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ORIGINAL ARTICLE

Interoception as a function of hypnotizability during rest and a heartbeat counting task

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Abstract

The hypnotizability-related differences in morpho-functional characteristics of the insula could at least partially account for the differences in interoceptive accuracy (IA) observed between high and low hypnotizable individuals (highs, lows). Our aim was to investigate interoceptive processing in highs, lows, and medium hypnotizable individuals (mediums), who represent most of the population, during a 10-minute open eyes relaxation condition (Part 1) and three repetitions of consecutive 2-minute open eyes, closed eyes, and heartbeat counting conditions, followed by a 2-minute post-counting condition (Part 2). Electrocardiogram and electroencephalogram were recorded in 14 highs, 14 mediums, and 18 lows, classified according to the Stanford Hypnotic Susceptibility Scale: Form A. Heartbeat-evoked cortical potentials (HEP) were extracted throughout the entire session, and IA index was obtained for the heartbeat counting task (HCT). In Part 1, significant hypnotizability-related differences were observed in the right central region in both early and late HEP components, with lows showing positive amplitudes and highs/mediums showing negative amplitudes. In Part 2, the same group differences were limited to the early component. Moreover, in the left frontal regions, only mediums modified their HEP during the counting task with respect to the open/closed eyes conditions, whereas highs displayed HEP differences between counting and post-counting rest. HCT did not show significant group differences. In conclusion, highs and mediums seem to be more similar than mediums and lows regarding HEP, despite the absence of significant differences in HCT. Nonetheless, a negative correlation between hypnotizability scores and HEP amplitudes was observed in the regions showing group differences.

KEYWORDS

Heartbeat counting, Heartbeat evoked cortical potential, Hypnotizability, Interoceptive Accuracy

Gioia Giusti and Žan Zelič contributed equally to this work.

1 | INTRODUCTION

Interoception, that is, the perception and integration of internal bodily signals in the brain (Khalsa & Lapidus, 2016), has recently gained significant scientific attention due to the discovery of its involvement in many emotional and cognitive processes (Critchley & Harrison, 2013). The ability to accurately perceive interoceptive signals has been found to influence emotion regulation and decision-making (Kever et al., 2015; North & O'Carroll, 2001) and is thought to play an important role in the maintenance of both physical and mental health (Brewer et al., 2021; Khalsa et al., 2018). The brain structures mainly involved in interoception are the insula and the cingulate cortex (Craig, 2002). However, depending on specific conditions (e.g., emotional arousal and hypnotic state), other structures such as fronto-temporo-parietal cortical regions, amygdala, and hypothalamus are also engaged in the interoceptive processing (Callara et al., 2023; Luft & Bhattacharya, 2015; Park & Blanke, 2019). Previous research has shown that the interoceptive abilities can be empirically differentiated into the dimensions of interoceptive accuracy (IA, the ability to accurately perceive and report interoceptive information), interoceptive sensitivity (IS, the subjective interpretation of interoceptive signals), and interoceptive awareness (IAW, the metacognitive awareness of interoceptive abilities; Garfinkel et al., 2015). Interoceptive accuracy is typically quantified using behavioral measures of cardiac interoceptive accuracy, such as the heartbeat counting task (HCT; Schandry, 1981). Interoceptive sensitivity is usually measured by the self-report questionnaires of interoceptive experience, such as the Multidimensional Assessment of Interoceptive Awareness (MAIA; Mehling, 2016; Mehling et al., 2012) and Body Perception Questionnaire (BPQ; Cabrera et al., 2018; Porges, 1993), whereas interoceptive awareness is typically calculated as the correlation between the measured and self-perceived accuracy (Garfinkel et al., 2015). However, the validity of the HCT, as a pure measure of interoceptive accuracy, has come under question due to the observed influence of other cognitive–emotional and external factors on its results (Desmedt et al., 2018; Pollatos et al., 2009; Ring et al., 2015; Vig et al., 2021). Thus, heartbeat-evoked cortical potentials (HEP) are increasingly used in conjunction with the HCT to assess cardiac interoceptive abilities (Coll et al., 2021; Park & Blanke, 2019). The earlier HEP component was found to be associated with the interoceptive accuracy as measured by the HCT (Pollatos & Schandry, 2004), whereas the later HEP component might be related to the elaboration of interoceptive signals and, thus, indicative of interoceptive sensitivity (Billeci et al., 2021). Nonetheless, several factors may also confound the association between interoception and HEP, such as arousal, attention, and heart rate (Callara et al., 2023; Coll et al., 2021).

According to the American Psychological Association (APA), hypnotizability is defined as an ability to experience suggested changes in perception, physiology, emotion, cognition, and behavior during hypnosis (Elkins et al., 2015) and can be measured by standardized scales, such as Stanford Hypnotic Susceptibility Scales (see, e.g., Weitzenhoffer & Hilgard, 1959), which allow for categorization of the subjects into groups with high, medium, and low hypnotizability (highs, mediums, lows). The definition provided by APA is, however, rather incomplete, as hypnotizability also predicts responsiveness to suggestions in the ordinary, wakeful state and is related to several psychophysiological characteristics that have important implications for everyday functioning even in the absence of specific suggestions (Santarcangelo & Scattina, 2016). Brain imaging, for example, highlighted several hypnotizability-related morpho-functional brain differences that might also modulate interoceptive processing (Craig, 2002; Critchley et al., 2004; Fermin et al., 2023), such as reduced gray matter volume in insula and cerebellum, increased white matter volume in corpus callosum, and higher functional connectivity between dorsolateral prefrontal cortex and anterior cingulate cortex (Landry et al., 2017; Picerni et al., 2019). In line with these findings, highs showed lower interoceptive accuracy compared to lows, as indicated by their lower scores on the heartbeat counting task (Rosati et al., 2021) and lower amplitudes of earlier component of heartbeat-evoked cortical potentials (Callara et al., 2023). On the other hand, highs' self-reports revealed more adaptive interoceptive sensitivity (Diolaiuti et al., 2020), potentially suggesting hypnotizability-related differences in different phases of processing of interoceptive signals.

As mediums, who represent most of the general population (De Pascalis et al., 2000; Elkins et al., 2015), were not included in the previous study of hypnotizability-related differences in HEP (Callara et al., 2023), the first aim of our study was to analyze the differences in HEP between highs, mediums, and lows during a long-lasting baseline condition. In addition, we aimed to assess the same difference during a heartbeat counting task and to study the relation between interoceptive accuracy, measured by the heartbeat counting test, and HEP in the three groups of participants.

2 | METHODS

2.1 | Participants

An a priori power analysis conducted using G*Power 3.1 software (Faul et al., 2009) showed that the minimum number of participants to achieve 90% statistical power for a 3 groups × 4 conditions mixed ANOVA (Part 2) with $\alpha = .05$ and $\eta^2 = 0.25$ (Callara et al., 2023) was 45 (15 participants per group). Following the approval of the Bioethics

Committee of the University of Pisa (N. 43/2022), 108 volunteers among students at the University of Pisa were invited for the assessment of their hypnotizability level by an Italian version of the Stanford Hypnotic Susceptibility Scale: Form A (SHSS: A, Weitzenhoffer & Hilgard, 1959). The scale allowed us to score the participants' responsiveness to hypnotic suggestions (from 0 to 12 points) and to classify them into groups of lows (0–4 points), mediums (5–7 points), and highs (8–12 points). Among them, 20 lows, 15 mediums, and 15 highs agreed to participate in further experiments. Due to technical problems with EEG or ECG recordings, two lows, one medium, and one high were excluded from further analyses. The final sample (see Table 1) consisted of 18 lows (12 females, 6 males), 14 mediums (6 females, 8 males), and 14 highs (8 females, 6 males). Except for three highs, none of the other participants had previous experience with meditation or hypnosis.

2.2 | Experimental procedure

Prior to the beginning of the experiments, participants filled-in two self-report questionnaires, namely the Italian versions of the State–Trait Anxiety Inventory, Form Y1 (STAI-Y1; Pedrabissi & Santinello, 1989; Spielberger et al., 1983) and the Tellegen Absorption Scale (TAS; Tellegen & Atkinson, 1974). The STAI-Y1 consists of 20 items scored on a 4-point scale (total score range: 20–80) and measures state anxiety. Its internal consistency was excellent (Cronbach's $\alpha = .91$). The TAS consists of 34 items scored on a dichotomous scale (total score range: 0–34) and measures individual's tendency to become absorbed in various sensory or imaginative experiences. Its internal consistency was good (Cronbach's $\alpha = .89$). Mean values of STAI-Y1 and TAS total scores are shown in Table 1.

The experiments were held in a sound- and light-controlled room with a stable temperature of 22°C and were conducted in the afternoon, between 12 and 5 p.m. Participants were not allowed to eat or drink coffee for at least 3 h before the experimental session or to drink alcohol for at least 24 hours before the session. At the beginning of the session, they were asked to sit in an armchair that provided support for their legs, arms, and head. Then, the experimental procedure was explained, followed by placement of the EEG and ECG electrodes. Each experimental session was divided into two parts (*Part 1*, *Part 2*), separated by a two-minute pause during which the participants were informed about the following part of the study and were allowed to talk with the experimenter. EEG and ECG were recorded throughout the entire session.

Part 1 consisted of a single baseline condition of awake rest with open eyes, lasting for 10 minutes. Participants were instructed to remain still in a comfortable position and look in front of themselves. After the initial explanation of the procedure, participants were given no further instructions other than to indicate the beginning and the end of the session.

Part 2 consisted of three consecutive conditions of open eyes rest (OE, 2 min), closed eyes rest (CE, 2 min), and closed eyes heartbeat counting (HCT, 2 min), which were repeated three times (T1, T2, T3) and were then followed by a single post-counting open eyes condition (POST, 2 min). Participants were instructed to count their heartbeats as they feel them within their bodies, without touching their arteries or using other similar strategies. During the session, researcher indicated the beginning and the end of every condition. After each counting condition, participants were instructed to report the number of the counted heartbeats. At the end of the session, participants were also asked to rate the level of attention they were paying to their heartbeats on an 11-point scale (score range: 0–10).

2.3 | Data acquisition and analysis

EEG and ECG data were acquired using a g.tec wireless Nautilus system. EEG electrodes were placed in 28 locations on the scalp according to a modified 10–10 international system (FP1, FP2, AF3, AF4, F7, F3, Fz, F4, F8, C3, FC1, FC2, C4, T7, Cz, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, Oz) and were all referenced to Cz. Two additional electrodes were positioned above the left orbital

TABLE 1 Study sample demographics and questionnaire scores.

Variable	Lows (18)		Mediums (14)		Highs (14)		Combined (46)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	23.28	2.32	24.79	3.85	25.64	4.57	24.46	3.66
SHSS: A score[a]	1.11	1.57	6.14	0.77	9.71	1.33	5.26	3.86
STAI-Y1	36.78	9.03	33.43	6.81	35.71	10.59	35.43	8.87
TAS[a]	16.56	6.27	22.00	6.42	22.00	8.50	19.87	7.41

[a]Indicates significant group differences.

ridge and close to the left lateral canthus to record eye movements, and two more electrodes were placed below left and right clavicle to record ECG signals. Impedance of all electrodes was measured prior to the recording session and was considered acceptable when below 30 kΩ. To reduce possible line noise, a notch filter set at frequency of 50 Hz was applied during the recording.

EEG signals were preprocessed in MATLAB 2022b (The Math Works, Inc, 2022), using EEGLAB toolbox (Delorme & Makeig, 2004). Firstly, a low-pass filter of 45 Hz was applied, followed by a high-pass filter of 0.5 Hz. Data were then visually inspected to identify bad channels and other large muscle or eye movement artifacts. Bad channels were interpolated by a spherical method, and large artifacts were manually removed. Next, independent component analysis (ICA, Makeig et al., 1995) was performed, allowing us to identify components of the recorded signals, which were not related to brain activity, but rather muscular, ocular, cardiac, or other artifacts. Such components were distinguished by the examination of their scalp maps, time course, and activity power spectrum. After artifact components were subtracted from the data, we reconstructed the electrode signals using only brain-related components.

Cleaned EEG signals underwent further processing to extract HEPs. First, R peaks were detected from ECG signals using Pan–Tompkins' algorithm (Pan & Tompkins, 1985). Peak detection artifacts were identified through visual inspection and manually corrected by an expert. R peaks were then used to synchronize the EEG signal analysis to heartbeats. Particularly, for each subject, for each experiment, and for each experimental condition (i.e., OE rest, CE rest, HCT, and post-HCT), we obtained a set of heartbeat-locked epochs from which we extracted single-subject HEPs. Epochs were covered from −200 to 600 ms around R peak, and each epoch was baseline-corrected by removing the average in the range from −200 to 0 ms before each R peak.

2.4 | Variables

Variables used are as follows: state anxiety (STAI-Y1), absorption (TAS), heartbeats number, interoceptive accuracy (IA), HEP, and attention paid to the counting task.

2.5 | Statistical analysis

Hypnotizability group differences in age, STAI-Y1, and TAS were analyzed using one-way ANOVA tests, followed by post-hoc t tests where applicable.

Part 1. Hypnotizability group differences in the number of heartbeats and the HEP amplitudes were analyzed using one-way ANOVA tests. For the latter, we implemented a permutation–bootstrap approach (with n = 2000 permutations), followed by cluster correction ($\alpha = .05$) to test for significant differences between groups (Oostenveld et al., 2011). Operationally, we used the Factorial Mass Univariate Toolbox (FMUT, Fields & Kuperberg, 2020). Tests were performed for each channel and for each time point in the range (200–600) ms in the epoch. Post-hoc analyses were carried out by means of unpaired t tests, followed by Bonferroni's correction. Of note, we voluntarily excluded the (0–200) ms range to limit the influence of potential residual cardiac artifacts on EEG epochs. This analysis allowed to identify the clusters (i.e., channels and time intervals) for which there were significant differences in HEP amplitudes for each main effect (i.e., conditions and groups) and for their interaction. Finally, for each of these clusters we extracted the mean HEP amplitude within the cluster to study the correlation with SHSS: A scores.

Part 2. Differences in the number of heartbeats were analyzed by a 4 conditions × 3 hypnotizability groups mixed ANOVA, with all trials (T1, T2, T3) averaged. Interoceptive accuracy was calculated for each separate counting trial, according to the following formula, and then averaged to obtain a total score.

$$IA = 1 - \left(\frac{\left| heartbeats_{recorded} - heartbeats_{count} \right|}{heartbeats_{recorded}} \right)$$

Hypnotizability group differences in interoceptive accuracy were assessed using one-way ANOVA test, followed by ANCOVA controlling for attention and STAI-Y1. Hypnotizability group differences in attention paid to the heartbeats were also assessed using one-way ANOVA, whereas the relationships between interoceptive accuracy, SHSS: A scores, and attention were analyzed using Pearson's correlations. Differences in the HEP amplitude were also analyzed with a 4 × 3 mixed ANOVA with condition (i.e., OE rest, CE rest, HCT, and post-HCT) as within-subject factor and group (i.e., highs, mediums, and lows) as between-subject factor. Particularly, condition and group main effects and interaction were tested. As for *Part 1*, the latter analysis was carried out using FMUT and by implementing a permutation–bootstrap analysis followed by cluster correction ($\alpha = .05$) (Fields & Kuperberg, 2020; Oostenveld et al., 2011). Post-hoc analyses were carried out by means of paired t tests for condition main effect, unpaired t tests for group main effect, and paired (for within factor) and unpaired (for between factor) t tests for interaction effect. Furthermore, mean amplitude value was calculated for an interval of significant HEP differences between hypnotizability groups and then correlated with SHSS: A scores and interoceptive accuracy.

A significance level of $\alpha = .05$ was used for all tests. When necessary, Greenhouse–Geisser ε and Bonferroni's corrections were applied.

3 | RESULTS

The hypnotizability groups did not differ in age ($F(2, 43) = 1.79$, $p = .179$) and state anxiety ($F(2, 43) = 0.56$, $p = .575$), but showed different absorption abilities ($F(2, 43) = 3.26$, $p = .048$), although post-hoc comparisons did not reveal any significant difference between groups.

In the following, all the EEG results correspond to significant clusters (i.e., electrodes and time intervals) for which a significant difference in HEP was observed (i.e., condition or group main effect or interaction).

3.1 | Part 1

The hypnotizability groups did not differ in the number of actual heartbeats during the baseline condition ($F(2, 43) = 1.00$, $p = .374$). The HEP amplitude was significantly different between hypnotizability groups in C4 (Figure 1a) in the time windows from 224 to 354 ms ($p = .009$) and from 490 to 548 ms ($p = .028$; for F statistics, see Table S1). Post-hoc comparisons of the groups showed significant differences between highs and lows in the time windows from 228 to 254 ms, from 306 to 354 ms, and from 490 to 548 ms; significant differences between mediums and lows in the time windows from 224 to 328 ms and from 498 to 534; and no differences between mediums and highs (for t statistics, see Table S2). However, there were significant negative correlations of the mean HEP amplitude in C4 at $t_{224\text{-}354}$ and $t_{490\text{-}548}$ with SHSS: A scores (Figure 1b; $t_{224\text{-}354}$: $r = -.47$, $p < .001$; $t_{490\text{-}548}$, $r = -.48$, $p < .001$), which also remained significant after controlling for STAI-Y1 and for the number of heartbeats. Additionally, mean HEP values for earlier ($t_{224\text{-}354}$) and later ($t_{490\text{-}548}$) intervals were highly correlated ($r = .81$, $p < .001$) and the correlation remained significant after controlling for SHSS: A scores.

3.2 | Part 2

In Table 2, we report the number of actual heartbeats during the second part of the experiment, which was similar in the three groups, but different among conditions ($F(3,129) = 9.73$, $p < .001$, $\eta^2 = .185$, $1\text{-}\beta = 1.00$). Post-hoc t tests revealed that the number of heartbeats was significantly higher in OE compared to CE condition (OE > CE: $t(45) = 3.40$, $p < .001$) and in POST compared to CE and HCT conditions (POST > CE: $t(45) = 4.70$, $p < .001$, POST > HCT: $t(45) = 3.61$, $p < .001$). The attention paid to the heartbeats count was significantly different among groups ($F(2, 43) = 4.81$, $p = .013$, $\eta^2 = .183$, $1\text{-}\beta = .769$)

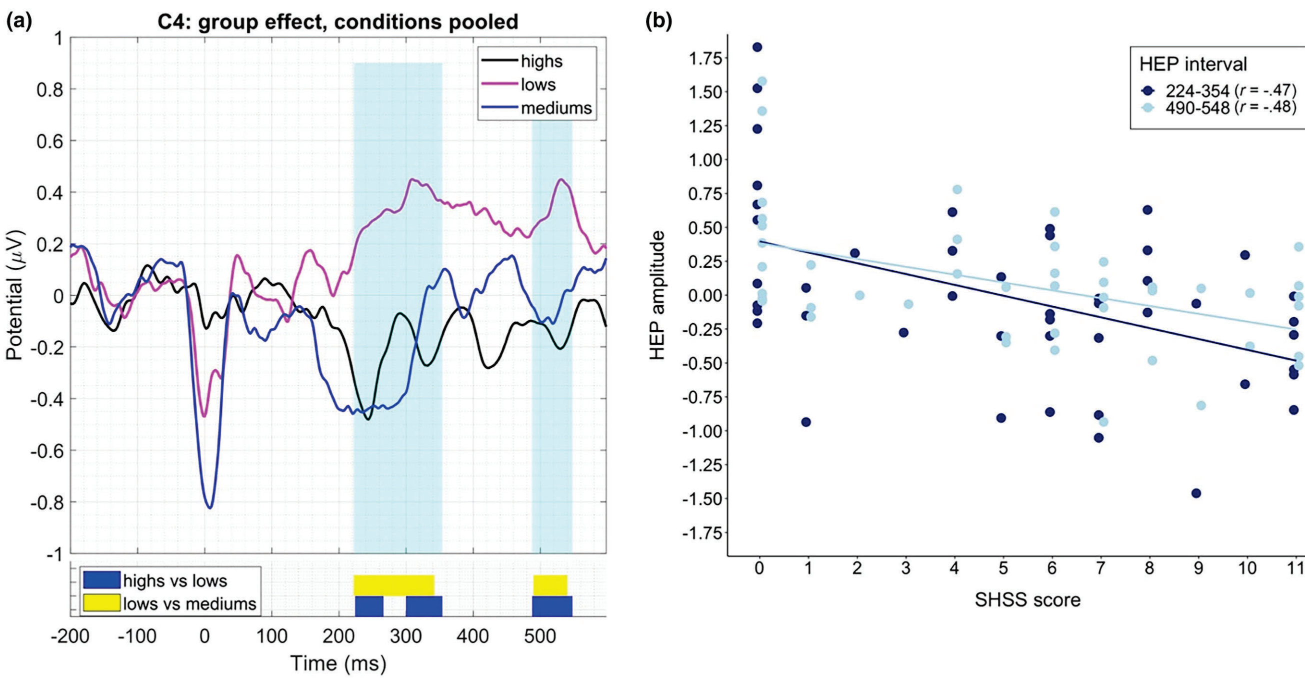

FIGURE 1 Heartbeat-evoked cortical potentials during long-lasting rest. (a) Hypnotizability group differences in HEP: Cyan vertical bars indicate the time intervals showing significant group differences based on the one-way ANOVA; blue and yellow horizontal bars below the plot indicate the time intervals for which highs versus lows and lows versus mediums post-hoc comparisons were significant, respectively. (b) Distribution of mean HEP amplitudes at $t_{224\text{-}354}$ and $t_{490\text{-}548}$ as a function of hypnotizability scores (SHSS: A).

TABLE 2 Mean number of actual heartbeats in different groups and conditions (2 min).

	Lows		Mediums		Highs		Combined	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
OE	147.31	21.16	138.76	20.27	145.17	19.75	144.06	20.34
CE	144.00	20.58	134.60	21.13	144.52	21.13	141.30	20.93
HCT	144.85	19.31	136.93	21.05	142.83	21.68	141.83	20.40
POST	149.22	22.80	139.79	20.88	147.64	20.95	145.87	21.59

with the highs' score (9.50 ± 1.23) higher than lows' score (7.44 ± 2.43; $p = .012$), whereas mediums exhibited intermediate scores (8.00 ± 1.62), not significantly different from both highs and lows.

3.3 | Interoceptive accuracy

No significant difference between hypnotizability groups was observed in mean IA (Figure 2b), and no difference appeared controlling for STAI-Y1 and for the attention paid to the task. The results also showed no significant group differences in the three consecutive counting trials (Figure 2a). Correlation analysis, however, showed that hypnotizability was negatively correlated with IA, although only in the first trial ($r = -.31$, $p = .035$). Furthermore, the correlation analysis revealed no significant association between mean IA and the attention paid to the task ($r = .23$, $p = .122$), which, however, became significant after controlling for SHSS: A score ($r = .32$, $p = .032$). A significant correlation between mean IA and attention could only be observed in lows ($r = .60$, $p = .009$), but not in mediums and highs.

3.4 | Heartbeat-evoked cortical potential

A significant group effect was observed for the HEP amplitude in C4 (Figure 3a) in the time window from 230 to 310 ms ($p = .035$; for F statistics, see Table S3). The HEP consisted of a positive deflection only in lows who exhibited larger HEP amplitude than mediums in the time window from 234 to 312 and larger HEP than highs in the time window from 230 to 260 ms (for t statistics, see Table S4). A significant negative correlation was found, however, between SHSS: A score and mean HEP amplitude in C4 at $t_{230\text{-}310}$ (Figure 3b; $r = -.40$, $p = .006$), which remained significant even after controlling for attention paid to the task, STAI, and the number of the heartbeats. No significant correlation was found between IA and mean $HEP_{230\text{-}310}$ ($r = .01$, $p = .940$), neither after controlling for STAI-Y1 and TAS scores.

A significant group × condition interaction was observed for HEP amplitude in F8 (262–308) and T8 (252–296 ms), in the earlier HEP component, and in FC1 (508–538 ms), Fz (494–546 ms), and F3 (510–544 ms), in the later HEP component (for F statistics, see Table S5). Post-hoc analysis between groups and contrast analysis between conditions in each group are shown in Table 3 (for t statistics, see Table S6). In both highs and lows, the HEP amplitude during the counting task did not differ from earlier conditions (OE, CE).

Only mediums exhibited significant differences between the counting task and earlier conditions (Figure 4). They consist of a larger peak in Fz, F3, and FC1 at the later interval during count with respect to OE/CE.

4 | DISCUSSION

The results of the *first part* of the study confirmed the previously observed amplitude difference between highs and lows in the earlier HEP component (Callara et al., 2023), although in the present study the difference was found in central rather than parietal right hemisphere regions, as expected (Coll et al., 2021). This may be due to the different conditions studied in the earlier paper, namely wakefulness, hypnotic induction, and hypnosis (Callara et al., 2023), which involve both frontal and parietal regions (Landry et al., 2017). In contrast, the present study was conducted in the absence of hypnotic induction and specific suggestions. Moreover, the longer duration of the resting condition in the presence of similar state anxiety scores and the absence of any instructions might better reflect the baseline differences in processing of cardiac information in the three hypnotizability groups. The HEP central localization, in fact, is in line with other reports indicating the right fronto-central regions as the brain areas most involved in the elaboration of cardiac signals (Coll et al., 2021).

A novelty arisen from the present study is that the HEP amplitudes of mediums' earlier and later HEP components were similar to those of highs, but significantly different from those of lows. Thus, the processing of the cardiac interoceptive signals of lows, but not highs, seems to differ from the interoceptive processing observed in the general population, which is represented by mediums (De Pascalis et al., 2000). As morpho-functional differences in

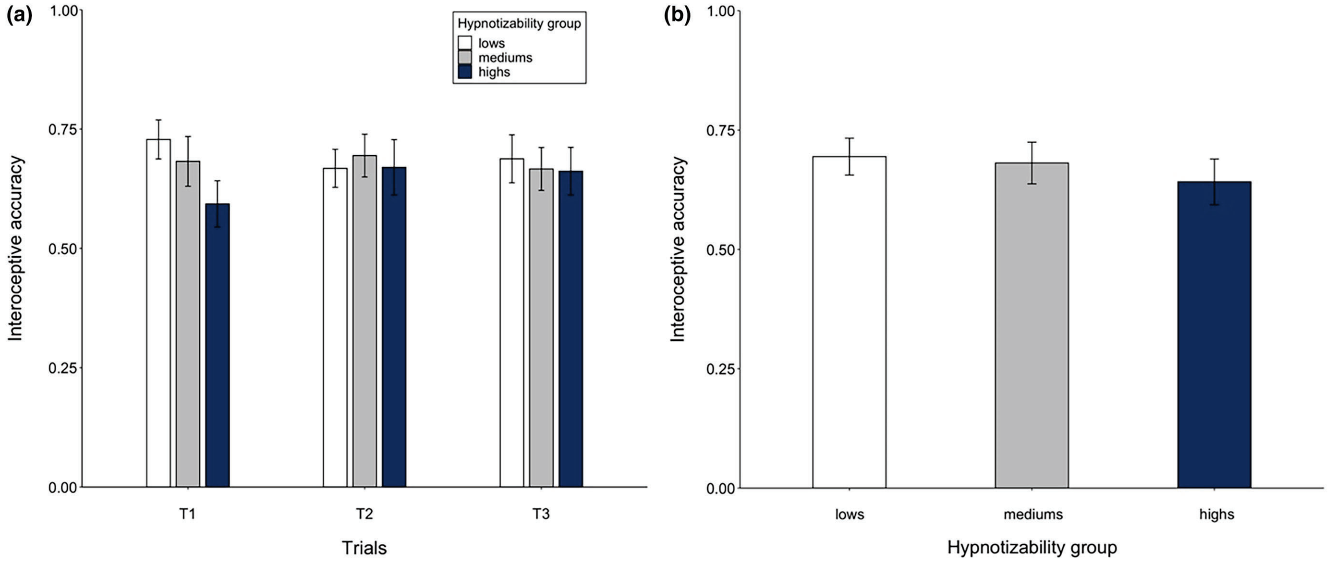

FIGURE 2 Cardiac interoceptive accuracy in the consecutive trials (a) and averaged across trials (b).

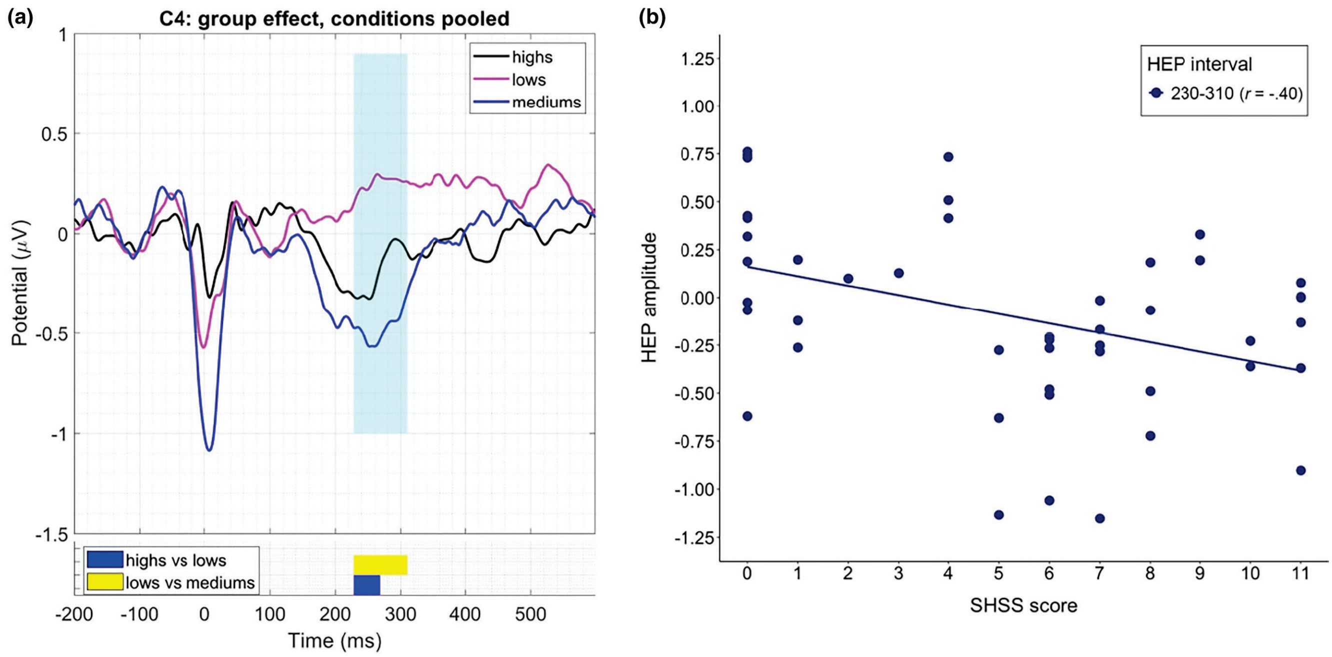

FIGURE 3 Heartbeat-evoked cortical potentials group main effect (i.e., conditions pooled across T1, T2, and T3, and across OE, CE, HCT, and POST). (a) Hypnotizability group differences in HEP: Cyan vertical bars indicate the time intervals showing significant group differences based on the mixed ANOVA; blue and yellow horizontal bars below the plot indicate the time intervals for which highs versus lows and lows versus mediums post-hoc comparisons were significant, respectively. (b) Distribution of mean HEP amplitudes at $t_{230\text{-}310}$ as a function of hypnotizability scores (SHSS: A).

interoceptive circuits, that is, the insula, have been studied only in highs and lows, with the former showing reduced gray matter volume in the insula with respect to the latter (Landry et al., 2017; Picerni et al., 2019), it is difficult to draw conclusions about the possible neurophysiological determinants of lower HEP amplitudes in mediums. Also, the activity of the default mode network has only been studied in highs and lows (Landry et al., 2017), which does not serve to predict the differences in the activity and functional connections of the insula in mediums during rest. Previous research that included mediums, for example, showed that they were sometimes found to be intermediate between highs and lows, although not significantly – that is, in interoceptive accuracy during the first trial of

TABLE 3 Significant HEP amplitude differences between groups and conditions.

Electrode	Condition	Highs	Mediums
Fz	POST: highs > lows (514–526 ms)	HCT < POST (506–534 ms)	CE < HCT (494–506, 526–536 ms)
		CE < POST (518–520 ms)	OE < HCT (494–518 ms)
		OE < POST (514–530 ms)	
FC1		HCT < POST (508–524 ms)	CE < HCT (508 ms)
		OE < POST (512–522 ms)	OE < HCT (508–530 ms)
F3	POST: highs > lows (512–534 ms)	HCT < POST (512–522 ms)	CE < HCT (530 ms)
		OE < POST (514–522 ms)	

Note: All significant differences were observed in later HEP intervals. No post-hoc test was significant in lows. The group × condition interaction decomposition at F8 is not shown due to the lack of significant post-hoc comparisons. The decomposition of interaction at T8 is not shown due to very short intervals of significant differences.

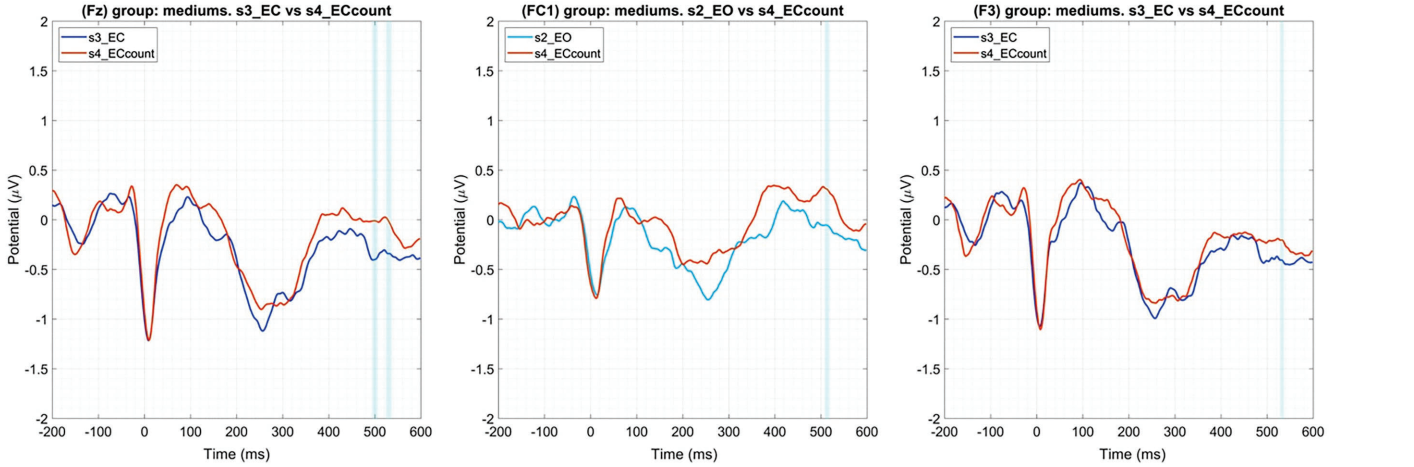

FIGURE 4 HEP differences between counting task and earlier (OE, CE) conditions (pooled across T1, T2, and T3) in mediums.

the heartbeat counting task (Rosati et al., 2021) and right motor cortex excitability at rest and during motor imagery (Spina et al., 2020) – sometimes similar to lows – that is, in a few scales of the Multidimensional Assessment of Interoceptive Awareness (Diolaiuti et al., 2020) – and sometimes significantly different from both highs and lows – that is, in the greater tendency to avoid potentially unpleasant situations (Diolaiuti et al., 2020). Therefore, in the future studies of hypnotizability, mediums should always be enrolled (Jensen et al., 2017).

The findings of the *second part* of the study addressed the role of attention to cardiac signals in their cortical elaboration. The lower number of actual heartbeats during counting with respect to the two open eyes conditions (OE, POST) could be simply accounted for by eye closure. However, the influence of attention itself cannot be excluded, as heart rate deceleration is a correlate of attention (Jennings, 1986; Porges, 1992).

In contrast to Part 1, in which hypnotizability-related differences were observed in the central region in both the earlier and later HEP components, in Part 2 the hypnotizability-related differences in the central region were only significant in the earlier HEP component. The absence of group differences in the later HEP component in Part 2 may be accounted for by the additional conditions included compared to Part 1, which introduced changes in sensory information (closed eyes) and a cognitive task (heartbeat counting). Nevertheless, in both parts of the study the earlier HEP component was marked by lows' positive peaks and negative deflections in highs and mediums. As there were no group differences in the number of actual heartbeats, it is also reasonable to conclude that the observed group differences in HEP did not depend on different cardiac activity. Furthermore, it is noteworthy that the correlation between hypnotizability and mean HEP amplitudes survived controlling for the attention paid to the task, STAI-Y1, and TAS scores, indicating a reliable association between the two measures.

Despite the similar interoceptive accuracy of highs and mediums (present study; Rosati et al., 2021), earlier findings indicated different interoceptive sensitivity in highs with respect to both mediums and lows (Diolaiuti et al., 2020) in that the differences in a few dimensions of the Multidimensional Assessment of Interoceptive Awareness (Mehling et al., 2012) indicated a different mode of cognitive–emotional elaboration of visceral signals. In this respect, the late

HEP component might not reflect the self-reported interoceptive sensitivity (Diolaiuti et al., 2020). It should be noted, however, that the different sensitivity of highs with respect to mediums and lows could be better indicated by instruments different from the Multidimensional Assessment of Interoceptive Awareness (Mehling et al., 2012). For instance, the Body Perception Questionnaire (Cabrera et al., 2018; Porges, 1993) provides a synthetic measure of sensitivity to supra- and subdiaphragmatic interoceptive information, which might be better associated with HEP amplitudes.

Furthermore, decomposition of the interaction observed between hypnotizability groups and conditions (Part 2) in left/medial frontal regions (Fz, Fc1, F3) in the later HEP component revealed significant differences between counting and the preceding resting conditions only in mediums. The absence of differences in lows could occur due to their lower task engagement and/or low ability to maintain stable attention (Tellegen & Atkinson, 1974), as attention has been found to increase the HEP amplitude (Coll et al., 2021). Indeed, lows reported paying the least attention to their heartbeats. Highs, on the other hand, reported paying greater attention than lows, but may not have been able to exhibit changes in the HEP owing to their peculiar mode of cognitive processing, which is scarcely networked so that EEG modifications are possibly not detectable through spatially focused analyses (Ibáñez-Marcelo et al., 2019). Nonetheless, the relationship between interoceptive accuracy and attention was found to be significant only in lows. This discrepancy could be explained, on the one hand, by the lows' higher variability of self-reported attention and, on the other hand, by the questionable validity of the heartbeat counting task (Desmedt et al., 2018; Pollatos et al., 2009; Ring et al., 2015; Vig et al., 2021), which was not found to correlate with HEP in the present study.

It is noticeable, however, that there were significant differences between lows and highs in their HEP amplitude after the counting task. This might be considered together with other authors' reports (García-Cordero et al., 2017), which indicated the post-counting condition as learned interoception (with respect to basal conditions) and showed that in the general population the functional connectivity between frontal and posterior regions observed was stronger after a counting task. From this perspective, the highs' larger HEP in POST than during the counting task may indicate learning effects, which are absent in lows and mediums. The same may be hypothesized for the highs' trend to improve their interoceptive accuracy from the first to the second heartbeat counting trial. If confirmed by further studies, this would represent a difference between the interoceptive and exteroceptive learning. It is absent in the highs' postural and visuomotor control during sensory alteration (Menzocchi et al., 2015; Santarcangelo et al., 2008), but apparently present in highs for interoceptive information. One might wonder whether this could be relevant to possible hypnotizability-related differences in the construction of consciousness.

5 | LIMITATIONS

A larger sample with a more representative distribution of the SHSS: A scores might reveal further differences between mediums and highs, which were not observed in the present study. Also, the assessment of interoceptive sensitivity by BPQ might have improved the interpretation of results. Furthermore, gender, which has been previously reported to be associated with interoception (Grabauskaitė et al., 2017), was not included as a variable in our study design in order to achieve a sufficient statistical power. Because the number of males and females in different hypnotizability groups varied, this may have partially influenced the results, as males generally show higher interoceptive accuracy.

Another potential limitation of our study could derive from the fact that EEG preprocessing relied on visual inspection of EEG epochs and independent components. Particularly, the risk is to introduce experimenter's subjective bias into the analysis. Indeed, although such a procedure is a common practice in the literature (see, e.g., Billeci et al., 2023; Loo et al., 2019; Makeig & Onton, 2011; Urigüen & Garcia-Zapirain, 2015), automatic procedures aiming at reducing such risks have been proposed (e.g., Bigdely-Shamlo et al., 2015; Gabard-Durnam et al., 2018; Nolan et al., 2010). In this light, although visual inspection was performed by experts, future studies could consider the use of automatic methods in the preprocessing pipeline.

6 | CONCLUSIONS

During a long-lasting resting state, lows showed higher positive amplitudes in central regions in both earlier and later HEP components compared to mediums and highs, which is in line with the previously observed lower insular gray matter volume of highs compared to lows (Landry et al., 2017; Picerni et al., 2019). The HEP amplitude of mediums did not significantly differ from that of highs, thus indicating similar interoceptive processing in highs and the general population (De Pascalis et al., 2000).

The counting task revealed an interaction between experimental conditions and hypnotizability groups in frontal regions, with significant differences between counting and the preceding resting conditions in mediums and significant differences between post-counting and preceding conditions in highs. The former finding might indicate the diverse effect of attention on interoceptive processing in the three hypnotizability groups, while the later finding might be related to different mechanisms of interoceptive learning among them (García-Cordero et al., 2017).

To conclude, our study provides a novel insight into the interoceptive abilities of mediums, the hypnotizability-related differences in the role of attention in the elaboration of interoceptive signals, and the hypnotizability-related differences in interoceptive learning. As interoception disturbances present a risk factor for various psychopathologies (Khalsa et al., 2018), our findings further emphasize the relevance of hypnotizability assessment in clinical work and development of personalized interoceptive trainings (Zelič et al., 2023).

Further studies should validate the position of mediums as similar to highs in the processing of interoceptive signals (e.g., by neuroimaging), assess the effectiveness of hypnotizability-based interventions, aimed at improving interoception, and address possible hypnotizability-related differences in the involvement of interoception in higher cognitive functions. Furthermore, as different interoceptive abilities related to the signals from cardiac, respiratory, gastrointestinal, and urinary systems can be observed in the same individuals (Murphy et al., 2017), the next research challenge may be to describe comprehensive individual interoceptive profiles and their specific relationships with emotion and cognition.

AUTHOR CONTRIBUTIONS

Gioia Giusti: Data curation; investigation; writing – original draft. **Žan Zelič:** Data curation; formal analysis; investigation; writing – original draft; writing – review and editing. **Alejandro Luis Callara:** Formal analysis; funding acquisition; methodology; writing – original draft; writing – review and editing. **Laura Sebastiani:** Funding acquisition; supervision; writing – original draft; writing – review and editing. **Enrica L. Santarcangelo:** Conceptualization; formal analysis; funding acquisition; methodology; supervision; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. ANOVA comparisons of HEP amplitudes in hypnotizability groups during Part 1 (*F* statistics and adjusted *p* values).

Table S2. Post-hoc comparisons of HEP amplitudes in hypnotizability groups at C4 during Part 1 (*t* statistics and adjusted *p* values).

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Table S3. ANOVA hypnotizability group main effects for the HEP amplitudes during Part 2 (*F* statistics and adjusted *p* values).
Table S4. Post-hoc comparisons of HEP amplitudes in hypnotizability groups at C4 during Part 2 (*t* statistics and adjusted *p* values).
Table S5. ANOVA hypnotizability group × condition interactions for HEP amplitudes during Part 2 (*F* statistics and adjusted *p* values).
Table S6. Decompositions of hypnotizability group × condition interactions for HEP amplitudes during Part 2 (*t* statistics and adjusted *p* values).

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