No Gender Difference in Cardiac Interoceptive Accuracy: Potential Psychophysiological Contributors in Heartbeat Counting Task

Running title: Gender Difference in Cardiac Interoception

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Abstract

Gender differences in interoceptive awareness—awareness of internal bodily signals such as heartbeat perception—have been suggested, with some findings indicating behaviourally reduced but subjectively enhanced awareness in women, though these findings are still contentious. This study aimed to comprehensively examine gender differences in three aspects of interoceptive awareness: behavioural accuracy, subjective confidence, and relationship between them (i.e., metacognition). We used a modified heartbeat counting task that prohibited estimation strategies and increased the number of trials up to 20. Using data from 74 healthy young adults (39 women and 35 men), we evaluated gender differences and practice effects for each measure via Bayesian linear mixed models, controlling for individual heart rate and trial duration on a trial-by-trial basis. Contrary to previous research, the results revealed no reduced interoceptive accuracy in women; instead, higher interoceptive accuracy score was associated with shorter trial durations and lower heart rates regardless of gender. Moreover, women exhibited underconfidence about their performance, and therefore lower metacognition scores, compared to men. Trial repetitions moderated women's lowered metacognition but did not affect accuracy or confidence. These findings highlight potential physiological and psychological confounding factors in the heartbeat counting task, such as heart rate and reporting style, and emphasize several cautions for studying gender differences in interoceptive awareness.

Keywords: interoceptive awareness, gender difference, interoceptive accuracy, metacognition, heartbeat counting task

Background

Interoception refers to the processes involved in sensing, integrating, and interpreting internal bodily states. As a fundamental aspect of human cognition, interoceptive awareness—or the subjective experience of interoceptive signals, such as heart contractions or digestive processes—plays a critical role in shaping our emotions, decision-making, and bodily self [1–4]. Consequently, individual differences in interoceptive awareness have garnered significant interest in relation to cognitive abilities and mental health conditions [5, 6]. Recent studies have particularly highlighted the importance of gender[1] differences in interoceptive awareness [7, 8], as these disparities could potentially explain a range of gender-specific health outcomes and psychopathological manifestations. The present study aims to comprehensively investigate gender differences in cardiac interoceptive awareness, or heartbeat perception, which remains a subject of controversy.

Previous research has depicted a complex picture regarding gender differences in interoceptive awareness. For example, women tend to exhibit a more sensitive response to experimentally induced pain, interoceptive awareness regarding nociceptive sensations, compared to men [9, 10]. Women's hypersensitivity is related to both pain threshold and intensity reporting [11–13], but see [14] for a null result. These gender differences may align with the higher incidence of mental health disorders involving alterations in bodily awareness in women [15, 16]. Notably, interoceptive somatic complaints including nausea, headache, and dizziness are more prevalent in women than in men [17–19]. Such manifestations often rely on misinterpretations or amplifications of actual bodily sensations, presumably associated with atypical interoceptive awareness [20, 21].

When considering more neutral interoceptive awareness, rather than affective, it has been discussed if women exhibit reduced behavioural interoceptive accuracy or sensitivity—the perceptual ability to detect one's own interoceptive signals. Some studies have revealed men's superiority in interoceptive accuracy across several bodily signals, including cardiac, respiratory, and gastric sensations in laboratory settings [22–24], while others have collaterally indicated no gender difference in such ability [25–29]. Two recent meta-analyses revealed a

[1] Throughout this paper, we use the term "gender" rather than "sex," except when referring specifically to purely biological or physiological distinctions between sexes. Similarly, we refer to "men" and "women" in general discussions but use "males" and "females" when addressing purely biological or physiological aspects. This distinction reflects the multi-dimensional nature of interoceptive awareness, which integrates psychological factors such as emotional states and individual dispositions alongside physiological processes.

weak but statistically significant decline in women's cardiac interoceptive accuracy [30, 31], suggesting a gender difference in interoceptive accuracy regarding visceral sensations when averaged across a large population. As outlined, there are conflicting findings regarding gender differences between affective and non-affective interoceptive awareness, leading to speculation that while women are more subjectively attuned to their interoceptive signals when affective, they may also be more prone to misinterpreting them. This dichotomy raises intriguing questions about gender differences in interoceptive metacognition—the metacognitive ability to monitor one's own perceptual skill regarding interoception [32].

Notably, gender differences in cardiac interoceptive awareness—the most frequently used paradigm in human interoception research—have not been tested across interoceptive accuracy, subjective confidence in task performance, and metacognitive ability as proposed in [32]. A multidimensional examination is necessary because previous studies have typically used the heartbeat counting task to investigate individual and gender differences in interoceptive awareness, primarily focusing on its accuracy aspect [22, 33, 34]. Recent criticism indicated that this task suffers from estimation bias and knowledge about the number of heartbeats [35, 36]. Therefore, in the present study, we employed a modified version of the heartbeat counting task that explicitly prohibits estimation strategies [27, 37]. Additionally, we increased the number of trials from typically four or six up to twenty. By doing so, we assessed individual interoceptive accuracy, confidence in performance, and metacognitive ability in a trial-by-trial manner, allowing us to test gender differences in each variable. Increasing the number of trials also enabled us to test the practice effect of heartbeat detection and to rule out changes in individual heart rate as a covariate, which had not been previously considered.

We primarily hypothesized that women will exhibit lower interoceptive accuracy compared to men, as previous studies have suggested [7, 8, 31]. It was also expected that women may demonstrate under- or over-confidence about their interoceptive accuracy as they exhibit subjectively enhanced but behaviourally decreased interoceptive awareness, leading to decreased metacognition [32]. However, null results were also anticipated, as recent findings using the Phase Adjustment Task suggest partial superiority of women in interoceptive accuracy [38], while no gender differences in interoceptive accuracy or metacognition were observed in the respiratory domain [39].

Methods

Participants

A total of 78 healthy volunteers (41 women, 37 men) took part in the experiment. All were undergraduate students at Hokkaido University and were physically and mentally healthy, with no history of diagnosed mental health disorders (e.g., anxiety, depression) or chronic physical conditions (e.g., cardiovascular disease). Participants also confirmed that they were not taking any medications that might affect physiological or psychological functioning. These criteria were implemented to minimise potential confounding factors, as mental and physical health conditions are known to influence interoceptive processes and physiological states [20]. They received a 1000 Japanese yen Amazon gift card for their participation in the one-hour experiment. One man could not perceive any heartbeat throughout twenty trials, and was therefore excluded from further analysis. Another man and three women were excluded from our statistical analysis due to noisy physiological recordings in some trials, which made it impossible to calculate their heart rates correctly. Therefore, our final sample consisted of 74 participants (39 women, 35 men), with an average age of 20.16±1.51 years. While results of prior meta-analyses imply larger sample sizes needed (e.g., more than 210) to robustly detect subtle gender differences in interoceptive accuracy [30, 31], our sample size was reasonable to explore medium-to-large effects within the practical and ethical constraints of this study. Specifically, a power analysis indicated that 34 participants per group is sufficient to detect an effect size of $d = 0.7$ with 80% power and a significance level of $\alpha = 0.05$. Written informed consent was obtained from all participants. This study was carried out in accordance with the Declaration of Helsinki and its amendments. The Ethics Committee of Hokkaido University approved the experimental protocol.

Heartbeat counting task

We used the heartbeat counting task to assess participants' interoceptive accuracy (the perceptual ability to detect internal bodily sensations), confidence (subjective confidence in interoceptive accuracy), and metacognition (metacognitive ability regarding their interoceptive accuracy). Pulse oximetry (IWS920, Tokyo Devices) was placed on the left index finger of participants to record each heartbeat. Participants sat in a comfortable chair with their arms on the desk in front of them and were instructed not to lean against a backrest. We asked participants to adjust their posture and the location of the apparatus to avoid feeling a bloodstream or pulse externally (i.e., outside of their body), as such pulsations can be detected in fingertips when using a pulse oximetry, potentially inflating interoceptive accuracy scores [40]. A monitor and mouse were placed on the desk for participants to respond during the task.

In each trial, participants silently counted the number of heartbeats that occurred in a given duration (15 s, 25 s, 35 s, or 45 s) by focusing on the heartbeat sensations. Immediately after the trial period, they reported the counted number via a visual slider indicating a digit. Participants were explicitly instructed to count only the heartbeats they detected for sure and were prohibited from using any strategies unrelated to the internal detection of heartbeats, such as taking their pulse or estimating the number of heartbeats based on time. While these instructions were designed to minimise estimation bias, they relied on participants' self-report and verbal compliance. To address this, we administered a post-task questionnaire to assess whether participants had adhered to the instructions or used estimation strategies. This questionnaire, combined with the explicit instructions, aimed to reduce confounding effects and biases that could inflate heartbeat counting scores, as noted in prior research [36, 41]. After reporting the counted number, participants rated their confidence in their performance using a visual slider ranging from 0 ("No perception") to 100 ("Full perception") [32]. The confidence rating screen displayed the question "How confident were you?" along with the slider. The instruction to participants was to rate their confidence in terms of the proportion of heartbeats they believed they had accurately perceived during the trial. For example, participants were told to select 100 if they felt they had perceived all the heartbeats in the trial or 50 if they believed they had perceived approximately half, asking them to estimate the number of heartbeats they perceived at this stage. By aligning the confidence scale with participants' subjective perceptions, the task captured the alignment or discrepancy between subjective confidence and behavioural performance.

Participants completed a total of 20 trials, five trials for each duration, presented in a randomized order. The entire task, including these components and rest periods, typically took 35 to 40 minutes to complete. After every five trials, a rest message was displayed on the screen, instructing participants to take a break. During these breaks, participants were required to remain seated and avoid unnecessary movements or activities to minimise changes in cardiac activity. Breaks lasted as long as needed, and participants could proceed to the next trial by pressing a key when they felt ready. While breaks were mandatory in the sense that participants could not skip directly to the next trial, the duration of the breaks was participant-initiated, ensuring individual readiness while maintaining consistency in the task flow.

The number of trials was largely increased compared to previous studies to quantify the robust relationship between interoceptive accuracy and confidence (i.e., interoceptive metacognition) while accommodating rest periods to reduce cognitive fatigue [42]. For example, Garfinkel and colleagues originally proposed interoceptive metacognition by calculating Pearson's correlation coefficient between interoceptive accuracy and confidence over six trials [32, 43]. This correlation-based method, while influential, is suboptimal due to the high statistical uncertainty and potential bias introduced by such a small sample size. For instance, calculating a correlation coefficient based on six pairs, assuming a medium-to-large population correlation coefficient (ρ = .50), results in a standard error of .43, leading to unreliable estimates. In contrast, we calculated interoceptive metacognition on a trial-by-trial basis, using the difference between interoceptive accuracy and confidence for each trial. This trial-based approach, while novel, improves statistical robustness by leveraging the increased number of trials and provides richer information about metacognitive patterns, specifically distinguishing between underconfidence and overconfidence. Scores above 0 reflect overconfidence, while scores below 0 indicate underconfidence relative to actual heartbeat perception.

We analyzed the photoplethysmography (PPG) signals using the Heartpy module in Python [44]. First, we checked the completeness of the PPG signals recorded during task trials for each participant. We applied a third-order low-pass filter to the PPG time series for denoising, then scrutinized each trial for erroneous or missing peak detection. The number of heartbeats and heart rate were calculated using the preprocessed PPG time series for each trial of each participant. Thereafter, we calculated interoceptive accuracy, confidence, and metacognition for each participant for each trial, based on the recorded and reported number of heartbeats and subjective confidence in task performance. The formulations with a lowercase *i* as an identical trial number are as follows:

$$Interoceptive\ Accuracy_i\ =\ (1 - \frac{|Recorded\ Nbeats_i\ -\ Reported\ Nbeats_i|}{Recorded\ Nbeats_i})$$

$$Interoceptive\ Confidence_i\ =\ \frac{1}{100}(Subjective\ Rating_i)$$

$$Interoceptive\ Metacognition_i = Interoceptive\ Confidence_i - Interoceptive\ Accuracy_i$$

Scores of interoceptive accuracy and confidence typically range from 0 to 1, with higher scores indicating more accurate heartbeat perception and stronger subjective estimate of one's own performance, respectively. However, the accuracy formula allows for the possibility of negative values if participants report more than twice the actual number of heartbeats, while such cases did not occur in the present study. The difference between them—interoceptive metacognition—could typically range from -1 to 1, where scores above 0 indicate overconfidence and scores below 0 reflect underconfidence relative to actual heartbeat perception. Importantly, while 20 trials may not suffice for certain metacognitive analyses requiring signal detection theory frameworks, it is reasonable for our trial-by-trial approach, which does not rely on these assumptions.

Questionnaires

After completing the heartbeat counting task, participants filled in the Japanese version of the Multidimensional Assessment of Interoceptive Awareness (MAIA) for interoceptive sensibility [45, 46], as well as a questionnaire regarding the strategy used during the heartbeat counting task. The MAIA comprises 32 statements describing daily experiences related to interoception (e.g., "When I am tense, I notice where the tension is located in my body"). Participants rated the extent to which these statements applied to them on a 5-point Likert scale ranging from 0 (never) to 5 (always). Individual dispositions towards bodily awareness were assessed as multidimensional components because the MAIA encompasses eight independent factors (noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting). The questionnaire was filled in via an online form, with the order of each statement randomized. A previous study found gender differences in five out of eight MAIA factors (noticing, not worrying, emotional awareness, body listening, and trusting) [22].

We also asked participants to respond from 1 (not at all) to 7 (completely) to the questionnaire, assessing whether they used an estimation strategy during the heartbeat counting task, which has been shown to inflate interoceptive accuracy scores. Two items of the questionnaire were developed for this study (see Supplementary Material), with each item asking, "How did you estimate the number of heartbeats throughout the task?" and "Did you report only the number of heartbeats you perceived for sure?" Data from this questionnaire were missing for 6 male participants due to technical issues with the crowd service we used.

Statistical analyses

All statistical analyses were conducted using JASP (version 0.18.3). Our primary focus was on examining gender differences in interoceptive awareness, utilizing both behavioral data and questionnaire responses. For the questionnaire data, Bayesian two-sample t-tests were conducted on each factor of the MAIA and items of the original questionnaire. Additionally, Bayesian one-sample t-tests were performed on two key items related to estimation strategies, using a test value of 4 as the midpoint of the 7-point scale. Scores significantly greater than 4 were interpreted as evidence of estimation bias, a threshold we considered reasonable for assessing adherence to task instructions. We used JASP's default prior (Cauchy distribution with a scale parameter of 0.707) for all Bayesian analyses. Bayes factors (BFs) were used to interpret gender differences: BFs greater than 3 indicated evidence for the alternative hypothesis, and BFs less than 0.33 supported the null hypothesis.

To investigate predictors of individual differences in interoceptive accuracy, confidence, and metacognition, we employed linear mixed models (LMMs), a flexible and robust statistical approach well-suited for hierarchical data structures, such as repeated measures within individuals [47]. The fixed effects included gender, trial session, trial duration, heart rate during the trial (beats per minute), and the interaction between gender and session. Trial session (1–4) and trial duration (15 s, 25 s, 35 s, and 45 s) were treated as ordered factors. Random intercepts and random slopes for session and duration were included as random effects to account for within-participant variability across trials. This approach ensures that trial-level fluctuations and baseline differences are accurately represented within the hierarchical structure, reducing bias in parameter estimates [48]. Thus, the model specification was as follows:

$$Measures \sim Gender + Session + Gender{:}Session + Duration + HeartRate + (1 + Session + Duration|Subject)$$

Parameters were estimated using Bayesian methods. For the Markov Chain Monte Carlo (MCMC) sampling, a burn-in of 2000 iterations was used, followed by 4000 samples from four chains. The adapt delta was set to 0.9, and the maximum tree depth was restricted to 10. The LMM allowed us to assess factors influencing interoceptive accuracy, confidence, and metacognition on a trial-by-trial basis. Specifically, we calculated four contrasts of interest: the gender difference (men vs. women) and practice effects (first two sessions vs. last two sessions) for women, men, and the combined sample. This approach enabled precise quantification of gender differences and practice effects while accounting for confounding variables such as heart rate and trial duration. By incorporating 95% Credible Intervals (CIs) and Highest Posterior Density Intervals (HPDIs), we transparently reported the uncertainty of our estimates, showing that while substantial uncertainty existed for interoceptive accuracy, confidence and metacognition scores were estimated more reliably. HPDIs were calculated for each contrast to emphasise the most probable parameter values, focusing on regions of highest posterior density.

Results

Group comparisons on the questionnaire data are presented in Table 1, indicating no supporting evidence for gender differences in MAIA subscales (BF_{10}s < 0.508) (also see Figure 1A). Rather, we found supporting evidence for the null hypothesis (BF_{10}s < 0.33), suggesting no gender difference in *noticing, not distracting, self-regulation, and body listening*, which are contradictory to the results of [22]. There was also no gender difference in the use of estimation strategy during the heartbeat counting task (BF_{10}s < 0.303). Importantly, the one sample t-tests revealed that participants did not estimate the number of heartbeats ($BF_{10} = 2.192\times10^{21}$) and did report only the heartbeats they perceived for sure ($BF_{10} = 1.863\times10^{12}$), ensuring a successful control for estimation bias by the modified instruction.

Individual and averaged scores in interoceptive accuracy, confidence, and metacognition are plotted separately for trial session and gender in Figures 1B, 1C, and 1D. Contrary to previous literature, the current results using Bayesian LMM did not support gender disparity in interoceptive accuracy. However, they did support women's underconfidence in their task performance and decreased metacognition compared to men. Specifically, higher interoceptive accuracy was predicted by the negative linear effect of trial duration (estimate = -0.027, 95% Credible Intervals (CI) = [-0.043, -0.010]) and heart rate during trials (estimate = -0.006, 95% CI = [-0.008, -0.004]) (Table 2). We found no evidence supporting the effect of gender or practice by directly contrasting the marginal means (gender difference: estimate = 0.162, 95% HDPI = [-0.202, 0.552]; practice effect in women: estimate = -0.057, 95% HDPI = [-0.122 , 0.011]; practice effect in men: estimate = -7.500×10^{4}, 95% HDPI= [-0.075, 0.066]; practice effect across groups: estimate = -0.057, 95% HDPI = [-0.154, 0.041]) (Figure 2A).

For interoceptive confidence, only the fixed effect of gender was predictive of data variance (estimate = 0.076, 95% CI = [0.011, 0.143]), while other factors were not (Table 2). The contrasts of marginal means revealed supportive evidence for a gender difference, with women showing lower confidence ratings compared to men (estimate = 0.429, 95% HDPI = [0.067, 0.812]). No supportive evidence for the practice effect was found in both men and women (practice effect in women: estimate = 0.049, 95% HDPI = [-0.010, 0.114]; practice effect in men: estimate = 0.031, 95% HDPI = [-0.037, 0.097]; practice effect across groups: estimate = 0.079, 95% HDPI = [-0.009, 0.173]) (Figure 2B).

The last LMM indicated that heart rate during trials, and the linear, quadratic, and cubic effects of the trial session predicted individual differences in interoceptive metacognition (estimate for heart rate = 0.006, 95% CI = [0.004, 0.007]; estimate for the linear effect of session = 0.023, 95% CI = [0.008, 0.039]; estimate for quadratic effect = -0.027, 95% CI = [-0.046, -0.007]; estimate for quadratic effect = -0.018, 95% CI = [-0.034, -0.002]) (Table 2). There was a general trend of underconfidence in women compared to men relative to their actual perceptual performance (estimate = 0.248, 95% HDPI = [0.013, 0.513]). Moreover, supportive evidence for the practice effect was found in women (estimate = 0.109, 95% HDPI = [0.056, 0.161]) and across both genders (estimate = 0.143, 95% HDPI = [0.068, 0.221]), suggesting a moderation of the relative underconfidence in women, which was absent in men (estimate = 0.034, 95% HDPI = [-0.021, 0.091]) (Figure 2C). We exploratory tested if the gender difference remains prominent in the later session, by contrasting men vs. women in session 3 and 4. The result indicated no gender difference in interoceptive metacognition in the later session (estimate = 0.086, 95% HDPI = [-0.035, 0.227]), suggesting a moderation effect of repeating trials in women.

Discussion

We investigated gender differences and practice effects in several aspects of interoceptive awareness, including accuracy, confidence, and metacognition, using the heartbeat counting task. Specifically, we increased the number of trials, allowing us to examine gender differences in practice effects on a trial-by-trial basis. Contrary to previous literature, the present Bayesian LMM, which simultaneously modeled the effects of gender, trial repetition, trial duration, and heart rate during trials, did not support the hypothesis of decreased interoceptive accuracy in women. Higher interoceptive accuracy was linearly predicted by shorter trial durations and lower individual heart rates during each trial, suggesting potential confounding factors. Instead, we found a gender difference in confidence and metacognition, with women exhibiting underconfidence in their heartbeat counting performance, resulting in lower interoceptive metacognition scores compared to men. We did not find supportive evidence for practice effects in heartbeat counting on interoceptive accuracy and confidence. However, trial repetition moderated underconfidence relative to actual accuracy in women but not in men. This practice effect led to comparable interoceptive metacognition between genders in the later trials.

First and foremost, our results supported the null hypothesis, indicating no significant gender differences in behavioural interoceptive accuracy after accounting for potential confounds. While some researchers have reported this gender difference [22, 33, 49], others have not [25–27]. A recent meta-analysis revealed a small effect size in the heartbeat counting score [31]. However, the data used in the meta-analysis likely did not account for potential confounding factors in heartbeat counting, such as heart rate and estimation bias [27, 36], which are critical points regarding gender differences in interoceptive accuracy in the previous literature. Our findings indicate that trial duration and heart rate are precise predictors of interoceptive accuracy, emphasising the importance of addressing these factors to avoid erroneous conclusions about gender differences. Specifically, we observed that a faster heart rate during trials was consistently, albeit weakly, associated with a decrease in interoceptive accuracy, aligning with previous findings [27, 30, 50]. Additionally, interoceptive accuracy was negatively associated with trial duration, consistent with reports that prolonged trials exacerbate declines in performance [50, 51]. This attenuation may reflect reduced attentional efficiency over time, a characteristic of heartbeat perception that is critical to consider when designing interoceptive tasks. Biologically, it is well-documented that females have a slightly but consistently faster heart rate compared to males[52]. In the current sample, women's heart rates were slightly higher than men's (women = 75.01±9.55; men = 72.40±10.58), although this difference was not evident (BF_{10} = 0.41). Therefore, along with our present behavioural results, we argue that the previously reported gender differences in interoceptive accuracy might be spurious, merely reflecting the sex difference in heart rate during the heartbeat counting task, as well as other confounding factors. This argument aligns with recent findings using the Phase Adjustment Task, which, being independent of heart rate, did not reveal a men's advantage in interoceptive accuracy [38].

The present LMM revealed that women tended to be underconfident about their heartbeat counting performance and therefore had lower interoceptive metacognition scores compared to men. This consistent underconfidence aligns with broader literature suggesting that women often exhibit lower confidence in their cognitive and perceptual abilities than men, regardless of actual performance levels [53, 54]. Importantly, this finding aligns with the recent finding which revealed women's consistent underconfidence in the Phase Adjustment Task [38]. Such gender differences in reporting style may reduce the number of perceived heartbeats reported in the heartbeat counting task, especially in studies where estimation strategies are not explicitly prohibited, potentially resulting in slightly decreased interoceptive accuracy in women in previous research [31]. While men's advantage in the heartbeat discrimination task—a method less influenced by heart rate confounding—has been similarly reported, women's tendency toward underconfidence may result in inconsistent response patterns in this task. This, in turn, could lead to a higher occurrence of chance-level performance, a phenomenon observed in approximately half of participants in this task [32]. Of note, this underconfidence towards heartbeat perception appears contradictory to clinical observations and psychosomatic literature, which report a higher prevalence of interoceptive symptoms in women and heightened sensitivity to pain stimuli, suggesting greater attention to interoceptive signals compared to men [7, 9, 19]. We argue that the difference between the present findings and these clinical observations lies in the affective context of the interoceptive signals. Specifically, women may exhibit heightened behavioural and subjective sensitivity to interoceptive signals associated with discomfort or negative affect (e.g., pain, palpitations, and gastrointestinal complaints), but not to affectively neutral signals such as resting heartbeats.

Based on our comprehensive examination, we argue that the previously reported decline in women's interoceptive accuracy might be explained by differences in heart rate and a tendency towards underconfidence. This necessitates distinguishing between affective interoceptive awareness, such as pain and somatic complaints, and neutral interoceptive awareness, such as heartbeat perception in lab studies. Although such discussions might sound trivial, they help reconcile the apparent discrepancy between reduced interoceptive accuracy and enhanced emotional awareness in women. For example, Prentice and colleagues struggled to explain this dichotomy by emphasizing the role of interoceptive accuracy in emotional awareness [8, 55]. When interoceptive accuracy is considered separately from the affective aspect of interoceptive awareness and noting the absence of gender differences, the story becomes clearer. That is, women possess comparable perceptual abilities regarding internal sensations but exhibit underconfidence compared to men, while being more sensitive to the subjective and affective aspects of interoceptive awareness. If so, future investigations into gender differences in interoceptive awareness should focus on psychological, social, and developmental factors, rather than perceptual ability [56–59].

The strength of the present study lies in the multidimensional investigation of interoceptive accuracy, confidence, and metacognition in a trial-by-trial manner using the modified instruction of the heartbeat counting task. This approach allowed us to model gender differences and practice effects simultaneously using Bayesian LMMs, while controlling for confounding variables such as heart rate, trial duration, and estimation bias. Some readers might suspect that trial repetition could result in participant fatigue and cognitive loss. However, evidence from a previous study revealed that 20 to 30 trial repetitions did not affect performance, as shown in the present results, while 60 trials can reduce participant concentration [42]. The heartbeat counting task has faced recent criticisms regarding its validity [35, 36, 41]. While we acknowledge its limitations, such as the reliance on verbal compliance and the inability to capture the exact timing of heartbeat perception, we believe the task retains several strengths. It allows tracking of heartbeat perception with minimal interference from exteroceptive cues, provides sensitivity to large individual differences, and demonstrates reasonable test-retest reliability in prior research [27, 60]. In the present study, we addressed known limitations by implementing strict instructions to minimise estimation strategies and administering a post-task questionnaire, which indicated minimal reliance on estimation. Additionally, by explicitly quantifying the uncertainty of each predictor, the Bayesian LMM approach provided clear and interpretable results even within the limitations of our sample size, strengthening our findings regarding gender differences and potential confounding factors in interoceptive awareness. Still, we acknowledge the absence of a behavioural control task as a limitation, as compliance with the instructions cannot be independently verified. One remaining issue with the heartbeat counting task is its inability to capture the exact timing of heartbeat perception, which might differ between men and women. Therefore, other tasks that can assess perceptual timing relative to actual sensations, such as the heartbeat tapping task [61], might be administered to further investigate gender differences in interoceptive awareness. While no single task can perfectly measure interoceptive accuracy, we believe that the heartbeat counting task, when used carefully and critically as in this study, continues to provide meaningful insights into interoceptive processes.

Conclusion

We did not find evidence supporting gender disparity in interoceptive accuracy in the heartbeat counting task. Our results revealed that a faster heart rate during the task reduces interoceptive accuracy regardless of gender. Additionally, we found that women tend to exhibit underconfidence in their task performance compared to men.

These findings suggest that previously reported decreases in women's interoceptive accuracy might be spurious, potentially reflecting physiological differences between men and women, as well as differences in their reporting styles. Our study highlights the importance of controlling for confounding factors such as heart rate and trial duration when investigating individual differences in interoceptive awareness using the heartbeat counting task. Future research should focus on psychological, social, and developmental factors to better understand gender differences in interoceptive awareness, particularly in relation to the affective aspects.

List of abbreviations

MAIA: Multidimensional Assessment of Interoceptive Awareness

LMM: Linear Mixed Model

PPG: Photoplethysmography

BF: Bayes Factor

Declarations

Ethics approval and consent to participate

This study was carried out in accordance with the Declaration of Helsinki and its amendments. The Ethics Committee of Hokkaido University approved the experimental protocol. Written informed consent was obtained from all participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets supporting the current study are not publicly available due to the absence of explicit informed consent from participants regarding open data sharing. However, the data are available from the corresponding author upon request.

Competing interests

We declare no competing interests related to this research.

Author contribution

YH conceived the idea, designed research, analyzed the data, and wrote the manuscript. KK conjointly conceived the idea, designed research, performed research, analyzed the data, and wrote the draft. KO also designed research and edited the manuscript. All authors read and approved the final manuscript.

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The manuscript was initially composed in English by the authors. For grammar corrections and language polishing, we utilized the ChatGPT tool (ver. ChatGPT 4o). Following these revisions, we thoroughly reviewed and edited the text to ensure no inaccuracies were introduced by the automated corrections.

Tables

Questionnaire	Women	Men	BF_{10}
MAIA Subscale			
Noticing	2.603±0.890	2.736±0.879	0.288
Not Distracting	2.265±1.148	2.295±0.986	0.242
Not Worrying	2.410±1.135	2.143±0.841	0.420
Attention Regulation	2.040±0.949	2.314±0.822	0.508
Emotional Awareness	2.610±0.812	2.377±0.925	0.427
Self-regulation	2.660±1.049	2.629±0.744	0.243
Body Listening	1.897±1.140	1.762±1.305	0.265
Trusting	2.726±1.092	2.486±0.991	0.366
Estimation Strategy			
Item 1	1.897±0.912	2.069±1.223	0.303
Item 2	5.846±1.565	5.931±1.510	0.257

Table 1. Gender differences in questionnaire responses. Scores for each subscale of the Multidimensional Assessment of Interoceptive Awareness (MAIA) and each item of our original questionnaire are grouped by gender. Bayesian two-sample t-tests revealed evidence favoring the null hypothesis for all subscales ($BF_{10} < 1$), suggesting no gender differences in self-reported interoceptive awareness or the usage of estimation strategies during the heartbeat counting task. The response scale for MAIA ranged from 0 (never) to 5 (always), while the response scale for the estimation strategy items ranged from 1 (not at all) to 7 (completely). MAIA: Multidimensional Assessment of Interoceptive Awareness; BF: Bayes Factor; Item 1: "How did you estimate the number of heartbeats throughout the task?"; Item 2: "Did you report only the number of heartbeats you perceived for sure?"

Model	Model term	Estimate	S.E.	95% Credible Intervals Lower	Upper	R-hat	E.S.S.
Accuracy ~ Gender + Session + Gender:Session + Duration + HeartRate + (1 + Session + Duration|Subject)							
	Intercept	0.931	0.084	0.765	1.096	1.002	1927.842
	Duration_Linear	-0.027	0.008	-0.043	-0.010	1.000	10009.662
	Duration_Quadratic	0.015	0.009	-0.002	0.032	1.000	9208.531
	Duration_Cubic	0.013	0.009	-0.003	0.031	1.000	9857.013
	Heart Rate	-0.006	0.001	-0.008	-0.004	1.001	2674.277
	Session_Linear	-0.006	0.011	-0.027	0.016	1.000	5037.183
	Session_Quadratic	0.012	0.012	-0.011	0.036	1.000	4925.349
	Session_Cubic	0.008	0.011	-0.013	0.029	1.001	5621.581
	Gender	0.029	0.035	-0.039	0.095	1.001	613.363
	Session:Gender_Linear	0.003	0.015	-0.026	0.031	1.000	5430.466
	Session:Gender_Quadratic	-0.014	0.017	-0.046	0.018	1.001	5008.521
	Session:Gender_Cubic	-0.014	0.015	-0.044	0.015	1.000	4723.951
Confidence ~ Gender + Session + Gender:Session + Duration + HeartRate + (1 + Session + Duration|Subject)							
	Intercept	0.517	0.087	0.344	0.682	1.001	1662.603
	Duration_Linear	-0.006	0.009	-0.025	0.012	1.000	6426.503
	Duration_Quadratic	0.013	0.011	-0.007	0.035	1.001	4711.383
	Duration_Cubic	-0.002	0.010	-0.021	0.018	1.000	5795.819
	Heart Rate	-8.633×10^{-4}	0.001	-0.003	0.001	1.002	2011.626
	Session_Linear	0.019	0.010	-5.464×10^{-4}	0.039	1.001	3288.615
	Session_Quadratic	-0.013	0.012	-0.035	0.010	1.000	5085.901
	Session_Cubic	-0.010	0.011	-0.032	0.012	1.000	5311.401

Gender	0.076	0.034	0.011	0.143	1.007	589.557
Session:Gender_Linear	-0.006	0.014	-0.033	0.022	1.001	3710.600
Session:Gender_Quadratic	2.512×10^{-4}	0.016	-0.031	0.032	1.001	6083.868
Session:Gender_Cubic	0.006	0.015	-0.024	0.036	1.000	5745.578
Metacognition ~ Gender + Session + Gender:Session + Duration + HeartRate + (1 + Session + Duration|Subject)						
Intercept	-0.426	0.067	-0.555	-0.293	1.002	1828.999
Duration_Linear	0.021	0.008	0.005	0.036	1.001	6799.989
Duration_Quadratic	-0.001	0.010	-0.020	0.018	1.000	4069.205
Duration_Cubic	-0.015	0.008	-0.030	-3.254×10^{-4}	1.000	6641.130
Heart Rate	0.006	8.785×10^{-4}	0.004	0.007	1.001	2178.695
Session_Linear	0.023	0.008	0.008	0.039	1.000	6954.251
Session_Quadratic	-0.027	0.010	-0.046	-0.007	1.001	4716.374
Session_Cubic	-0.018	0.008	-0.034	-0.002	1.000	6786.191
Gender	0.044	0.022	8.819×10^{-4}	0.089	1.008	974.060
Session:Gender_Linear	-0.013	0.011	-0.034	0.009	1.000	7271.166
Session:Gender_Quadratic	0.009	0.014	-0.018	0.036	1.001	4756.226
Session:Gender_Cubic	0.023	0.011	9.947×10^{-4}	0.046	1.000	6532.366

Table 2. Results of Bayesian Linear Mixed Models on interoceptive accuracy, confidence, and metacognition. Each model included gender, trial session, the interaction between them, trial duration, and heart rate during trials as fixed effects. Random intercepts and slopes for trial session and trial duration were included as random effects. Trial session and duration were modeled as ordered factors. Parameters were estimated using Markov Chain Monte Carlo sampling. S.E.: standard error; E.S.S.: effective sample size.

Figure captions

Figure 1. Gender differences in interoceptive awareness. A) Parameter estimates for each factor of the Multidimensional Assessment of Interoceptive Awareness, contrasted between women and men, are displayed as a forest plot. Values greater than zero indicate higher scores in women compared to men, and vice versa. All 95% credible intervals estimated via Bayesian independent samples t-tests contain zero, suggesting no gender difference in interoceptive sensibility assessed by the questionnaire. B), C), and D) Individual scores for interoceptive accuracy, confidence, and metacognition, respectively, are plotted by gender and trial session. Each point represents an individual score within the session, with group means and 95% confidence intervals depicted.

Figure 2. Forest plots of gender and practice effects in the heartbeat counting task, estimated via Bayesian Linear Mixed Model analyses. Marginal means for four contrasts of interest were defined: gender differences (men vs. women) over four trial sessions (W<M); practice effects (latter two sessions vs. initial two sessions) in women (W), in men (M), and in both women and men (W&M). Each parameter was estimated by Markov Chain Monte Carlo sampling. The models included trial duration, heart rate, and the interaction between gender and session as fixed effects, with random intercepts and random slopes for each variable modeled as random effects. A) All 95% credible intervals for contrasted estimates of marginal means in interoceptive accuracy contained zero, indicating no gender difference or practice effect in either men or women. B) The 95% credible intervals for gender differences did not contain zero, suggesting general underconfidence in women. C) The 95% credible intervals for gender differences, practice effects in women, and practice effects in the whole sample did not contain zero, though the lower limit of gender difference was close to zero (0.013).

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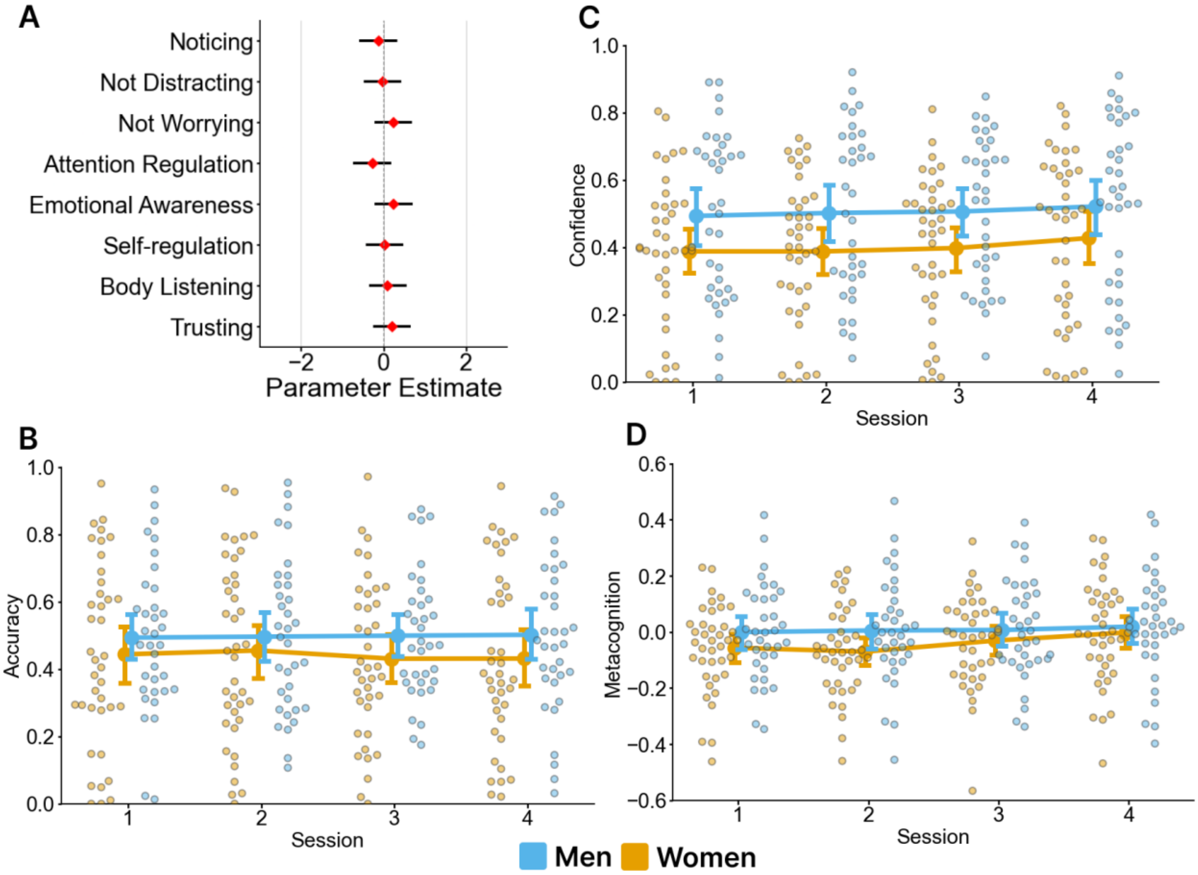

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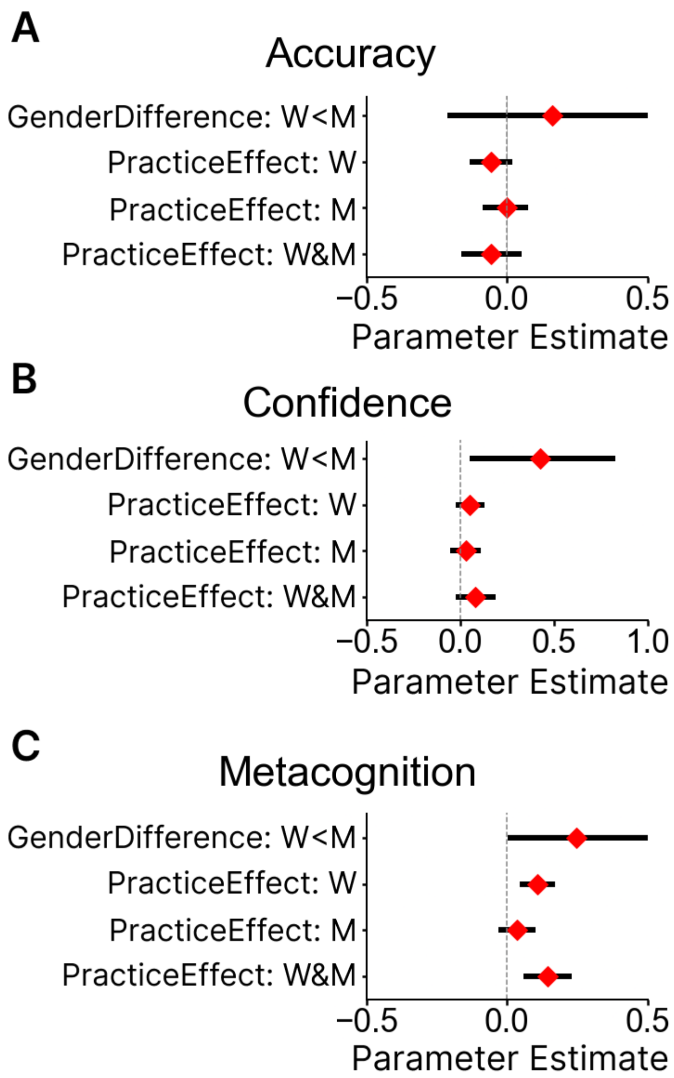
A
Accuracy
GenderDifference: W<M
PracticeEffect: W
PracticeEffect: M
PracticeEffect: W&M
−0.5
0.0
0.5
Parameter Estimate
B
Confidence
GenderDifference: W<M
PracticeEffect: W
PracticeEffect: M
PracticeEffect: W&M
−0.5
0.0
0.5
1.0
Parameter Estimate
C
Metacognition
GenderDifference: W<M
PracticeEffect: W
PracticeEffect: M
PracticeEffect: W&M
−0.5
0.0
0.5
Parameter Estimate

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