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Age-Related Differences in Interoceptive Accuracy: A Functional Near-Infrared Spectroscopy (fNIRS) Study

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Abstract

Interoceptive accuracy (IAcc), the objective capacity to sense internal bodily signals, declines with aging, yet its underlying neural mechanisms remain unclear. This study utilized functional near-infrared spectroscopy (fNIRS) to investigate age-related differences in cortical activation and functional connectivity of cortical regions during interoceptive tasks to uncover neural mechanisms that may explain age-related differences in IAcc. This study recruited 29 young adults (M_{age}=23.76) and 25 older adults (M_{age}=64.32) to undertake a breath-focused interoceptive task and a resting-state scan. IAcc was assessed by the heartbeat perception task. This study showed that young adults exhibited significantly greater activation in the supplementary motor cortex (SMC), prefrontal cortex (PFC), inferior frontal gyrus (IFG), left primary somatosensory cortex (S1-L), and right primary motor cortex (M1-R) during the interoceptive task compared to older adults. Critically, higher IAcc was positively correlated with the IFG-L activation. Older adults demonstrated significantly stronger functional connectivity between S1-L and IFG-R, PFC-R, as well as PFC-L during the interoceptive task relative to the resting state. Importantly, between-group comparisons revealed a trend enhanced functional connectivity in older adults for M1-L/M1-R, S1-L/IFG-R and PFC networkers before the FDR correction for multiple comparisons. These findings suggest that age-related cortical changes may compromise the neural efficiency of interoceptive networks. This research provides novel insights into the age-specific neural patterns underlying IAcc decline, highlighting potential biomarkers for early identification of interoceptive decline risks and informing the development of targeted interventions to mitigate age-related changes in interoceptive function.

Introduction

Interoception, defined as the process by which an organism senses, interprets, integrates, and regulates signals from within itself, is fundamental for physiological homeostasis, emotional regulation, and cognitive processing (Chen et al., 2021). As a multi-dimensional construct, its predominant model frequently used is the three-dimensional model proposed by Garfinkel et al. (2015), including interoceptive accuracy (IAcc), interoceptive sensitivity (IS), and interoceptive awareness (IAw). Unlike the subjective assessment of IS and the metacognitive awareness reflected by IAw, IAcc specifically captures an individual's objective interoceptive capacity using the heartbeat-detection task, thus distinguishing it from the subjective experiences associated with the other two dimensions (Khalsa et al., 2018). It is well-established that aging may alter correlate with dysfunction of interoception, thereby affecting cognitive and emotional processing (Brennan et al., 2023; Qi et al., 2025). These changes, however, are not uniform across all dimensions (Nusser et al., 2020). Specifically, aging is consistently linked to a decline in IAcc, whereas findings regarding IS are mixed: while aging may increase specific aspects of IS, it often leaves general IS unaffected (Li et al., 2025; Nusser et al., 2020). Older adults have consistently shown lower heartbeat-detection performance compared to younger cohorts (Dobrushina et al., 2024; Pfeifer & Cawkwell, 2025). This dimension-specific decline in IAcc raises critical questions

about its relationship to the emergence of ageing in older adults. However, the neural mechanisms underlying this age-related IAcc decline remain unclear.

With the increase in age, alterations in the structure and function of brain regions associated with interoception may be closely correlated with the decline in IAcc (La Corte et al., 2016; Ueno et al., 2020). Neuroimaging studies have indicated an "interoceptive neural network" in the brain, primarily composed of the insula, cingulate cortex, prefrontal cortex, somatosensory cortex, and somatomotor cortex (Nord & Garfinkel, 2022; Zhang et al., 2025). Among these regions, the insula, in particular, known as the "interoceptive hub", while the anterior cingulate cortex (ACC) collaborates with the insula to prioritize and allocate attentional resources towards internal bodily signals (Farb et al., 2023; Fermin et al., 2024; McIntosh et al., 2022). The strength of functional connectivity (FC) within this network, particularly between the insula and ACC as part of the salience network, has also been linked to individual differences in IAcc (Chong et al., 2016; Murray et al., 2024). IAcc in younger adults is also related to connectivity between the insula and the orbitofrontal cortex within the salience network (Li et al., 2025). Although most research has focused on these core regions, broader cortical networks may also contribute significantly to interoceptive processing by encoding and localizing bodily signals (Bergamino et al., 2024; La Corte et al., 2016; Stern et al., 2017). For instance, the somatosensory cortex contribute to interoception by providing essential sensory processing for interoceptive stimuli, thereby localizing and encoding internal signal(Stern et al., 2017). Furthermore, the interoceptive network is now understood to encompass elements of the salience network (e.g., supplementary motor area), default mode network (e.g., dorsomedial prefrontal cortex, posterior cingulate cortex, and dorsolateral prefrontal cortex) and other connecting ‘hub’ regions (e.g., inferior frontal gyrus) (Zhang et al., 2025). Age-related cortical thinning, reduced connectivity, and alterations in cerebrovascular of the above broader cortical networks may compromise the efficiency of interoceptive signal processing (Bergamino et al., 2024; La Corte et al., 2016). Despite this, how aging affects the activation and functional integration of these broader cortical networks during interoceptive tasks remains poorly understood.

Functional near-infrared spectroscopy (fNIRS) is a non-invasive neuroimaging modality that, by virtue of its portability, tolerance to motion artefacts, and operational feasibility across ecological environments, has gained rapid traction for the investigation of fronto-temporal cortical dynamic (Ehlis et al., 2014). It has been utilized to investigate brain activity patterns in various contexts, such as cognitive load, social cognition, and neurodegenerative diseases(Naseer et al., 2023; Xie et al., 2024). However, its application specifically to interoceptive processing is less explored (Balconi & Angioletti, 2024; Candia-Rivera et al., 2022). The insula, a deep cortical structure central to interoception, presents a challenge for fNIRS measurement due to its location. However, it is situated at the junction of the frontal, temporal, and parietal lobes, and brain function of these overlying cortical regions are accessible to fNIRS. Thus, this study applys fNIRS-based haemodynamic recordings in these accessible cortical regions to uncover neural mechanisms that may explain age-related differences in IAcc. The findings may ultimately inform the development of early-intervention strategies and health-monitoring systems aimed at mitigating age-related IAcc decline.

Material and Methods

Study design and Participants

This study employed a two-factor mixed experimental design of 2 (Group: older adults, younger adults) × 2 (Condition: resting state, interoceptive task state). Stimulus presentation and response collection were controlled using Eprime3.0 software. The study protocol was reviewed and approved by the Institutional Review Board of the Authors' University (*blinded for review*).

Potential participants were recruited through posters and personalized invitation from May to October 2025. All eligible participants had to meet the inclusion criteria: 1) aged over 60 years (i.e., older adults) or between 18 and 45 years old (i.e., young adults), 2) right-handed, 3) normal uncorrected or corrected visual acuity, 4) normal hearing and color vision, (5) normal cognitive function, and (6) provided a voluntary informed consent. Exclusion criteria included: 1) chronic disease, such as hypertension, diabetes, 2) a prior history of major medical or psychiatric disorders, 3) head injury or neurological disorders, 4) current pregnancy among young adults, 5) lifetime history of substance dependence, substance abuse within 1 year, 6) exposure within 3 weeks to psychotropic or other medications expected to influence cerebral blood flow or function, or general fNIRS exclusions.

Procedure

Upon arrival at the laboratory, participants completed a written questionnaire that collected demographic details and psychological measures. Participants then first underwent a resting-state, during which they viewed a white fixation-cross "+" presented against a black background. Upon completing the resting-state, participants received verbal instruction about the experimental procedures where they practiced the interoceptive attention to breathing. Before the fNIRS data collection, participants were instructed to perform 1–2 trial runs to familiarize themselves with the resting-state and interoceptive task. Following this, participants were asked to clear their mind and not think of anything in particular for the duration of the 8 minutes resting-state scan. Participants then performed the experimental task tests following the verbal instruction, consisting of five blocks of 25-second interoceptive tasks. Each full block was followed by a 20-second rest period. During the rest period, participants could only see a white fixation-cross "+" presented against a black background. A researcher was present to provide assistance if needed. The total experimental task lasted for approximately 12 minutes. A heartbeat counting task was then undertaken after the experimental task. Figure 1A shows the complete procedure.

<Figure 1 goes about here>

Interoceptive task

During the interoception condition, participants viewed the word "BREATH" in white against a black background for 15 seconds. Participants were instructed to focus their attention on their breath

sensations without through sensations experienced by touching body parts such as the mouth, neck, and chest for the entire duration that the word remained on the screen. Immediately following the interoception task, participants were asked to rate the intensity of their breath sensations during the preceding 15-second period. Ratings were provided by typing a number from 1 to 7, where 1 indicated “no sensation” and 7 indicated “an extremely intense sensation”. Participants had 5 seconds to provide their intensity rating. Following the intensity rating, participants were asked, “Was your mind wandering during the preceding 15-second period?” They then had 5 seconds to respond by typing either 1 or 3, where 1 indicated “no wandering” and 3 indicated “wandering”. These rating and questioning periods were included to help ensure participants remained attentive to the task.

Additional measures

Interoceptive accuracy (IAcc) was measured using a modified version of the Schandry (1981) heartbeat perception task. Participants were asked to silently count their heartbeats across three trials of varying durations (25, 35, and 45 seconds). During the task, participants remained seated with both feet flat on the floor and both hands resting on the table. They were instructed not to take their pulse physically or use any other aids. Participants’ reported number of heartbeats was then compared to the actual number recorded using a finger-clip pulse oximeter. IAcc was calculated according to the formula: $1/3\ \Sigma(1-(|n \text{ actual heartbeats} - n \text{ reported heartbeats}|)/ n \text{ actual heartbeats})$. Perfect correspondence between the reported and actual heartbeats is represented by a value of 1.

A series of questionnaires were used to characterize the participants in terms of demographic details, and psychological status. Demographic information included age, gender, height, weight, educational level, family economic status, smoking habits, and alcohol consumption. Given the influence of psychological factors on interoception, psychological covariates were assessed as covariances using the Generalized Anxiety Disorder scale (GAD) to measure anxiety symptoms over the previous two weeks, as well as the Patient Health Questionnaire-9 (PHQ-9) and 15-item Geriatric Depression Scale (GDS-15) scales to evaluate depressive symptoms in young and older adults, respectively.

fNIRS data collection

We applied a NIRS optical imaging system (NirSmart-3000A, Danyang Huichuang Medical Equipment Co., Ltd., China) for the data record. A total of 39 effective channels were constituted by 19 light sources and 13 detectors, which could cover the bilateral frontal, temporal and parietal cortex with a fixed channel distance of 3 cm spacing (referred to as the 10/20 international system) (Fig. 1B). The sub-sampling rate was 11Hz, and the major wavelengths were 730 nm, and 850 nm was the isotopic wavelength used for correction.

In fNIRS, a channel may span multiple brain regions, and the brain region to which it belongs may include several channels. Therefore, we first classified according to which brain region the channel belongs to

(refer to the LPBA40 Brain Atlas for the channel correction), and then regarded the brain region with the largest coverage percentage as the channel belongs (see Table 1). Finally, five regions of interest (ROIs) on each side were identified (Fig. 1C), including the supplementary motor cortex (SMC, BA6), primary somatosensory cortex (S1, BA 1, 2 and 3;), prefrontal cortex (PFC, BA 10, 11, 46), inferior frontal gyrus (IFG, BA45, BA47) and primary motor cortex (M1, BA4).

Table 1
Information of each channel in brain regions

BA region	**Channel ID**
BA1,2,3 Primary Somatosensory Cortex	CH 30,32,35
BA4 Primary Motor Cortex	CH 15,16,31,42,44
BA6 Supplementary Motor Cortex	CH 1,2,13,14,27,28,29,43,45
BA10 Frontopolar area	CH 5,7,9,10,20,21,22
BA11 Orbitofrontal area	CH 6,8
BA45 Pars triangularis Broca's area	CH 4,12,18,25,
BA46 Dorsolateral prefrontal cortex	CH 3,17,19,23,24,
BA47 Inferior prefrontal gyrus	CH 11

<Table 1 goes about here>

fNIRS Data Analysis

Signal preprocessing was performed using the NirSpark software (HuiChuang, China) following these steps: (1) Motion artifact correction was applied to the raw optical density data using a wavelet-based method; (2) The data were bandpass filtered with a frequency range of 0.1 – 0.01 Hz; (3) The filtered optical density data were converted into concentration changes of HbO and HbR, denoted as Δ[HbO] and Δ[HbR], based on the modified Beer-Lambert law. According to previous research, Δ[HbO] exhibits a higher signal-to-noise ratio and greater sensitivity to cerebral blood flow changes compared to Δ[HbR]. Therefore, Δ[HbO] data were uniformly used for statistical analysis.

To quantify cerebral activation during the interoceptive tasks in older and young adults, the difference of mean value in average HbO levels between interoceptive tasks and resting time was considered as the hemodynamic response for each condition. When performing the FC analysis on the changes in blood concentration between ROIs for each subject, Pearson correlation analysis was performed on the HbO values obtained by sampling to get the correlation coefficients between ROIs. All fNIRS data changes in cerebral activation and FC levels during interoceptive task in two groups was analyzed by independent t-test in the NirSpark software package. Paired samples t-test was performed to assess the within-group differences during resting-state and interoceptive task, respectively. Also, we made corrections for

multiple testing using the false discovery rate (FDR) correction for each task for all fNIRS analyses, and $p < 0.05$ indicated significance. In addition, Spearman correlation coefficient was employed to examine the relationship between IAcc and brain activation of ROI areas. A two-tailed *p*-value < 0.05 was considered statistical significance. All statistical analyses were performed using SPSS 27.0.

Results

Demographic characteristics of subjects

A total of 54 eligible participants, including 29 university students (M_{age}=23.76, SD = 2.081) and 25 older adults (M_{age}=64.32, SD = 3.520), were included in the final data analysis. 68.5% of them are female, including 23 young adults and 14 older adults. More than half of the participants (59.3%) resided in urban area. Regarding living arrangements, over half of the older adults lived with one other person. All young adults reported having at least a bachelor's degree, whereas the majority of older adults (88%) had an education level below a high school diploma. In terms of health behaviors, almost all participants were non-smokers, with only four older adults reporting a history of smoking. Similarly, most participants did not consume alcohol, with only 20.3% (5 older adults and 6 young adults) reporting current or past alcohol use. Additionally, old adults reported greater Body Mass Index (BMI) than young adults, with mean BMI being 25.74 and 21.37, respectively. None of the participants reported symptoms of depression and anxiety, and there are also no differences in terms of levels of anxiety and depression in the two groups.

Comparison of cerebral cortical activation during interoceptive task

After FDR correction, there was no significant differences in brain activation at the left area of primary motor cortex and right area of primary somatosensory cortex between the young and older adults. However, young participants showed increased brain activity in the right area of primary motor cortex and left area of primary somatosensory cortex (t = -2.789 and − 3.13 respectively, p = 0.018). Young adults also reported greater brain activity in supplementary motor cortex, including SMC-R (t = -2.764, p = 0.018) and SMC-L (t = -2.491, p = 0.027). Similar findings were also observed in prefrontal cortex (PFC-R, t = -2.711, p = 0.018, and PFC-L, t = -2.302, p = 0.036) and inferior frontal gyrus (IFG-R, t = -2.705, p = 0.018, and IFG-L, t = -2.203, p = 0.040). The HbO concentration changes between the young and older subjects are shown in Fig. 2.

<Figure 2 goes about here>

Comparison of FC during resting-state and interoceptive task

In Pearson correlation analysis with matrix type of Z, compared with young adults, there were weaker FC strengths in older adults during resting-state among all the channels, with average FC in young and older

adults being 0.618 and 0.588 respectively. However, there were slightly stronger FC strengths in older adults during interoceptive task among all the channels, with average FC in young and older adults being 0.543 and 0.657 respectively.

In between-group level, the correlation coefficients matrix between ROIs and average FC of ROIs of older and young adults during resting-state are similar (Fig. 3A-D). The FC between all ROI areas is not significant between the two groups (all $p \geq 0.05$, FDR corrected) (Fig. 3I). The correlation coefficients matrix between ROIs and average FC of ROIs of older and young adults during interoceptive task are shown in Fig. 3E-H. Interestingly, the difference of FC in certain ROIs between young and older adults during interoceptive task remained significant, but was not significant after FDR corrected (all $p \geq 0.05$) (Fig. 3J). Specifically, before the FDR corrected, the FC in ROIs areas between M1-L and M1-R is increased in the older group ($p = 0.016$, t=-2.497). In addition, the functional connectively in ROIs between S1-L and IFG-R ($p = 0.027$, t=-2.272), PFC-R ($p = 0.023$, t=-2.338), as well as PFC-L ($p = 0.026$, t=-2.230) is also significantly increased in older group.

This study also applied paired-t test to evaluate the within-group levels of two different tasks in old and young groups, respectively. The Correlation coefficients matrix between ROIs and average FC of ROIs of resting-state and interoceptive task are different in old group. The FC between two tasks in old group is significant between S1-L and IFG-R ($p \leq 0.05$, FDR corrected; t = -3.383), PFC-R ($p \leq 0.01$, FDR corrected; t = -4.253), as well as PFC-L ($p \leq 0.01$, FDR corrected; t = -4.080), with higher functional connectively in the interoceptive task (Fig. 3K**)**. Differently, the Correlation coefficients matrix between ROIs and average FC of ROIs of resting-state and interoceptive task are similar in young group. The FC between all ROI areas is not significant between the different tasks in young group (all $p \geq 0.05$, FDR corrected) (Fig. 3L**)**.

<Figure 3 goes about here>

The relationship between heartbeat perception task and brain activation during interoceptive task

The correlation between heartbeat perception task and relevant brain activation of M1-L, M1-R, S1-L, S1-R, PFC-L, PFC-R, IFG-L, IFG-R, SMC-L and SMC-R during the interoceptive task was examined. This study found a significant relationship between IAcc and brain activation of IFG-L ($r = 0.312$, $p = 0.020$), indicating higher IAcc and higher brain activation of the IFG-L. However, there is no significant relationship between the IAcc with brain activation of other ROIs.

Discussion

This study explored age-related differences of cerebral cortical activation, FC and IAcc between young and older adults during rest and interoceptive task states. The primary findings are as follows: (1) Young adults exhibited significantly greater activation in SMC, PFC, IFG, S1-L, and M1-R, and IAcc was positively correlated with IFG-L activation. (3) Older adults showed significantly stronger FC between S1-L with IFG-R, PFC-R, and PFC-L during interoceptive tasks compared with resting-state; (4) Specific ROI pairs (i.e.,

M1-L/M1-R, S1-L/IFG-R, PFC-R, PFC-L) in older adults demonstrated enhanced FC during the interoceptive task compared to young adults, though these differences did not remained after the FDR correction. These results collectively reveal age-specific neural patterns underlying interoceptive processing, complementing prior behavioral observations of age-related declines in IAcc.

Age-Related Differences in Cerebral Activation

Age-related differences in brain activation levels may reflect the decline in neural efficiency associated with aging. As individuals age, the brain undergoes structural and functional changes that collectively reduce neuronal recruitment and information processing efficiency (Dinsdale et al., 2021; Ueno et al., 2020). The high activation of the PFC in young adults indicates that they can effectively allocate their cognitive resources to perceive and respond to interoceptive signals (Contreras-Huerta et al., 2023), which further supports its adaptability to the cognitive demands of interoceptive tasks (Pan & Zhang, 2025). The reduced active of IFG in older adults may attribute to age-related factors such as local blood flow reduction or changes in neurotransmitter levels, which may decrease the efficiency of attention inhibition and ability in internal information processing (Fermin et al., 2023). Hence, the lower activation in these regions indicates a decline in the allocation of cognitive resources or the efficiency of information integration in interoceptive tasks among older adults.

Young adults typically have higher neural plasticity and motor-perception integration capabilities than older adults, which may explain the significant activation of the SMC (Leuk et al., 2025; Lin et al., 2022). During interoceptive task, when the SMC senses internal changes such as heartbeat or breathing during interoceptive tasks, it can optimize perception efficiency by regulating the movement state (Van Ruitenbeek et al., 2023). Similarly, the M1-R is also responsible for motor execution, while S1-L receives sensory input from the body. Notably, S1 is closely related to the interoceptive signals process and relays refined movement-adjustment information to M1 based on interoceptive feedback (e.g., heartbeat and breathing) (Gómez et al., 2021; Mishra et al., 2024). In older adults, however, activation in these regions is often reduced or delayed, potentially due to age-related thinning of the somatosensory cortex or decline in FC efficiency. Research indicates that age-related changes in S1 can have a negative impact on the understanding of the body's interoceptive state, thereby diminishing overall performance on interoceptive task (George & Joseph, 2020; Van Ruitenbeek et al., 2023). Therefore, differential activation of the SMC, M1-R, and S1-L during interoceptive tasks likely reflects age-related variations in bodily perception and motor control.

Correlation Between IAcc and IFG-L Activation

This study indicates that IAcc exhibits a significant positive correlation with the activation of the IFG-L, suggesting that the neural activity in this region play a potential crucial role in the precise processing of interoceptive signals. The IFG-L is a critical structure for higher-order cognitive processes, including attention control and emotion regulation (van der Burght et al., 2022). Within the interoceptive tasks, its activation may reflect the orchestration of attentional reallocation and cognitive control to facilitate the monitoring and interpretation of internal bodily states (Li et al., 2023; Luo et al., 2022). The cognitive

demands of interoceptive tasks, such as detecting heartbeat signals at precise intervals, further highlight the involvement of working memory and cognitive inhibition, both of which are mediated by IFG-L (Luo et al., 2022; Suzuki & Yamamoto, 2023). Furthermore, the positive correlation between IAcc and IFG-L activation highlights the need to consider not only the specific neural and behavioral associations of this region to interoception, but also its integration within broader networks, for example, prefrontal cortex, ACC, Insula (Hübner et al., 2022; Luo et al., 2022). The IFG-L may thus act as a multifunctional integrative hub, bridging interoceptive, social-cognitive, and emotional processing domains, which further underscores its broad relevance in human cognition and psychological wellbeing.

Age-Specific Within-and Between-Group FC Patterns

For young adults, stable FC between rest and interoceptive states may reflect the efficiency of their intrinsic neural networks. This stability suggests that their interoceptive cortical network is sufficiently specialized to support interoceptive processing without requiring significant connectivity adjustments. In contrast, older adults exhibit increased FC demands during interoceptive processing relative to the resting state. Furthermore, while older adults showed marginally weaker average resting-state FC across all channels compared to younger adults, between-group analyses yielded an interesting pattern: several ROI pairs (i.e., M1-L/M1-R, S1-L/IFG-R, PFC) exhibited enhanced FC in the older group at the uncorrected level, yet these differences failed to survive FDR correction for multiple comparisons. The widespread attenuation of FC in the resting state may reflect age-related decline in neural efficiency, impaired white matter integrity, morphological changes in the brain, and reduced cortical thickness (Dinsdale et al., 2021; Zorzi et al., 2021). Yet, the brain exhibits remarkable neuroplasticity, which enables it to maintain or compensate for specific functions by adjusting functional connections (Dinsdale et al., 2021; Spedden et al., 2020). Older adults exhibit stronger FC during the interoceptive task, which may represent a neural compensatory strategy (Spedden et al., 2020). This pattern of compensatory neural recruitment is well-documented in aging research, for example, older adults show alterations in cortico-cortical communication among the M1, PMC, and prefrontal regions to maintain motor control ability during ankle strength control task (Spedden et al., 2020). Thus, interoceptive tasks may impose higher cognitive demands on older adults, prompting the mobilization of additional neural resources to maintain performance, albeit with relatively low efficiency, thereby reflecting this compensatory mechanism (Sanchez et al., 2025; Taube & Lauber, 2025). This may help further explain why young people demonstrate higher accuracy and flexibility in interoceptive tasks.

It is important to note that FDR correction is a rigorous method for controlling multiple comparisons and limiting Type I errors (false positives). When the results after FDR correction are no longer significant, it may indicate that the original uncorrected effect size was too small to reach significance at the strict statistical threshold (Zaixu Cui, 2018). This does not negate the biological relevance of the uncorrected findings but rather may highlight the need for larger sample sizes to detect small-to-medium effect sizes in aging research. Thus, while this study did not reveal significant between-group differences after FDR correction, its preliminary findings suggest that older adults' brains may employ unique compensatory strategies during cognitive challenges. Optimizing research design and expanding sample sizes in future

work could help clarify the neurobiological basis and clinical significance of these age-related FC patterns.

Clinical Implications

Understanding these age-related differences in brain activity holds potential significance for assessing the interoceptive function of the elderly and developing intervention measures. Changes in the activation patterns of SMC, PFC, IFG, M1-R, and S1-L may potentially serve as potential biomarkers for early identification of interoceptive decline risks or monitoring of intervention effects. On the other hand, combining appropriate physical activity and sensory-motor training may help delay the age-related decline in activation of these brain regions and optimize FC patterns. Moreover, if the enhancement of FC during the interoceptive task state does indeed reflect compensatory mechanisms, then targeted interoceptive-based training or rehabilitation programs could consider optimizing the brain function of the elderly through interoceptive tasks (Mekbib et al., 2020). Based on these findings, interoceptive-based training or neurofeedback interventions specifically for the elderly can be developed, aiming to optimize the activation patterns or compensatory strategies of these key brain regions and enhance internal perception abilities and overall interoceptive function.

Limitations

This study has several limitations that warrant consideration. First, the cross-sectional design precludes causal inferences about aging effects. Longitudinal studies are needed to track within-and between-individual neural changes and better reveal the dynamic evolution of the FC patterns in the elderly, and distinguish between normal aging and the early manifestations of pathological conditions. This will help reveal the dynamic evolution of compensatory mechanisms. Second, the small sample size may have limited statistical power, particularly for FC analyses where several between-group differences did not survive FDR correction. Third, the interoceptive task scan was relatively brief, potentially limiting reliability of interoceptive task connectivity measures. Lastly, notable differences in educational attainment and BMI were observed between the two groups, which may have confounded the neural findings. Future research should explicitly account for these demographic confounders to enhance the validity of results.

Conclusion

This fNIRS study provides novel evidence for age-specific neural difference underlying IAcc. Young adults demonstrated significantly greater activation in SMC, PFC, IFG, M1-R, S1-L during breath-focused interoception. Critically, individual differences in IAcc correlated specifically with left IFG activation. Older adults exhibited enhanced FC among M1-L/IFG-R and PFC during the interoceptive task compared to the resting-state. While direct between-group comparisons of connectivity (e.g., M1-L/M1-R, S1-L/IFG-R, PFC) showed a trend toward enhancement in older adults, these differences were not statistically robust after correction for multiple comparisons. These findings illuminate how age-related cortical changes

may compromise the neural efficiency of interoceptive networks, with implications for emotional regulation.

Declarations

Conflict of interest

The authors declare no competing interests.

Ethics approval

Ethics approval for this study was received from the Human Research Ethics Committee of the author's institution (2025-R-050). Written informed consent was obtained from all participants prior to the study.

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Author Contribution

Meiling Qi: Writing - review & editing, Supervision, Project administration, Visualization, Methodology, Formal analysis, Conceptualization, Funding acquisition. Feiping Yu: Writing-original draft, Investigation. Lijuan Chai: Writing - original draft, Data curation. Xinyi Liu: Investigation. Xiaolei Li: Methodology, Investigation. Yuli Li: Data curation. Xuan Zhang: Investigation. Ping Li: Conceptualization, Supervision.

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Data Availability

The data that support the findings of this study are available on request from the corresponding author.

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Figures

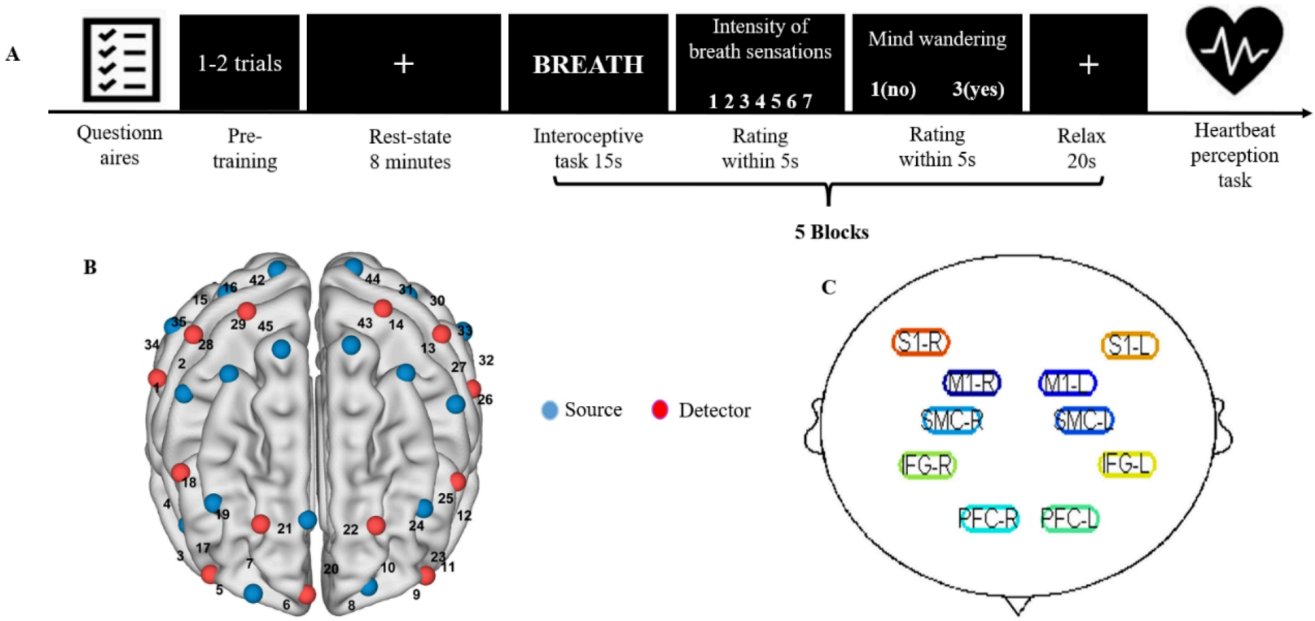


Figure 1

Experimental procedures. **A:** Overview of the phases of the experiment including survey data, heartbeat perception task, resting-state and five blocks of interoceptive task; **B:** Schematic of fNIRS channel localization on the brain surface; **C:** Schematic of fNIRS of the regions of interest (ROI).

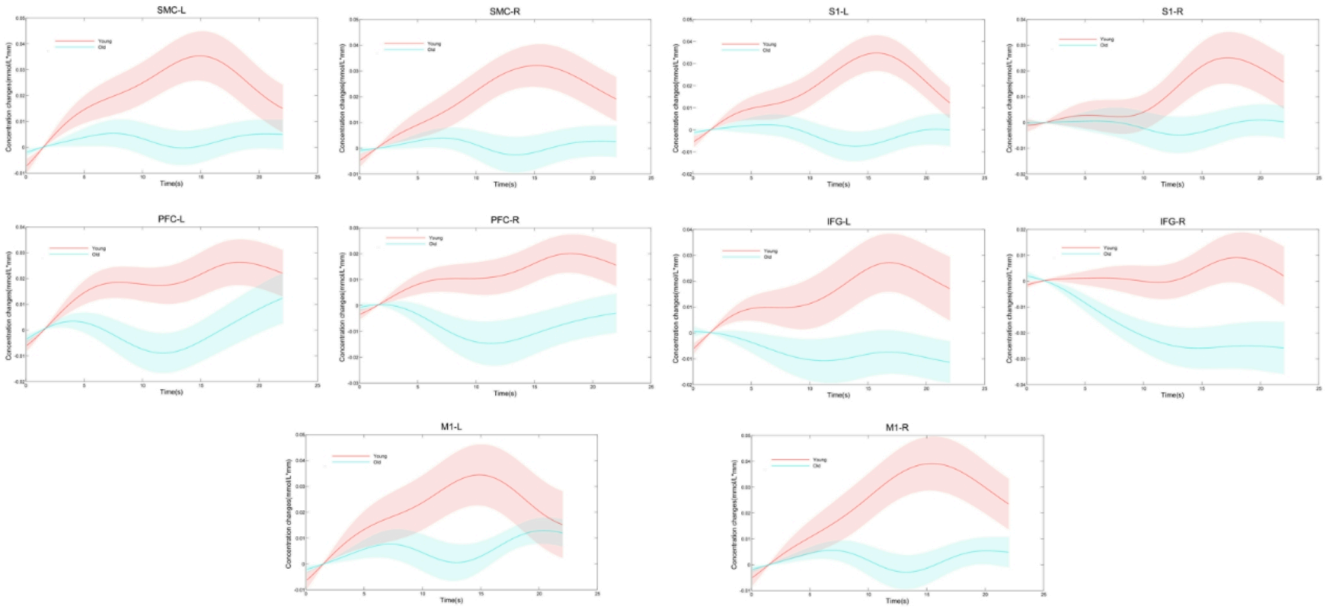


Figure 2

Cerebral cortical activation of ROIs in two groups.**SMC-L**: left area of supplementary motor cortex; **SMC-R:** right area of supplementary motor cortex; **S1-L**: left area of primary somatosensory cortex; **S1-R**: right area of primary somatosensory cortex; **PFC-L**: left area of prefrontal cortex; **PFC-R**: right area of prefrontal cortex; **IFG-L**: left area of inferior frontal gyrus. **IFG-R**: right area of inferior frontal gyrus; **M1-L**: left area of primary motor cortex; **M1-R**: right area of primary motor cortex.

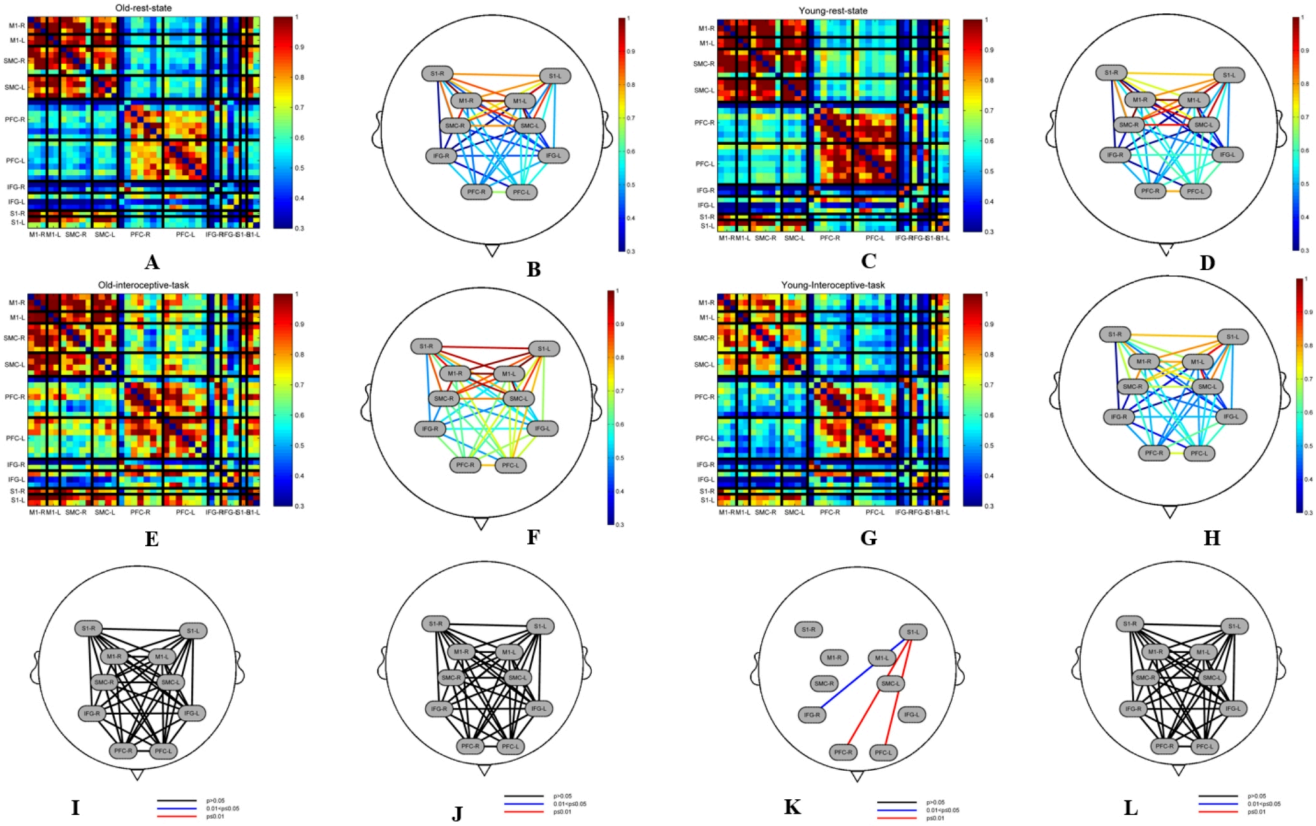


Figure 3

The difference of functional connectivity (FC) and regions of interest (ROI) during resting-state and interoceptive task between two groups by Z matrix typeanalysis. **A**: Correlation coefficients matrix between ROIs in old group during resting-state; **B**: The FC in ROIs in old group during resting-state; **C**: Correlation coefficients matrix between ROIs in young group during resting-state; **D:** The FC in ROIs in young group during resting-state. **E**: Correlation coefficients matrix between ROIs in old group druing interoceptive task; **F**: The FC in ROIs in old group druing interoceptive task**; G**: Correlation coefficients matrix between ROIs in young group druing interoceptive task; **H**: The FC in ROIs in young group druing interoceptive task; **I:** The differentce of FC in ROIs between two groups during resting-state, all p value after FDR corrected. **J:** The differentce of FC in ROIs between two groups during interoceptive task, all p value after FDR corrected; **K:** The differentce of FC in ROIs between two tasks in old group, all p value

after FDR corrected. **L:** The differentce of FC in ROIs between two tasks in young group, all p value after FDR corrected;