking (Makarova et al., 2025). TMS pulses were triggered at three fixed latencies following the R-peak of the cardiac cycle: 0 m, 250 m, and 500 m, ensuring synchronization with specific phases of cardiac activity.

To verify that the fixed post-R-peak delays corresponded to the intended cardiac phases, the angular phase of the cardiac cycle (0°–360°, where 0° = R-peak) was computed for each TMS pulse. Heart rate and R–R interval statistics were derived from these phase estimates.

2.7 Heartbeat perception test

Interoceptive accuracy (IAc) was assessed using a modified heartbeat counting task (Schandry, 1981). The task required participants to silently count their own heartbeats during six experimental intervals, without taking their pulse, crossing their arms or legs, or using any other physical strategies to facilitate heartbeat detection. The intervals were presented in a randomized order, with durations of 25, 30, 35, 40, 45, and 50 s. Participants were instructed to sit comfortably in a chair and not to cross their arms or legs or to use any other physical strategies (e.g., taking their pulse) to facilitate heartbeat detection. The task consisted of six trials. At the beginning of each trial, a brief auditory tone signaled the start of a counting period. At the end of the counting period, a second auditory tone signaled them to stop. Immediately afterward, a response field appeared on the screen, prompting participants to enter the number of heartbeats they had counted.

Throughout the entire task, an electrocardiogram (ECG) was recorded continuously. The actual number of heartbeats (R-peaks) during each counting period was extracted from the ECG for comparison with the participant's subjective count. Due to a technical issue at the start of the session, all participants severely underestimated their heartbeats during the first trial of the heartbeat counting task. Therefore, we calculated two separate interoceptive accuracy (IAc) scores for each participant: one based on all six trials and another based on the last five trials only, excluding the first (IAc_5trials). A standard IAc score was calculated for each trial using the following transformation formula to account for individual differences in heart rate:

IAc = 1/N (trials) × Σ[1 - |Recorded Heartbeats - Counted Heartbeats|/Recorded Heartbeats].

While these two scores were strongly correlated ($r = 0.98$, $p < 0.001$), we conservatively chose to use IAc_5trials as the primary measure for all subsequent analyses to ensure the integrity of the accuracy measure. This decision did not alter the pattern of the main results. Therefore, all further references to interoceptive accuracy (IAc) in this manuscript pertain to the score derived from the 5-trial block.

2.8 Data processing

2.8.1 Modulation index

All analyses were conducted using Python 3.10. Motor-evoked potential (MEP) amplitudes were first transformed with the base-10 logarithm to reduce positive skew and approximate a normal distribution. To quantify the magnitude of cardiac-phase modulation independent of its direction (i.e., facilitation or suppression), a Modulation Index (MI) was computed for each participant, experimental condition, and cardiac time point. For a given target cardiac delay (e.g., 0 m), the MI was defined as the absolute deviation of the log-transformed MEP at that delay from the average of the other two delays, normalized by the sum of all three log-MEP values. The formula for the delay of 0 m was.

$$MI_0 = \frac{\left|\log_{10}(MEP_0) - \frac{\log_{10}(\mathrm{MEP}_{250}) + \log_{10}(\mathrm{MEP}_{500})}{2}\right|}{\log_{10}(MEP_0) + \log_{10}(MEP_{250}) + \log_{10}(MEP_{500})}$$

Analogous indices were calculated for the 250 m and 500 m delays. For each experimental condition (Self-face, Other-face), the three delay-specific MI values were averaged to yield a single aggregate Modulation Index per participant per condition, representing the overall strength of cardiac-phase modulation. We chose MI as our primary outcome measure because it quantifies the magnitude of cardiac-phase modulation independently of its direction (facilitation vs. suppression). At the individual level, cardiac phase can lead to either increases or decreases in corticospinal excitability, and our main interest was in how strongly excitability is coupled to the cardiac cycle rather than in the sign of this effect.

2.8.2 Cardiac pre-ejection period (PEP) and stroke volume (SV) computation

PEP represents the time interval between the beginning of ventricular depolarization and the opening of the aortic valve, when left ventricular blood ejection occurs. PEP is a non-invasive marker of cardiac sympathetic nervous system activity; shorter PEP means stronger sympathetic drive (faster heart response), while longer PEP indicates reduced contractility or increased load. PEP is measured as the time interval between the Q-wave of the ECG and the B-point of the impedance cardiogram (Forouzanfar et al., 2018). For signal processing, a 4th-order Butterworth bandpass filter was applied: 1–40 Hz for ECG and 0.5–25 Hz for ICG. The signals were then segmented into epochs ranging from −1–5 s relative to the stimulus onset. Within each epoch, the time of the Q-peaks during the presentation of the stimulus was identified. Subsequently, periods from −0.1–0.4 s relative to the Q-peaks were extracted for both ECG and ICG signals.

In the present study, the NeuroKit package was used to determine the Q-peak time in the ECG. The timing of the B-point on the impedance cardiogram (ICG) was determined using the algorithm described by (Forouzanfar et al., 2018).

Stroke volume is the amount of blood the heart's left ventricle pumps out with each beat. It can be computed non-invasively by integrating the ICG waveform between the B- and X-points.

The interval corresponding to each stimulus presentation typically encompassed between one and three Q-peaks. The PEP and SV values derived from these cardiac cycles were then averaged per stimulus.

2.9 Statistics

2.9.1 Primary hypothesis testing: mixed-effects models

Our primary hypothesis was that directing attention to one's own versus another's face modulates cardiac-phase dependent auditory processing, and that this modulation is influenced by individual differences in interoceptive accuracy.

To formally test this hypothesis, we fitted a linear mixed-effects model using the mixedlm function from the statsmodels package (Version 0.14.6 (Seabold and Perktold, 2010)) in Python. Before the main analysis, the interoceptive accuracy (IAc) score was grand-mean centered to create the predictor Iac_centered.

The core linear mixed-effects model examined the fixed effects of Face Condition (Self-face vs. Other-face), centered interoceptive accuracy (Iac_centered), and their interaction on the log-transformed absolute modulation index (MI) averaged across three post-R-peak intervals (0, 250, 500 m), which reflected the strength of cardiac-phase modulation.

The model was specified as:

$$MI \sim C(Face\,Condition) \times Iac\_centered + (1 \mid Participant\ ID),$$

with a by-participant random intercept (re_formula = "1") included to account for individual baseline differences. This model corresponded to a random-intercept structure with a within-subject factor (Face Condition) and a between-subject covariate (Iac_centered).

As a complementary, non-parametric validation of the mixed-model results, a Wilcoxon signed-rank test was performed on subject-wise mean MI values (Self-face vs. Other-face).

To address the phase-specific effects of TMS timing relative to the R-peak, we fitted a single mixed-effects model with delay as a within-subject factor. The model included the main effects of condition, delay, and Iac_centered (a participant-level covariate), as well as the interaction between condition and delay:

$$MI \sim C(Face\,Condition) \times delay + Iac\_centered + (1 \mid Participant\ ID)$$

Both mixed-effects models were evaluated using standard diagnostics, including inspection of residual normality (Q–Q plots; Shapiro–Wilk test), homoscedasticity (Breusch–Pagan test), and influence of individual participants (leave-one-subject-out refits).

As an exploratory analysis aimed at improving the physiological interpretability of our findings and facilitating comparison with previous cardiac-phase TMS studies, we additionally fitted a separate mixed-effects model to the raw log-transformed MEP amplitudes:

$$amplitude\_lg \sim C(Face\,Condition) \times delay + Iac\_centered + (1 \mid Participant\ ID)$$

This model provided signed phase differences in corticospinal excitability by estimating (1) the effect of Face Condition (Self-face vs. Other-face) at each post-R-peak delay, and (2) within-condition contrasts between systolic and diastolic intervals (e.g., 500 m − 250 m). Linear contrasts of the fixed effects (Wald tests) were used to obtain these signed differences and their associated confidence intervals and p-values.

2.9.2 Correlational analysis

To analyze the relationship between interoceptive accuracy and modulation strength within each condition, separate Spearman rank-order correlations were computed between Iac and MI averaged across all cardiac phases for the Self-face and Other-face conditions. Because both correlations were obtained from the same participants and shared a common variable (interoceptive accuracy), we additionally compared them using Steiger's Z test for dependent correlations.

3 Results

3.1 Cardiac modulation of corticospinal excitability

To investigate how self-referential processing interacts with cardiac rhythms in modulating corticospinal excitability, we assessed the effect of face condition (self vs. other) and interoceptive accuracy on the absolute index of cardiac-phase modulation (averaged over 0, 250 and 500 m post-R-peak). Model diagnostics indicated residuals deviated from normality (Shapiro–Wilk: $W = 0.896$, $p = 0.007$), but showed no systematic bias (mean ≈0); homoscedasticity was supported (Breusch–Pagan: $p = 0.126$), and leave-one-subject-out analyses indicated robust effects (condition coefficient range: 0.0146 to −0.0107). The mixed-effects model yielded a significant main effect, demonstrating that self-face viewing suppresses the cardiac-cycle modulation of corticospinal excitability observed during other-face viewing ($\beta = -0.014$, $SE = 0.004$, $z = -3.682$, $p < 0.001$). This suppression effect was highly consistent across participants, as validated by a follow-up Wilcoxon signed-rank test ($W = 4.000$, $p = 0.0004$) (Figure 1).

Second, we observed a significant positive main effect of interoceptive accuracy ($\beta = 0.183$, $SE = 0.054$, $z = 3.379$, $p = 0.001$). This indicates that, overall, individuals with higher interoceptive accuracy show stronger cardiac-phase modulation of corticospinal excitability across both face conditions.

The model yielded a trend-level interaction between face condition and interoceptive accuracy ($\beta = -0.085$, $SE = 0.045$, $p = 0.059$). The negative coefficient indicates that the otherwise positive association between interoceptive accuracy and modulation strength might be reduced in the self-face condition. This finding raises the possibility that self-face viewing was associated with

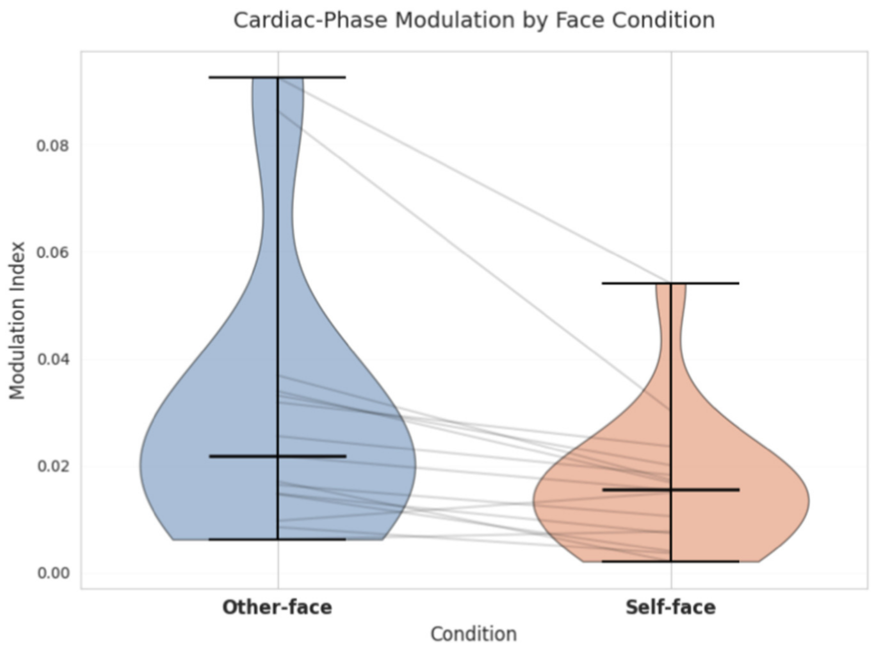

FIGURE 1
Modulation strength differs between face conditions. Violin plots depict the distribution of cardiac-phase modulation index for other-face (blue) and self-face (orange) viewing. Lines connect paired measurements from the same participants (N = 15). Modulation was significantly reduced for self-face processing (Wilcoxon signed-rank test: W = 4.000, p = 0.0004). Probability density is shown by violin width, medians by horizontal lines, and data ranges by thin vertical lines.

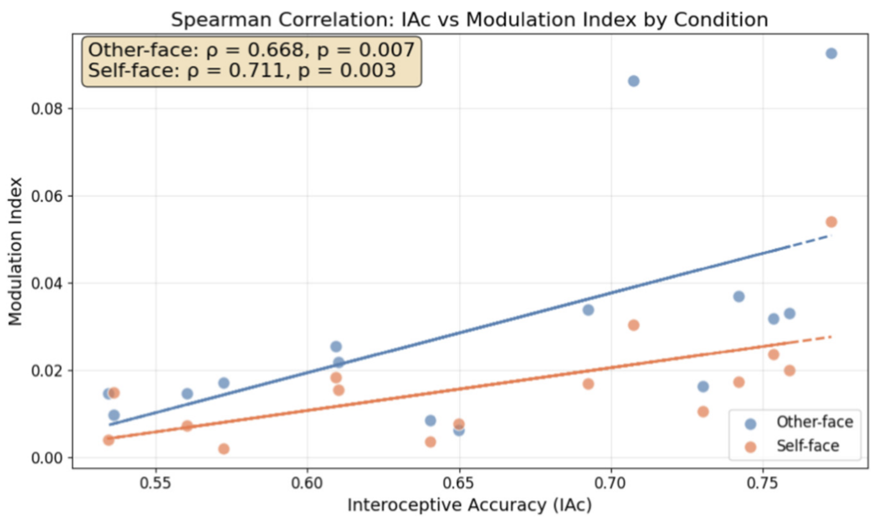

FIGURE 2
Interoceptive accuracy predicts modulation strength in both attentional conditions. Scatter plots show the relationship between interoceptive accuracy (Iac) and cardiac-phase modulation index for other-face (blue) and self-face (orange) viewing. Dashed lines represent linear regression fits. Separate Spearman rank-order correlations revealed significant positive associations in both conditions: for other-face viewing ($\rho = 0.668$, $p = 0.007$) and for self-face viewing ($\rho = 0.711$, $p = 0.003$). Each point represents one participant (N = 15 per condition). The similarity in correlation magnitudes suggests that individual differences in cardiac perception ability consistently relate to modulation strength across attentional states.

reduced cardiac-phase modulation under the current task conditions.

To further illustrate the relationship between interoceptive accuracy and cardiac-phase modulation strength, separate Spearman rank-order correlations were computed for each attentional condition. For both conditions strong positive correlation was revealed (other-face condition: $\rho = 0.668$, $p = 0.007$; self-face condition: $\rho = 0.711$, $p = 0.003$). A Steiger's Z test confirmed that these correlations did not differ significantly between conditions ($z = -0.62$, $p = 0.54$), indicating that the strength of the

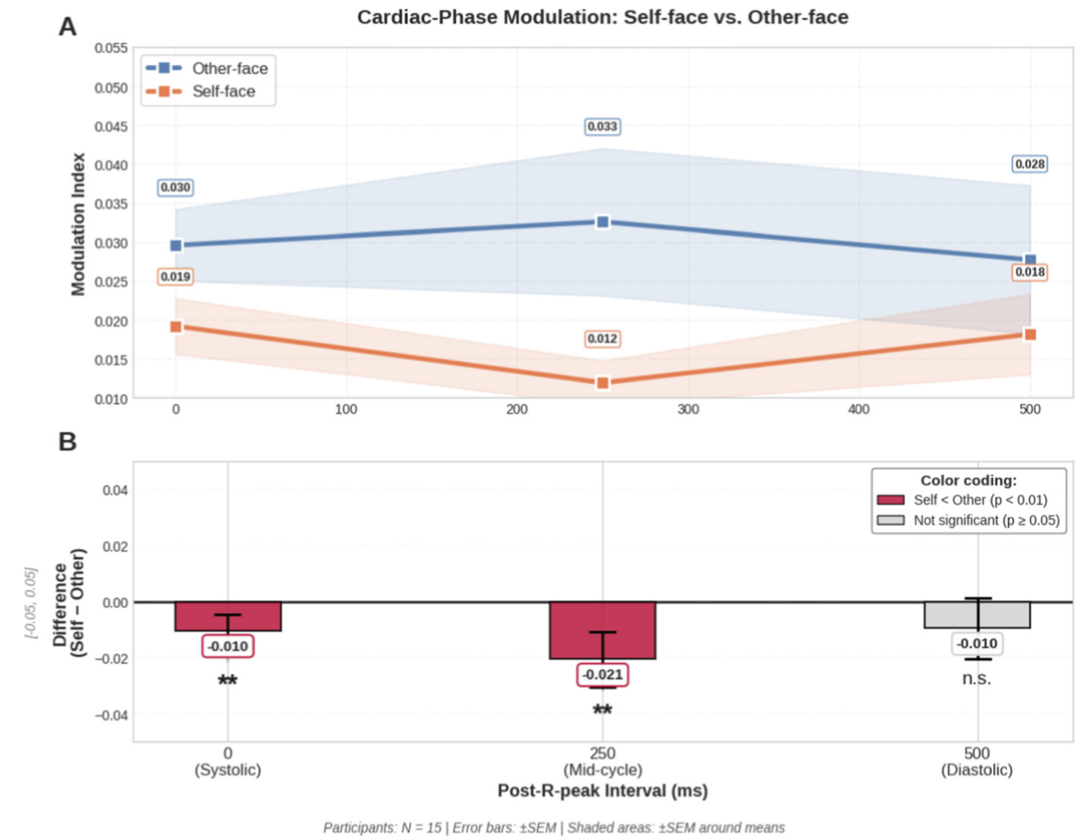

FIGURE 3
Cardiac-phase modulation of corticospinal excitability during self-face and other-face viewing. **(A)** Mean modulation index (±SEM) as a function of time after the R-peak (0, 250, and 500 m) for other-face (blue) and self-face (orange) conditions. Shaded areas represent the standard error of the mean (SEM). **(B)** Mean difference in modulation index (Self – Other) for each post-R interval. Bar colors indicate the direction and statistical significance of the difference between conditions (Self – Other): red indicates that self-face modulation is significantly lower than other-face modulation ($p < 0.01$); gray indicates non-significant differences ($p \geq 0.05$). Colors are based on the fixed effect of Face Condition in the linear mixed-effects model at each delay. Error bars represent the standard error of the difference. Asterisks denote statistical significance: $p < 0.01$. The overall reduction in modulation strength during self-face viewing was most pronounced at 250 m after the R-peak. N = 15 participants.

relationship between interoceptive accuracy and modulation strength is statistically comparable across self-face and other-face viewing (Figure 2).

3.2 Phase-specific analysis of cardiac-phase modulation

To verify that the fixed post-R-peak delays corresponded to the intended cardiac phases in our sample, we computed the angular phase of the cardiac cycle at the moment of each TMS pulse. The mean heart rate during the experiment was 71.6 bpm (SD = 8.5, range: 54.7–88.0), corresponding to a mean R–R interval of 850 m (SD = 103). Angular phase analysis confirmed that the 250 m delay fell within the systolic phase for all participants (M = 107.5°, SD = 12.8°, range: 82.5°–130.6°; all values <180°), whereas the 500 m delay fell within the diastolic phase for all participants (M = 214.9°, SD = 25.6°, range: 163.5°–267.0°; all values >180°). The angular phase at the time of stimulation did not differ between conditions at either delay (250 m: $p = 0.92$; 500 m: $p = 0.48$), confirming that conditions were comparable in cardiac-phase timing.

To determine whether the reduction in modulation strength during self-face viewing was specific to particular cardiac phases, we conducted a single mixed-effects model with delay as a within-subject factor. Residuals deviated from normality (Shapiro–Wilk: $W = 0.881$, $p < 0.001$), but there was no systematic bias (mean residual ≈0), homoscedasticity was supported (Breusch–Pagan: $p = 0.054$), and leave-one-subject-out analyses indicated stable effects.

At the 0 m delay, the suppression of modulation for the self-face condition showed a trend toward significance ($\beta = -0.010$, SE = 0.006, $z = -1.683$, $p = 0.092$). The suppressive effect was significant at the 250 m delay ($\beta = -0.021$, SE = 0.006, $z = -3.342$, $p < 0.001$), a timeframe that coincides with the systolic period. At the 500 m delay, which falls within the diastolic phase, the reduction in modulation strength during self-face viewing was not statistically significant ($\beta = -0.010$, SE = 0.006, $z = -1.552$, $p = 0.121$) (Figure 3). The interaction between delay and condition was not statistically significant (delay_250 × condition: $\beta = -0.010$, $z = -1.173$, $p = 0.241$; delay_500 × condition: $\beta = 0.001$, $z = 0.093$, $p = 0.926$). However, the pattern of simple effects suggests that the suppressive effect of self-face viewing may be most pronounced during the systolic phase (250 m delay), where it reached statistical significance, compared to the early (0 m) and late (500 m) phases, where effects were weaker and non-significant. Together, these results suggest that the attentional modulation of cardiac–cortical coupling may be phase-dependent, with the effect of viewing one's own face being strongest during the systolic phase, peaking around 250 m after the R-peak.

To facilitate comparison with prior work that reports signed phase differences, we additionally examined phase-specific raw log-MEP amplitudes using this exploratory mixed-effects model. Mean log-MEP amplitudes for each condition and phase were as follows: other-face condition (0 m: M = 2.708, SD = 0.596; 250 m: M = 2.714, SD = 0.549; 500 m: M = 2.666, SD = 0.593); self-face condition (0 m: M = 2.674, SD = 0.615; 250 m: M = 2.675, SD = 0.593; 500 m: M = 2.662, SD = 0.612). The effect of Face Condition on log-MEP amplitude showed trends toward lower excitability in the self-face relative to the other-face condition at 0 m ($\beta = -0.036$, SE = 0.022, $z = -1.66$, $p = 0.097$) and 250 m ($\beta = -0.040$, SE = 0.022, $z = -1.84$, $p = 0.066$), but not at 500 m ($\beta = -0.006$, SE = 0.022, $z = -0.28$, $p = 0.78$). Within-condition signed contrasts between systolic and diastolic phases revealed a significant reduction in log-MEP amplitude from 250 m to 500 m in the other-face condition (500 m − 250 m: $\beta = -0.048$, SE = 0.022, $z = -2.23$, $p = 0.026$), whereas the analogous contrast in the self-face condition was not significant ($\beta = -0.015$, SE = 0.022, $z = -0.67$, $p = 0.50$).

3.3 Cardiac impedance parameters

To assess whether the observed modulation of corticospinal excitability could be attributed to changes in cardiac contractility, an additional analysis of impedance cardiography parameters was performed, focusing on pre-ejection period (PEP) and stroke volume (SV). PEP and SV were estimated for heartbeats occurring between the onset of face presentation and the TMS pulse in each trial and then averaged within each TMS-delay condition, as trials were intermixed and participants could not predict the delay.

For the main comparison of interest, PEP and SV values were further averaged within the Self-face and Other-face conditions, and paired Wilcoxon signed-rank tests were conducted on these subject-wise means. This analysis revealed no significant differences between Self-face and Other-face viewing periods for either PEP (Wilcoxon signed-rank test: $W = 51$, $z = 0.384$, $p = 0.735$) or SV (Wilcoxon signed-rank test: $W = 27$, $z = -1.293$, $p = 0.216$), indicating that differences in corticospinal modulation were unlikely to be driven by changes in cardiac contractility.

4 Discussion

The present study investigated how self-referential visual processing, particularly viewing one's own face, modulates the cardiac-phase influence on corticospinal excitability, and whether this modulation depends on individual interoceptive accuracy. Contrary to our initial hypothesis, which predicted that self-face viewing would enhance cardiac–motor coupling by fostering an inward attentional focus, we found a significant reduction in cardiac-phase modulation during self-face compared to other-face processing. This effect was temporally specific, being strongest at 0 m and 250 m after the R-peak - time points that correspond to early- and mid-systolic phases, when baroreceptor firing and corticospinal excitability are typically heightened (Al et al., 2023; Engelen et al., 2025; Lucarelli et al., 2025). Consistent with this, an exploratory analysis of signed phase contrasts on raw log-MEP amplitudes confirmed that in the other-face condition corticospinal excitability was significantly higher during systole (250 m after R-peak) than diastole (500 m after R-peak), replicating the well-documented systolic facilitation of motor excitability (Al et al., 2023). Critically, this phase difference was absent during self-face viewing, indicating that self-referential processing selectively attenuates the cardiac-phase modulation of corticospinal excitability that is otherwise present under neutral attentional conditions.

Moreover, whereas interoceptive accuracy positively correlated with modulation strength in both conditions, this relationship tended to be attenuated during self-face viewing.

Our primary finding that self-face viewing weakens cardiac modulation of motor excitability seems to contrast with previous work suggesting that self-referential stimuli can direct attention inward and enhance the processing of interoceptive and other body-related signals ((Weisz et al., 1988; Mirams et al., 2010; Ainley et al., 2013; Farb et al., 2013; Maister and Tsakiris, 2014; Sacchetti et al., 2020)). We propose that this discrepancy depends on the experimental paradigm.

In previous studies reported enhanced interoceptive accuracy, participants were instructed to focus inward on bodily sensations to count the heartbeats without competing external demands (Weisz et al., 1988; Ainley et al., 2013; Farb et al., 2013; Maister and Tsakiris, 2014). Conversely, in our task, participants were required to make an explicit external judgment about each photograph immediately after its presentation. This was done to keep participants focused on the pictures and avoid distraction during the 1-h experimental session. This requirement likely oriented attention toward the exteroceptive, visual, and evaluative features of the stimulus. Therefore, rather than serving as a cue for inward focus, the self-face may have acted, at least in part, as an exteroceptive attractor, capturing attention away from internal cardiac signals. This shift from interoceptive to exteroceptive attention could explain the observed decoupling of cardiac rhythms from corticospinal excitability.

This interpretation aligns with the contextual nature of self-face processing. Self-faces are highly salient stimuli that automatically engage cortical networks specialized for self-recognition and socio-emotional evaluation (Kircher et al., 2001; Kelley et al., 2002; Northoff and Bermpohl, 2004; Platek et al., 2008; Kim and Johnson, 2015; Yin et al., 2019). However, the relationship between self-face processing and activation of brain regions involved in bodily awareness appears to be dynamically modulated by task demands and experimental context (Gusnard et al., 2001). Importantly, this contextual modulation extends to self-referential processing in general. When self-referential judgments involve personal value assignment and affective evaluation, such as assessing one's traits, medial prefrontal regions, including ventromedial prefrontal cortex (vmPFC), show robust activation (Northoff and Bermpohl, 2004; Denny et al., 2012; D'Argembeau, 2013). These same regions integrate interoceptive signals with self-representations, serving as a key hub for somatic marker processing and the embodied sense of self (Damasio, 1996; Candia-Rivera et al., 2024). In contrast, when self-evaluation tasks demand explicit social comparison or objective reflection on one's characteristics, lateral prefrontal cortex and dorsolateral regions show enhanced engagement, reflecting a shift toward controlled, abstract reasoning (Northoff and Bermpohl, 2004). Our experimental paradigm can be primarily characterized as a task of explicit social evaluation and trait judgment. The requirement to analytically assess the degree to which a photographed person possesses specific positive traits (e.g., "charismatic," "intelligent") aligns it with cognitive operations classically supported by lateral prefrontal cortical (LPFC) networks, which subserve controlled reasoning and social-cognitive analysis.

In neural terms, this context-dependent shift in network engagement reflects a fundamental principle of competitive resource allocation in the brain. Thus, from a mechanistic perspective, our results can be framed within resource-competition models of attention (Chun et al., 2011). Processing a salient self-relevant stimulus likely consumes cognitive resources, leaving fewer available for monitoring interoceptive signals. The consequent attenuation of cardiac modulation was most pronounced during early systolic timepoints (0 and 250 m post-R-peak), a period when baroreceptor firing normally facilitates motor cortex excitability (Al et al., 2023; Engelen et al., 2025; Lucarelli et al., 2025). This specificity suggests that externally cued attention can effectively gate the integration of phasic cardiovascular signals into motor planning processes.

However, attentional competition is likely only one of several mechanisms that may contribute to the observed attenuation of cardiac-phase modulation during self-face viewing. Self-face stimuli carry heightened affective salience: they automatically elicit stronger emotional and arousal responses than unfamiliar faces (Devue and Brédart, 2011), and affective arousal has been shown to modulate cardiac afferent processing independently of attentional allocation (Luft and Bhattacharya, 2015; Candia-Rivera et al., 2022). In addition, the self-evaluative demands inherent in judging one's own traits may engage additional cognitive processes, such as social comparison, self-reflection, and self-discrepancy monitoring, that are not present when evaluating another person (Northoff and Bermpohl, 2004; Denny et al., 2012). These evaluative processes recruit prefrontal networks that may interfere with interoceptive processing through mechanisms distinct from simple attentional diversion. The present design does not allow us to disentangle these mechanisms, and future studies that orthogonally manipulate attentional load, affective content, and self-relevance would be needed to isolate their relative contributions to the modulation of cardiac–cortical coupling.

In summary, the direction of self-relevance's effect (enhancing versus reducing bodily coupling) may be critically determined by whether the attentional set is inward- or outward-directed. Future studies could test this moderator directly by manipulating task instructions (e.g., "focus on your heartbeat" versus "judge the photograph") within the same paradigm.

The second key finding of the study is the strong positive association between interoceptive accuracy, measured by the heartbeat-counting task (HCT), and cardiac modulation of motor excitability. This indicates that in our sample, individuals with better heartbeat-detection ability exhibit stronger cardiac-phase coupling of corticospinal excitability, irrespective of attentional focus. This finding extends previous work linking interoceptive accuracy to physiological markers of interoceptive processing (e.g., heartbeat-evoked potentials (Mai et al., 2018; Coll et al., 2021); by demonstrating that such accuracy also predicts the functional impact of cardiac signals on motor output. In other words, higher interoceptive acuity is associated with a greater magnitude of heartbeat-driven modulation of corticospinal excitability, establishing a direct link between subjective interoceptive ability and objective neurophysiological coupling. A closely related finding was reported by (Otsuru et al., 2020), who also examined the relationship between interoceptive accuracy and cardiac-phase modulation of corticospinal excitability using TMS. However, their analysis quantified the directional pattern of phase-specific effects, revealing positive correlations at 200 m and negative correlations at 400 m post-R-peak. By contrast, our approach measured the overall strength of modulation across all cardiac phases, independent of whether excitability increased or decreased. Thus, while Otsuru et al. (2020) identified which phases show phase-dependent enhancement or suppression as a function of heartbeat perception, our metric quantifies how pronounced the cardiac modulation is regardless of direction. Both approaches converge on the conclusion that interoceptive accuracy is functionally linked to heart-brain coupling.

This result suggests a potential avenue for future research. State-dependent TMS protocols, which deliver stimulation at specific phases of physiological cycles, represent a promising approach for enhancing the efficacy of clinical TMS interventions (Zrenner et al., 2018; Zrenner et al., 2019; Rösch et al., 2023; Makarova et al., 2025). Given that higher interoceptive accuracy is associated with more pronounced cardiac modulation of corticospinal excitability, interoceptive training designed to improve accuracy (Sugawara et al., 2024; Rusinova et al., 2025) could be incorporated into clinical protocols prior to stimulation to potentially enhance its physiological and therapeutic effects. However, it is important to emphasize that the present study was conducted in a healthy pilot sample and did not test any clinical, or therapeutic outcomes. Whether improving interoceptive accuracy would translate into enhanced stimulation effects remains an open and important question for future empirical studies, rather than a direct implication of the current data.

Moreover, given the small sample size ($n = 15$) and the known limitations of the HCT as a measure of interoceptive ability, this finding should be interpreted with caution and requires replication in a larger sample.

The trend-level interaction ($p = 0.059$) between face condition and HCT-based interoceptive accuracy provides preliminary, exploratory evidence that the positive relationship between accuracy and modulation strength might be attenuated during self-face viewing. One speculative explanation is that the high salience of the self-face attenuates the expression of individual differences in interoceptive sensitivity, resulting in a more uniform, externally-focused attentional state.

Finally, impedance cardiography indices of cardiac contractility, namely, pre-ejection period (PEP) and stroke volume (SV), did not differ between viewing one's own and another person's face. This pattern indicates that cardiac activity *per se* is unlikely to account for the observed cardiac-phase modulation of MI, which is more plausibly attributed to central processes, such as differential attention to self-versus other-related stimuli.

5 Limitations

Several limitations of this pilot study warrant consideration. First, the relatively small sample size (n = 15) limits the generalizability of our findings and reduces confidence in the stability of effect estimates, particularly for complex effects such as the trend-level interaction between condition and interoceptive accuracy. Additionally, the all-male composition of our sample further restricts generalizability, as hormonal fluctuations across the menstrual cycle are known to influence cortical excitability and plasticity (Zoghi et al., 2015; Hernandez-Pavon et al., 2023; Ramdeo et al., 2024). While this choice was made to minimize variability in our already complex ECG–TMS protocol, it precludes extrapolation of the findings to female populations. Replication in a larger cohort is essential to confirm the robustness of the primary effects and would allow for a more nuanced investigation of potential moderators, including psychological factors such as subjective body awareness or the affective appraisal of one's own appearance, which may influence responses to self-face stimuli. In addition, the heartbeat-counting task used to assess interoceptive accuracy is known to be influenced by non-interoceptive factors, including beliefs about one's heart rate and time-estimation strategies (Ring and Brener, 1996; Desmedt et al., 2018, p. 20), and the observed associations between HCT-based interoceptive accuracy and cardiac-phase modulation should therefore be considered exploratory. Second, the cardiac-phase analysis used fixed post-R-peak delays (0, 250, and 500 m) rather than an adaptive algorithm that accounts for individual heart-rate variability. While this allows for consistent targeting of specific cardiac phases across participants, it does not reflect potential inter-individual differences in cardiac dynamics. Future studies employing real-time, heart-rate-adjusted stimulation protocols could determine whether the observed modulation patterns are consistent across variations in individual cardiac timing.

6 Conclusion

Contrary to the hypothesis that self-face viewing would enhance cardiac-motor coupling via inward attentional focus, we found that self-referential processing reduced the influence of cardiac phase on corticospinal excitability, most prominently during systolic intervals. This reduction may involve a shift of attentional resources from interoceptive signals to the salient external stimulus of one's own face, particularly under task conditions requiring explicit evaluation of that stimulus, although other mechanisms could also contribute. At the same time, individual differences in interoceptive accuracy positively predicted the strength of cardiac-phase modulation across conditions, indicating that heartbeat-counting task performance was associated with objective heart–brain–body coupling in this sample. These results highlight the context-dependency of self-processing effects on interoception and underscore the importance of task demands in determining whether self-focus amplifies or attenuates bodily awareness.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by HSE University Committee for Interuniversity Surveys and Ethical Assessment of Empirical Research (Protocol No. 80, dated 07.02.2022). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review and editing. NF: Conceptualization, Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – original draft. IM: Data curation, Formal Analysis, Investigation, Writing – original draft. MN: Data curation, Formal Analysis, Investigation, Writing – original draft. AO: Conceptualization, Funding acquisition, Resources, Writing – review and editing. AT: Conceptualization, Formal Analysis, Methodology, Software, Writing – review and editing. MV: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. Work was funded by the Basic Research Program at the National Research University Higher School of Economics (HSE University).

Conflict of interest

Author AO was employed by LLC "Life Improvement by Future Technologies Center".

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsip.2026.1776807/full#supplementary-material

References

Ainley, V., Maister, L., Brokfeld, J., Farmer, H., and Tsakiris, M. (2013). More of myself: manipulating interoceptive awareness by heightened attention to bodily and narrative aspects of the self. *Conscious. Cogn.* 22, 1231–1238. doi:10.1016/j.concog.2013.08.004

Al, E., Iliopoulos, F., Forschack, N., Nierhaus, T., Grund, M., Motyka, P., et al. (2020). Heart–brain interactions shape somatosensory perception and evoked potentials. *Proc. Natl. Acad. Sci.* 117, 10575–10584. doi:10.1073/pnas.1915629117

Al, E., Stephani, T., and Engelhardt, M. (2021). *Cardiac activity impacts cortical motor excitability*.

Al, E., Stephani, T., Engelhardt, M., Haegens, S., Villringer, A., and Nikulin, V. V. (2023). Cardiac activity impacts cortical motor excitability. *PLoS Biol.* 21, 1–23. doi:10.1371/journal.pbio.3002393

Barrett, L. F., and Simmons, W. K. (2015). Interoceptive predictions in the brain. *Nat. Rev. Neurosci.* 16, 419–429. doi:10.1038/nrn3950

Candia-Rivera, D., Catrambone, V., Thayer, J. F., Gentili, C., and Valenza, G. (2022). Cardiac sympathetic-vagal activity initiates a functional brain–body response to emotional arousal. *Proc. Natl. Acad. Sci.* 119, e2119599119. doi:10.1073/pnas.2119599119

Candia-Rivera, D., Engelen, T., Babo-Rebelo, M., and Salamone, P. C. (2024). Interoception, network physiology and the emergence of bodily self-awareness. *Neurosci. Biobehav. Rev.* 165, 105864. doi:10.1016/j.neubiorev.2024.105864

Chun, M. M., Golomb, J. D., and Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annu. Rev. Psychol.* 62, 73–101. doi:10.1146/annurev.psych.093008.100427

Coll, M. P., Hobson, H., Bird, G., and Murphy, J. (2021). Systematic review and meta-analysis of the relationship between the heartbeat-evoked potential and interoception. *Neurosci. Biobehav. Rev.* 122, 190–200. doi:10.1016/J.NEUBIOREV.2020.12.012

Craig, A. D. (2002). How do you feel? Interoception: the sense of the physiological condition of the body. *Nat. Rev. Neurosci.* 3, 655–666. doi:10.1038/nrn894

Damasio, A. R. (1996). The somatic marker hypothesis and the possible functions of the prefrontal cortex. *Philos. Trans. R. Soc. B Biol. Sci.* 351, 1413–1420. doi:10.1098/rstb.1996.0125

Denny, B. T., Kober, H., Wager, T. D., and Ochsner, K. N. (2012). A meta-analysis of functional neuroimaging studies of self- and other judgments reveals a spatial gradient for mentalizing in medial prefrontal cortex. *J. Cogn. Neurosci.* 24, 1742–1752. doi:10.1162/jocn_a_00233

Desmedt, O., Luminet, O., and Corneille, O. (2018). The heartbeat counting task largely involves non-interoceptive processes: evidence from both the original and an adapted counting task. *Biol. Psychol.* 138, 185–188. doi:10.1016/j.biopsycho.2018.09.004

Devue, C., and Brédart, S. (2011). The neural correlates of visual self-recognition. *Conscious. Cogn.* 20, 40–51. doi:10.1016/j.concog.2010.09.007

D'Argembeau, A. (2013). On the role of the ventromedial prefrontal cortex in self-processing: the valuation hypothesis. *Front. Hum. Neurosci.* 7, 372. doi:10.3389/fnhum.2013.00372

Edwards, L., Ring, C., McIntyre, D., Winer, J. B., and Martin, U. (2009). Sensory detection thresholds are modulated across the cardiac cycle: evidence that cutaneous sensibility is greatest for systolic stimulation. *Psychophysiology* 46, 252–256. doi:10.1111/j.1469-8986.2008.00769.x

Engelen, T., Schuhmann, T., Sack, A. T., and Tallon-Baudry, C. (2025). Cardiac, respiratory, and gastric rhythms independently modulate motor corticospinal excitability in humans. *PLOS Biol.* 23, e3003478. doi:10.1371/journal.pbio.3003478

Farb, N. A. S., Segal, Z. V., and Anderson, A. K. (2013). Mindfulness meditation training alters cortical representations of interoceptive attention. *Soc. Cogn. Affect. Neurosci.* 8, 15–26. doi:10.1093/scan/nss066

Forouzanfar, M., Baker, F. C., De Zambotti, M., McCall, C., Giovangrandi, L., and Kovacs, G. T. A. (2018). Toward a better noninvasive assessment of preejection period: a novel automatic algorithm for B-point detection and correction on thoracic impedance cardiogram. *Psychophysiology* 55, e13072. doi:10.1111/psyp.13072

Galvez-Pol, A., McConnell, R., and Kilner, J. M. (2020). Active sampling in visual search is coupled to the cardiac cycle. *Cognition* 196, 104149. doi:10.1016/j.cognition.2019.104149

Garfinkel, S. N., and Critchley, H. D. (2016). Threat and the body: how the heart supports fear processing. *Trends Cogn. Sci.* 20, 34–46. doi:10.1016/j.tics.2015.10.005

Gentile, G., Björnsdotter, M., Petkova, V. I., Abdulkarim, Z., and Ehrsson, H. H. (2015). Patterns of neural activity in the human ventral premotor cortex reflect a whole-body multisensory percept. *NeuroImage* 109, 328–340. doi:10.1016/j.neuroimage.2015.01.008

Giustiniani, A., Vallesi, A., Oliveri, M., Tarantino, V., Ambrosini, E., Bortoletto, M., et al. (2022). A questionnaire to collect unintended effects of transcranial magnetic stimulation: a consensus based approach. *Clin. Neurophysiol.* 141, 101–108. doi:10.1016/j.clinph.2022.06.008

Gray, M. A., Beacher, F. D., Minati, L., Nagai, Y., Kemp, A. H., Harrison, N. A., et al. (2012). Emotional appraisal is influenced by cardiac afferent information. *Emot. Wash. D.C.* 12, 180–191. doi:10.1037/a0025083

Gusnard, D. A., Akbudak, E., Shulman, G. L., and Raichle, M. E. (2001). Medial prefrontal cortex and self-referential mental activity: relation to a default mode of brain function. *Proc. Natl. Acad. Sci.* 98, 4259–4264. doi:10.1073/pnas.071043098

Hernandez-Pavon, J. C., Veniero, D., Bergmann, T. O., Belardinelli, P., Bortoletto, M., Casarotto, S., et al. (2023). TMS combined with EEG: recommendations and open issues for data collection and analysis. *Brain Stimul.* 16, 567–593. doi:10.1016/j.brs.2023.02.009

Jeannerod, M. (2003). The mechanism of self-recognition in humans. *Behav. Brain Res.* 142, 1–15. doi:10.1016/S0166-4328(02)00384-4

Kelley, W. M., Macrae, C. N., Wyland, C. L., Caglar, S., Inati, S., and Heatherton, T. F. (2002). Finding the self? An event-related fMRI study. *J. Cogn. Neurosci.* 14, 785–794. doi:10.1162/08989290260138672

Kim, K., and Johnson, M. K. (2015). Activity in ventromedial prefrontal cortex during self-related processing: positive subjective value or personal significance? *Soc. Cogn. Affect. Neurosci* 10, 494–500. doi:10.1093/scan/nsu078

Kircher, T. T. J., Senior, C., Phillips, M. L., Rabe-Hesketh, S., Benson, P. J., Bullmore, E. T., et al. (2001). Recognizing one's own face. *Cognition* 78, B1–B15. doi:10.1016/S0010-0277(00)00104-9

Konttinen, N., Mets, T., Lyytinen, H., and Paananen, M. (2003). Timing of triggering in relation to the cardiac cycle in nonelite rifle shooters. *Res. Q. Exerc. Sport* 74, 395–400. doi:10.1080/02701367.2003.10609110

Krieg, S. M., Lioumis, P., Mäkelä, J. P., Wilenius, J., Karhu, J., Hannula, H., et al. (2017). Protocol for motor and language mapping by navigated TMS in patients and healthy volunteers; workshop report. *Acta Neurochir. (Wien)* 159, 1187–1195. doi:10.1007/s00701-017-3187-z

Legrand, D. (2006). The bodily self: the Sensori-Motor roots of pre-reflective self-consciousness. *Phenomenol. Cogn. Sci.* 5, 89–118. doi:10.1007/s11097-005-9015-6

Legrand, N., Engen, S. S., Correa, C. M. C., Mathiasen, N. K., Nikolova, N., Fardo, F., et al. (2021). Emotional metacognition: stimulus valence modulates cardiac arousal and metamemory. *Cogn. Emot.* 35, 705–721. doi:10.1080/02699931.2020.1859993

Lucarelli, D., Guidotti, R., Pieramico, G., Voso, D., Romani, G. L., Pizzella, V., et al. (2025). Motor system excitability is influenced by the cardiac cycle: a TMS-EEG study. *Brain Stimul.* 18, 1339. doi:10.1016/j.brs.2025.05.031

Luft, C. D. B., and Bhattacharya, J. (2015). Aroused with heart: modulation of heartbeat evoked potential by arousal induction and its oscillatory correlates. *Sci. Rep.* 51 (5), 1–11. doi:10.1038/srep15717

Machetanz, K., Gallotti, A. L., Leao Tatagiba, M. T., Liebsch, M., Trakolis, L., Wang, S., et al. (2020). Time-frequency representation of motor evoked potentials in brain tumor patients. *Front. Neurol.* 11, 633224. doi:10.3389/fneur.2020.633224

Mai, S., Wong, C. K., Georgiou, E., and Pollatos, O. (2018). Interoception is associated with heartbeat-evoked brain potentials (HEPs) in adolescents. *Biol. Psychol.* 137, 24–33. doi:10.1016/j.biopsycho.2018.06.007

Maister, L., and Tsakiris, M. (2014). My face, my heart: cultural differences in integrated bodily self-awareness. *Cogn. Neurosci.* 5, 10–16. doi:10.1080/17588928.2013.808613

Makarova, M., Fedosov, N., Nekrasova, J., and Ossadtchi, A. (2025). Hardware-enabled low latency rhythmic brain state tracking for brain stimulation applications. *NeuroImage* 319, 121437. doi:10.1016/j.neuroimage.2025.121437

Memarian Sorkhabi, M., Wendt, K., O'Shea, J., and Denison, T. (2022). Pulse width modulation-based TMS: primary motor cortex responses compared to conventional monophasic stimuli. *Brain Stimul.* 15, 980–983. doi:10.1016/j.brs.2022.06.013

Mirams, L., Poliakoff, E., Brown, R. J., and Lloyd, D. M. (2010). Vision of the body increases interference on the somatic signal detection task. *Exp. Brain Res.* 202, 787–794. doi:10.1007/s00221-010-2185-7

Nazarova, M., Novikov, P., Ivanina, E., Kozlova, K., Dobrynina, L., and Nikulin, V. V. (2021). Mapping of multiple muscles with transcranial magnetic stimulation: absolute and relative test–retest reliability. *Hum. Brain Mapp.* 42, 2508–2528. doi:10.1002/hbm.25383

Northoff, G., and Bermpohl, F. (2004). Cortical midline structures and the self. *Trends Cogn. Sci.* 8, 102–107. doi:10.1016/j.tics.2004.01.004

Northoff, G., Heinzel, A., De Greck, M., Bermpohl, F., Dobrowolny, H., and Panksepp, J. (2006). Self-referential processing in our brain—A meta-analysis of imaging studies on the self. *NeuroImage* 31, 440–457. doi:10.1016/j.neuroimage.2005.12.002

Otsuru, N., Miyaguchi, S., Kojima, S., Yamashiro, K., Sato, D., Yokota, H., et al. (2020). Timing of modulation of corticospinal excitability by heartbeat differs with interoceptive accuracy. *Neuroscience* 433, 156–162. doi:10.1016/j.neuroscience.2020.03.014

Park, H. D., and Blanke, O. (2019a). Coupling inner and outer body for self-consciousness. *Trends Cogn. Sci.* 23, 377–388. doi:10.1016/j.tics.2019.02.002

Park, H. D., and Blanke, O. (2019b). Heartbeat-evoked cortical responses: underlying mechanisms, functional roles, and methodological considerations. *NeuroImage* 197, 502–511. doi:10.1016/j.neuroimage.2019.04.081

Platek, S. M., Wathne, K., Tierney, N. G., and Thomson, J. W. (2008). Neural correlates of self-face recognition: an effect-location meta-analysis. *Brain Res.* 1232, 173–184. doi:10.1016/j.brainres.2008.07.010

Potts, J. T., and Li, J. (1998). Interaction between carotid baroreflex and exercise pressor reflex depends on baroreceptor afferent input. *Am. J. Physiol.* 274, H1841–H1847. doi:10.1152/ajpheart.1998.274.5.H1841

Pramme, L., Larra, M. F., Schächinger, H., and Frings, C. (2014). Cardiac cycle time effects on mask inhibition. *Biol. Psychol.* 100, 115–121. doi:10.1016/j.biopsycho.2014.05.008

Qin, P., and Northoff, G. (2011). How is our self related to midline regions and the default-mode network? *NeuroImage* 57, 1221–1233. doi:10.1016/j.neuroimage.2011.05.028

Rae, C. L., Botan, V. E., Gould Van Praag, C. D., Herman, A. M., Nyyssönen, J. A. K., Watson, D. R., et al. (2018). Response inhibition on the stop signal task improves during cardiac contraction. *Sci. Rep.* 8, 9136. doi:10.1038/s41598-018-27513-y

Ramdeo, K. R., Adams, F. C., Drapeau, C. C., Foglia, S. D., Cuizon, M. C., Sader, M. A., et al. (2024). The influence of menstrual phase on synaptic plasticity induced via intermittent theta-burst stimulation. *Neuroscience* 558, 122–127. doi:10.1016/j.neuroscience.2024.08.023

Ring, C., and Brener, J. (1996). Influence of beliefs about heart rate and actual heart rate on heartbeat counting. *Psychophysiology* 33, 541–546. doi:10.1111/j.1469-8986.1996.tb02430.x

Rösch, J., Emanuel Vetter, D., Baldassarre, A., Souza, V. H., Lioumis, P., Roine, T., et al. (2023). Individualized treatment of motor stroke: a perspective on open-loop, closed-loop and adaptive closed-loop brain state-dependent TMS. *Clin. Neurophysiol.* 158, 211. doi:10.1016/j.clinph.2023.10.004

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmöller, J., et al. (2021). Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: expert guidelines. *Clin. Neurophysiol. Off. J. Int. Fed. Clin. Neurophysiol.* 132, 269–306. doi:10.1016/j.clinph.2020.10.003

Rusinova, A., Aksiotis, V., Potapkina, E., Kozhanova, E., Akimov, V., Ossadtchi, A., et al. (2025). *Interoceptive training enhances emotional awareness and body image perception: evidence from improved heartbeat detection and psychological outcomes*. doi:10.1101/2025.06.16.659873

Sacchetti, S., Mirams, L., McGlone, F., and Cazzato, V. (2020). Self-focused attention enhances tactile sensitivity in women at risk from eating disorders. *Sci. Rep.* 10, 11614. doi:10.1038/s41598-020-68500-6

Schandry, R. (1981). Heart beat perception and emotional experience. *Psychophysiology* 18, 483–488. doi:10.1111/j.1469-8986.1981.tb02486.x

Seabold, S., and Perktold, J. (2010). *Statsmodels: econometric and statistical modeling with python*. Austin, Texas, 92–96. doi:10.25080/Majora-92bf1922-011

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends Cogn. Sci.* 17, 565–573. doi:10.1016/j.tics.2013.09.007

Seth, A. K., and Tsakiris, M. (2018). Being a beast machine: the somatic basis of selfhood. *Trends Cogn. Sci.* 22, 969–981. doi:10.1016/j.tics.2018.08.008

Sugawara, A., Katsunuma, R., Terasawa, Y., and Sekiguchi, A. (2024). Interoceptive training impacts the neural circuit of the anterior insula cortex. *Transl. Psychiatry* 14, 206. doi:10.1038/s41398-024-02933-9

Tsakiris, M. (2017). The multisensory basis of the self: from body to identity to others. *Q. J. Exp. Psychol.* 70, 597–609. doi:10.1080/17470218.2016.1181768

Wang, B., Peterchev, A. V., and Goetz, S. M. (2023). Three novel methods for determining motor threshold with transcranial magnetic stimulation outperform conventional procedures. *J. Neural Eng.* 20, 056002. doi:10.1088/1741-2552/acf1cc

Weisz, J., Bálazs, L., and Ádám, G. (1988). The influence of self-focused attention on heartbeat perception. *Psychophysiology* 25, 193–199. doi:10.1111/j.1469-8986.1988.tb00987.x

Wilkinson, M., McIntyre, D., and Edwards, L. (2013). Electrocutaneous pain thresholds are higher during systole than diastole. *Biol. Psychol.* 94, 71–73. doi:10.1016/j.biopsycho.2013.05.002

Yin, S., Sui, J., Chiu, Y.-C., Chen, A., and Egner, T. (2019). Automatic prioritization of self-referential stimuli in working memory. *Psychol. Sci.* 30, 415–423. doi:10.1177/0956797618818483

Zoghi, M., Vaseghi, B., Bastani, A., Jaberzadeh, S., and Galea, M. P. (2015). The effects of sex hormonal fluctuations during menstrual cycle on cortical excitability and manual dexterity (A pilot study). *PloS One* 10, e0136081. doi:10.1371/journal.pone.0136081

Zrenner, C., Desideri, D., Belardinelli, P., and Ziemann, U. (2018). Real-time EEG-Defined excitability states determine efficacy of TMS-Induced plasticity in human motor cortex. *Brain Stimul.* 11, 374–389. doi:10.1016/j.brs.2017.11.016

Zrenner, B., Gordon, P., Kempf, A., Belardinelli, P., McDermott, E., Soekadar, S., et al. (2019). Alpha-synchronized stimulation of the left DLPFC in depression using real-time EEG-Triggered TMS. *Brain Stimul.* 12, 532. doi:10.1016/j.brs.2018.12.753