Relationship between interoceptive awareness and resilience: a longitudinal study on arterial stiffness and EEG

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# Introduction

Interoception refers to the sensation of the body's internal states, such as those of the viscera and the autonomic nervous system (Craig 2002, Craig 2003). It is essential for maintaining balance within the body (homeostasis) and for adjusting our internal conditions in response to external changes and anticipated needs (allostasis) (Seth and Friston 2016, Stephan, Manjaly et al. 2016, Tsakiris and Critchley 2016). When faced with physical stress, such as the fight-or-flight response to immediate threats, the body automatically gears up, utilizing energy and resources. After this period of heightened alertness, it shifts into a state of relaxation and recuperation, methodically reverting to its standard, stress-free condition. This process requires a seamless connection between the brain's evaluative functions of situations and the body's control mechanisms, primarily through the autonomic nervous system. Interoception plays a crucial role in linking these areas. Evidence shows that individuals with heightened interoceptive accuracy (IAcc) can return to baseline blood sugar levels more quickly following sugar intake (Young, Gaylor et al. 2019).

In psychological terms, resilience is defined as the capacity to endure stress or adversity and recover from such challenges (Luthar, Cicchetti et al. 2000). It involves the effective use of cognitive, emotional, and physiological resources to confront stressors and the ability to reallocate these resources once the stress has passed (McEwen and Gianaros 2011). Interoception underpins the neurophysiological and physiological bases of resilience by linking stress induced internal state perturbation with goal-directed behaviors that restore the body's homeostatic balance (Paulus, Potterat et al. 2009). Research indicates that individuals with lower resilience levels show reduced interoceptive awareness (IAw) and increased brain activity in response to adverse interoceptive stimuli, which may lead to poor ability of adaptation to stress (Haase, Stewart et al. 2016). Furthermore, the IAw and resilience scores have both been correlated with intra-insula, insula-cortical and insula-subcortical networks, suggesting a shared neurobiological foundation (Fermin et al., XXX).

However, the relationship between interoception and resilience has mainly been explored through self-reported questionnaires, with few evidence from objective measures. It's important to note that interoception involves a spectrum of processes, from basic afferent signaling to complex cognitive functions (Suksasilp and Garfinkel 2022). Although these processes are interconnected, they do not fully overlap. Furthermore, subjective assessments are highly susceptible to non-intentional and intentional biases (Carnevali, Koenig et al. 2018). Therefore, it's crucial to delve into the effects of interoceptive signals that are closer to physiological responses, which are beyond the scope of questionnaires, to gain deeper insights into their impact on resilience.

To objectively assess individual differences in interoceptive sensitivity, methods using heartbeat are widely employed. The most popular of these methods is the heartbeat counting task, where participants internally count their heartbeats within a specified period (Schandry 1981). However, this method has faced several criticisms, including the influence of participants' prior knowledge of their heart rate on their performance (Murphy, Millgate et al. 2018, Zamariola, Maurage et al. 2018). To address these issues, alternative tasks have been developed, including those that detect synchronization between heartbeats and sounds (Ring and Brener 2018)（笹岡先生の論文）, match the timing of heartbeats to sounds (Plans, Ponzo et al. 2020), detecting increases in heart rate (Khalsa, Rudrauf et al. 2009), and use modalities other than heartbeats (Ferentzi, Bogdány et al. 2018, Murphy, Catmur et al. 2018). These tasks aim to refine the assessment of interoceptive sensitivity by circumventing the limitations of the heartbeat counting task.

Research into resilience has also employed physiological markers to objectively evaluate its functioning (Walker, Pfingst et al. 2017, Carnevali, Koenig et al. 2018, Perna, Riva et al. 2020). Studies have demonstrated that individual differences in resilience influence recovery time and degree from stress-induced physiological responses. For example, it has been shown that individuals with higher resilience recover more quickly from cardiovascular changes induced by the psychological stress of a speech preparation task (Tugade and Fredrickson 2004). Additionally, in experiments involving peacekeeping force participants, significant correlations were found between resilience and the amount of recovery in cardiovascular parameters following speech preparation and mental arithmetic tasks (Souza, Magalhães et al. 2013). Electroencephalograms (EEG) measurements during a memory recall task indicated that participants with lower scores on the Mental Toughness Questionnaire exhibited a greater reduction in alpha amplitude as task difficulty increased (Zhozhikashvili, Zakharov et al. 2022). Supporting these human studies, animal research indicates that although heart rate, blood pressure, and corticosterone levels rise similarly during territorial fights, physiological recovery to baseline is significantly quicker in winners compared to losers (Koolhaas, Bartolomucci et al. 2011).

Past research on the connection between interoception and resilience has primarily relied on cross-sectional studies. This method, while valuable, is constrained by its susceptibility to biases arising from natural variations or selection effects (Maxwell and Cole 2007, Maier, Thatcher et al. 2023). To address these constraints and deepen our understanding of how interoception and resilience are interrelated and change over time, our research adopts a short-term longitudinal design. This approach enables the assessment of changes over time, offering a more nuanced and dynamic perspective than what cross-sectional studies can provide.

Based on these previous findings, we hypothesized that individuals with higher interoceptive sensitivity would exhibit greater resilience in their physiological responses to stress. Specifically, we assumed that individuals with higher interoceptive sensitivity would demonstrate superior recovery from stress-induced physiological changes during cognitive load. To assess interoceptive sensitivity, we employed the heartbeat discrimination task (HDT), which involves determining the synchronization or asynchronization of heartbeats with auditory stimuli. For objective indicators of resilience, we measured peripheral arterial stiffness, known as an index of autonomic nervous activity (Hirano, Maruyama et al. 2011, Matsubara, Hirano et al. 2018, Tsuji, Arikuni et al. 2021), and recorded EEGs to monitor recovery levels following a mental arithmetic task. To reduce the potential for bias due to natural variability, we conducted these measurements twice, one month apart, enabling a longitudinal analysis of changes in interoception and resilience.

# Methods

## Participants

Participants were recruited from the residents of Kita-Hiroshima, Japan. The study initially included 30 individuals. However, due to the withdrawal of one participant and the exclusion of six others due to data quality issues, the analysis focused on 23 participants (XX females, XX males). The age range of participants was XX to XX years, with an average age of XX±XX. Hiroshima University's Ethical Committee for Epidemiology granted ethical approval for this study (approval number: E2022-0130), ensuring adherence to the Declaration of Helsinki's principles. Before participating in the experiment, all individuals provided written informed consent. For their participation in the study, participants received 8,000 Japanese yen.

## Research Design

This study was carried out over a span of roughly two months, during which participants made three visits to our laboratory at three distinct times: T0, T1, T2. At the initial visit (T0), after an explanation of the experiment and confirmation of consent, participants installed a questionnaire response app on their smartphones and completed the questionnaires. This visit did not include any psychophysical experiments. In the later visits (T1 and T2), participants were equipped with EEG and autonomic nervous system measurement devices to engage in a mental arithmetic task. Subsequently, they moved to a different room to perform the heartbeat discrimination task, which served to measure interoceptive sensitivity. The intervals between T0 and T1, and T1 and T2 were XX±XX days and XX±XX days, respectively.

The sample size was estimated using an online calculator (Arifin 2022). The experiment was designed to detect a moderate correlation (r=0.5) between changes in interoceptive sensitivity and changes in brain/autonomic responses, with a 5% significance level (α) and 80% statistical power (1-β). These parameters suggested a necessary sample size of N=29, prompting us to recruit 30 participants for our study.

## Mental arithmetic task

### Apparatus

Participants were equipped with a 30-channel dry electrode EEG system (Quick-30, Cogninonics, USA), operating at a sampling rate of 500Hz. The EEG setup included with 20 channels based on the standard 10-20 system (Klem, Lüders et al. 1999), with an additional 10 channels. The reference electrode was placed on the right earlobe (A2), and the ground electrode was placed on the left earlobe (A1). For cardiovascular measures, participants had a fingertip photoplethysmograph (PPG; Oxypal R, XX) attached to the index finger of the left hand and a fingertip continuous sphygmomanometer (Finapres Nova, XX) on the middle finger of the same hand. These devices were connected to an AD converter (National Instruments, XX) and recorded at 1000Hz. Participants conducted the experiment seated in front of a monitor. Earplugs were used to reduce external noise interference. Task instructions and signal acquisition were managed via MATLAB software (Mathworks, USA).

### Procedure

The study employed a mental arithmetic task to assess participants' autonomic nervous system responses and brain activity under cognitive load. This task required participants to sequentially subtract 7 from 1000 (Kim, Kim et al. 2016). The procedure began with a resting phase, where participants sat with closed eyes for 5 minutes to establish baseline measurements. Subsequently, they answered a questionnaire regarding their state during the rest period (Diaz, Van Der Sluis et al. 2014). Following this, participants received instructions for the mental arithmetic task and proceeded to perform it. The task sequence was as follows: a 30-second measurement with eyes open during rest (baseline phase), a 5-second interval, 30 seconds of mental arithmetic (task phase), a 7-second period for responding, and a final 30-second measurement with eyes open during rest (recovery phase). During the 7-second response period, participants verbally reported the final result of their calculations. The start and end of each section were indicated by a beep sound. This entire sequence was performed once.

### Analysis (peripheral arterial stiffness)

Peripheral arterial stiffness is calculated using a log-linearized peripheral arterial viscoelastic model, which simplifies the nonlinear relationship between arterial wall impedance and blood pressure (Hirano, Maruyama et al. 2011, Matsubara, Hirano et al. 2018, Tsuji, Arikuni et al. 2021). This approach accurately evaluates the arterial viscoelasticity, excluding effects from blood pressure variation unrelated to the activity of the sympathetic nervous system. Previous research has indicated that the peripheral arterial stiffness index derived from this method is highly responsive to direct stimulation of the sympathetic nerves (Hirano, Maruyama et al. 2011), establishing it as an effective measure for analyzing the function of these nerves.

The log-linearized peripheral arterial viscoelastic model is described by the following equation:

(1)

where is the inertia, is the viscosity, is the peripheral arterial stiffness, is the constant pressure component, and is the nonlinear stiffness pressure component originating in the vein. and are estimated using continuous sphygmomanometer and PPG, respectively. Peripheral arterial stiffness was approximated for each heartbeat from these measured signals (Hirano, Maruyama et al. 2011). To assure the estimation accuracy, the determination coefficient R2 between the measured blood pressure values and the estimated blood pressure values is calculated, and evaluation was performed only when R2 ≥ 0.7. The data was low pass filtered at 0.15 Hz.

In the context of cardiovascular and autonomic nervous system interactions, it is well-documented that variations in the cardiovascular system reflect autonomic nervous activity. This is evident through the link between heart rate variability (Electrophysiology 1996) and blood pressure variability (Freeman and Chapleau 2013) to autonomic nerve function. Considering these aspects, the variability in peripheral arterial stiffness was chosen as an indicator. Furthermore, considering the variations in values obtained from PPG devices, we utilized the Coefficient of Variation (CV), which is a normalized measure of variability relative to the mean value. Consequently, we calculated the average of peripheral arterial stiffness and its CV during the baseline, task, and recovery phases as measures of autonomic nervous system activity.

### Analysis (EEG preprocessing)

EEG data were preprocessed offline using the EEGLAB toolbox (Delorme and Makeig 2004) within MATLAB 2021a. Initially, DC offsets were corrected, and data filtered between 0.5-40 Hz using a bidirectional FIR filter, with 60 and 120 Hz line noise reduced via adaptive filtering. Ear electrode re-referencing followed, excluding channels above 500 kΩ impedance, which were interpolated spherically. To isolate and remove residual artifacts, we employed the Adaptive Mixture Independent Component Analysis (AMICA) algorithm (Hsu, Pion-Tonachini et al. 2018), which adapts to the dataset's unique characteristics by using multiple density models (Palmer, Makeig et al. 2008). Non-cerebral components, including eye movement and muscle artifacts, were identified and excluded using ICLabel, a machine learning-based component classification utility (Pion-Tonachini, Kreutz-Delgado et al. 2019). The cleaned EEG signal was then reconstructed from the remaining components.

For frequency analysis of the EEG data, we utilized the FieldTrip toolbox (Oostenveld, Fries et al. 2011). Data were segmented into 30-second intervals for baseline, task, and recovery phases. We applied the Multitaper Frequency Transformation Method (MTMFFT) with Discrete Prolate Spheroidal Sequences (DPSS) tapers, aiming to maximize time-frequency resolution. Analysis focused on the 0.5 to 40 Hz frequency range, including standard EEG bands, with a 0.5 Hz step and 1 Hz smoothing applied to spectral estimation for enhanced precision.

### Analysis (recovery index)

In this study, we evaluated resilience through the magnitude of physiological recovery following the mental arithmetic task. As previously mentioned, resilience has been associated with both the speed (Tugade and Fredrickson 2004) and magnitude(Souza, Magalhães et al. 2013, Zhozhikashvili, Zakharov et al. 2022) of recovery from stress-induced physiological changes. Because of the short duration of our measurements, focusing on recovery speed was impractical. Thus, we concentrated on recovery magnitude as our resilience measure. The recovery index was calculated by comparing the change in peripheral arterial stiffness and EEG oscillation amplitude from the task phase to the recovery phase. Hereafter, this difference is referred to as the recovery index in this document.

## Heartbeat discrimination task

### Apparatus and procedure

HDT assesses participants' ability to judge the synchrony between external auditory beeps and their own heartbeat perception (Whitehead, Drescher et al. 1977). Participants were equipped with a three-lead chest electrocardiograph (ECG; BIOPAC MP 160?) and were seated in front of the monitor. ECG recording (1000Hz) and sound stimulus control were performed with Psychophysics Toolbox extensions (Brainard and Vision 1997, Pelli and Vision 1997, Kleiner, Brainard et al. 2007). Prior to the task, participants' resting ECG was recorded for 15 seconds to set a threshold for detecting R-peaks. R-peaks were identified every 50ms by comparing the ECG to this threshold. In each trial, a beep sound (100ms) corresponding to the participant's R-peak was presented 10 times. Participants made a two-alternative forced choice on whether the beep's timing was synchronous with their heartbeat and rated their confidence using a visual analogue scale. Trials were conducted under two conditions: immediate beep after R-peak detection and a 450ms delayed beep from the R-peak detection. After two practice trials, participants underwent 20 trials, with 10 trials per condition.

### Analysis

In evaluating performance in the HDT, we focus on two key measures: interoceptive accuracy (IAcc), also known as sensitivity, and interoceptive awareness (IAw) (Garfinkel, Seth et al. 2015, Hickman, Seyedsalehi et al. 2020). Our study specifically measures IAcc through the discriminability index (d'), rather than merely tallying correct responses. The d' is derived by calculating the difference between the z-transformed rates of correct detections and false alarms (Forkmann, Scherer et al. 2016). To prevent d' from reaching infinity, we add 0.5 to the total number of responses (Stanislaw and Todorov 1999). Given the known variability in individuals' perception of heartbeat timing (Ring and Brener 2018), we do not assume a predetermined correct delay time. Instead, we identify the delay that yields the most synchronous responses for each participant as the correct timing, thereby ensuring d’ remains positive.

IAw represents a meta-cognitive measure, reflecting the correspondence between IAcc and self-beliefs about interoceptive abilities. This measure is determined using receiver operating characteristic (ROC) curves, which are plotted based on the congruence between participants' synchronous responses and their confidence in these responses. The area under the curve (AUC) of the ROC curve is then used as an index of IAw, providing insight into the congruence between self-reported and actual IAcc (Ewing, Manassei et al. 2017, Herman, Rae et al. 2019, Leganes-Fonteneau, Cheang et al. 2019, Rae, Larsson et al. 2019).

## Questionnaire

At T0, participants completed several questionnaires, including but not limited to those directly related to the study's theme, which are not reported here. The questionnaires included the Body Perception Questionnaire very short form (BPQ) (Cabrera, Kolacz et al. 2018, 小林, 本多 et al. 2021), the Multidimensional Assessment of Interoceptive Awareness (MAIA) (Mehling, Price et al. 2012, 庄司, 大野 et al. 2014), and the 14-item Resilience Scale (RS) (Wagnild 2009, Nishi, Uehara et al. 2010). For the MAIA, both the mean scores of each subscale and the overall mean were utilized. This approach aligns with the original recommendation to examine subscales individually (Mehling, Price et al. 2012), while also acknowledging the utility of total scores in providing a comprehensive view of IAw, as evidenced by subsequent research (Harrison, Köchli et al. 2021).

## Statistics

We set the significance threshold at 0.05 for all statistical analyses. Adjusted p-values are presented in the results section whenever corrections for significance levels were applied.

### Peripheral arterial stiffness and interoceptive indices

For each autonomic nervous system indicator (mean and CV of peripheral arterial stiffness), a two-way repeated measures ANOVA was performed considering the phase of the task (baseline, task, recovery) and term (T1, T2). Subsequent tests for any significant main effects or interactions were conducted, employing the Bonferroni method for correction of multiple comparisons.

Then, we calculated correlation coefficients to explore the relationship between the recovery index from peripheral arterial stiffness and both IAcc and IAw, controlling for age and sex using partial correlations. Spearman's rank correlation was chosen for its non-parametric nature. The permutation test was used to test for statistical significance, incorporating 2000 permutations and using the max statistic method to adjust for multiple comparisons (Groppe, Urbach et al. 2011, Groppe, Urbach et al. 2011). This analysis procedure was performed for T1 and T2, respectively. Furthermore, we investigated long-term effects. Initially, we examined whether T1 HDT could predict the T2 recovery index, aiming to assess if a better HDT at T1 indicates improved future resilience. Additionally, we explored the relationship between the changes over one month in HDT and the recovery index by calculating the difference between T2 and T1 for each index.

### EEG oscillations and interoceptive indices

Initially, we performed a statistical analysis of EEG data utilizing the FieldTrip toolbox, with a focus on evaluating task-related changes. We employed a Monte Carlo method alongside a dependent samples T-test to compare frequency power between baseline and recovery phase, as well as between task and recovery phase. To address multiple comparisons, we applied a spatial-frequency cluster-based correction method using weighted cluster mass (wcm) statistics, based on 2,000 randomizations.

Again using the FieldTrip toolbox, we calculated correlation coefficients between the EEG recovery index and both IAcc and IAw. Monte Carlo methods paired with T-tests assessed the significance of these correlations, while a spatial-frequency cluster-based correction strategy using the wcm statistic addressed the complexities of multiple comparisons.

### Correlation among questionnaires

Correlation coefficients between the resilience questionnaire (RS) and interoceptive sensation-related questionnaires (MAIA, BPQ) were calculated using Spearman's rank correlation coefficient, controlling for age and sex using partial correlations. Permutation tests were conducted for statistical significance testing, with multiple comparison corrections using the max statistic method.

### Re-test reliability of HDT

The re-test reliability of the HDT for d’ and AUC at T1 and T2 was evaluated using the Intraclass Correlation Coefficient (ICC) for case 3 (McGraw and Wong 1996, Weir 2005). Additionally, a paired t-test was conducted to determine if there were any significant differences in the mean values of d’ and AUC between T1 and T2.

# Results

## Correlation between recovery index of peripheral arterial stiffness and IAw

Initially, we confirmed that cognitive load induced by the mental arithmetic task elicited changes in peripheral arterial stiffness, as indicators of autonomic nervous function. Using a two-way repeated measures ANOVA, we examined changes in peripheral arterial stiffness, both the mean values and the CV, across different phases of the task and over time. The results, detailed in Table 1 and illustrated in Figure 1A, indicated a significant main effect of task phase on both indicators, suggesting that the task phase significantly impacts autonomic nervous system activity. No significant differences were found for the term or for the interaction between phase and term, implying consistent effects across the study period. Subsequent analysis focusing on task phases uncovered significant changes between the task and recovery phases for both examined indicators, signifying an autonomic return to baseline post-task. These insights confirm the autonomic nervous system's dynamic response to cognitive stress and its subsequent normalization following task completion.

**Table 1: Peripheral arterial stiffness in mental arithmetic task**

This table presents the mean values and standard deviations for peripheral arterial stiffness indicator, alongside the results of ANOVA and subsequent post hoc tests. The degrees of freedom for the F values in the ANOVA were as follows: for term (1, 115), for phase (2, 115), and for the interaction between term and phase (2, 115). The degrees of freedom for the t-values in the post hoc tests were 115. Significance levels are denoted as follows: \*p<0.05, \*\*p<0.01, \*\*\*p<0.001. CV: Coefficient of Variation.





**Figure 1: Peripheral arterial stiffness in mental arithmetic task**

(A) Mean peripheral arterial stiffness (right graph) alongside the coefficient of variation (CV) of peripheral arterial stiffness (left graph) throughout different phases of the task. Significant phase differences, as identified by post hoc tests following ANOVA, are marked with asterisks. (B) Correlation between the CV of peripheral arterial stiffness and IAw. Each point represents data from an individual participant. The solid line represents a linear regression line calculated by the least squares method. Significance levels are denoted as follows: \*p<0.05, \*\*p<0.01, \*\*\*p<0.001. CV: Coefficient of Variation.

We next assessed the recovery index of peripheral arterial stiffness and investigated its relationship with interoceptive indices through correlation analysis (Table 2). This involved computing correlation coefficients between the recovery index and each interoceptive index at T1 and T2. Our analysis did not reveal any significant correlation initially. We also assessed whether the HDT at T1 could predict the recovery index at T2, but found no significant relationship. Furthermore, we explored the relationship over time by calculating the difference between T2 and T1 values for both the recovery index and the interoceptive index, again computing correlation coefficients (Table 2). Here, we identified a significant correlation between IAw and the CV of peripheral arterial stiffness (r=0.50, p=0.041; Figure 1B), indicating a meaningful relationship over time. Additionally, while not reaching statistical significance, the relationship between IAw and the CV of peripheral arterial stiffness at T1 (r=0.34, p=0.24) and T2 (r=0.13, p=0.54) also showed positive correlations. These findings suggest an evolving connection between changes in autonomic nervous system activity, as reflected by peripheral arterial stiffness, and IAw.

**Table 2: Correlation coefficients between recovery index of peripheral arterial stiffness and interoceptive indices**

\*p<0.05. HDT: Heartbeat Discrimination Task, IAcc: Interoceptive Accuracy, IAw: Interoceptive awareness, CV: Coefficient of Variation



## Correlation between recovery index of EEG oscillation and IAw

Initially, we established that cognitive load in a mental arithmetic task induces stress-related changes observable in EEG. A frequency analysis was conducted to assess variations between the baseline and task phases, as well as between the task and recovery phases, across a frequency range of 0.5-40 Hz. T-tests were utilized for these comparisons, with p-values adjusted through spatial-frequency clustering. Our findings indicate an increase in EEG power during the recovery phase compared to the task phase, particularly notable in the frontal and left temporal regions within the 7 to 9.5 Hz frequency band (Figure 3A). Conversely, no significant EEG power differences were detected between the baseline and task phases.



**Figure 3: EEG oscillation changes in mental arithmetic task and correlations with IAw**

(A) Difference in EEG activity between task and recovery phase. (B) Correlation between EEG recovery index and IAw. Only frequencies for which significant difference or correlations were found by cluster analysis are depicted. Asterisks denote channels within significant clusters.

Subsequently, we conducted a correlation analysis to explore the relationship between the EEG recovery index and interoceptive indices, calculating correlation coefficients for both T1 and T2 and applying spatial-frequency clustering. However, this analysis did not reveal significant correlations for any of the assessed combinations. To further investigate if changes over time between the EEG recovery index and interoceptive indices were associated, we calculated the differences (T2-T1) and then computed correlation coefficients. This led to the identification of a significant cluster of correlations between the EEG recovery index's magnitude and IAw within the 11-12.5 Hz frequency range, specifically from the frontal to the left temporal region (Figure 3B). Conversely, no significant correlation was found between the EEG recovery index and IAcc.

## Correlation between resilience and interoception questionnaires

We explored the relationship between resilience, as measured by the RS, and IAw, assessed through questionnaires including the MAIA and the BPQ (Table 3). The results revealed strong and significant correlations between specific MAIA subscales, Attention Regulation (r=0.70, p=0.039) and Trusting (r=0.60, p=0.008) and resilience. Furthermore, the overall mean score of the MAIA was also significantly correlated with the RS (r=0.55, p=0.01), indicating a meaningful association between IAw and resilience.

**Table 3: Correlation Between Resilience Scale and Interoception-related questionnaires**

This table presents the correlation coefficients between the Resilience Scale and questionnaires assessing IAw, BPQ and MAIA. Significance levels are indicated as follows: \*\*p<0.01, \*\*\*p<0.001. BPQ: Body Perception Questionnaire, MAIA: Multidimensional Assessment of IAw.



## Re-test reliability of HDT

To evaluate the stability of the HDT measures, d' for IAcc and AUC for IAw, across two assessments spaced one month apart, we calculated the ICCs. The ICC for d' was r = 0.42, indicating a moderate yet significant correlation (F(28, 28)=2.46, p=0.02; Figure 3), suggesting consistency in IAcc over time. Likewise, the ICC for AUC stood at r = 0.48, also showing a moderate and significant correlation (F(28, 28)=2.83, p=0.009; Figure 3), pointing towards stable IAw across the two measurements.

Additionally, a t-test comparing the mean values of d' and AUC at T1 and T2 was conducted to assess any potential changes attributable to participation in the study. The mean d' scores were 0.65±0.69 at T1 and 0.68±0.69 at T2, with no significant difference between the two times (t(28)=0.22, p=0.83). Similarly, mean AUC values were 0.62±0.16 at T1 and 0.65±0.17 at T2, also showing no significant change (t(28)=0.91, p=0.37). These results indicate that both measures of interoceptive processing remained consistent over the duration of the study.



**Figure 3: Scatterplots of the HDT measures over time**

This figure presents scatterplots for the HDT’s d' and AUC across two time points, T1 and T2. The left graph illustrates d', while the right graph focuses on AUC, with each data point corresponding to an individual participant's scores. The solid line represents a linear regression line calculated using the least squares method. HDT: heartbeat discrimination task, AUC: area under the curve.

# Discussion

In this study, we investigated the correlations between peripheral arterial stiffness, EEG oscillations during a cognitive load task, and interoceptive ability. Our findings reveal a significant relationship between the CV of peripheral arterial stiffness during recovery and high levels of IAw. This indicates that individuals with greater awareness of their internal bodily states tend to exhibit more pronounced physiological recovery after cognitive stress. Additionally, we observed a correlation between EEG alpha power during recovery and enhanced IAw, suggesting that the recovery phase of cognitive load is associated with both autonomic and central nervous system markers of interoception.

Peripheral blood vessels, including microvessels, are mainly regulated by the sympathetic nervous system, and are known to exhibit pronounced acute responses, such as contraction and relaxation, in response to external stimuli (Hirano, Maruyama et al. 2011). Similarly, Psychological stress triggers sympathoexcitatory responses, such as vasoconstriction in the skin and viscera, facilitating the body's acute response to stress (Nakamura and Morrison 2022). This implies that individuals with enhanced IAw may be better able to modulate their autonomic response to stress and quickly return to a baseline or calm state. Indeed, it has been proposed that interoceptive processing may modulate autonomic activity, including sympathetic activity, and promote more balanced sympathetic and parasympathetic interactions during stress (Schulz and Vögele 2015, Berntson, Gianaros et al. 2018). This ability to manage autonomic nervous system to stress effectively could enhance long-term stress resilience and, by extension, psychological well-being (Critchley and Garfinkel 2017). This aligns with the idea that advanced interoceptive sensitivity could form the physiological foundation for robust resilience, bridging the gap between bodily awareness and mental health (Khalsa, Adolphs et al. 2018).

However, the specific physiological implications of the CV in peripheral arterial stiffness remain undetermined, with the underlying mechanisms unclear. In the context of cardiovascular variability and autonomic nervous system interactions, established indices like heart rate variability (Electrophysiology 1996) and blood pressure variability (Freeman and Chapleau 2013) point towards possible similar autonomic activities influencing peripheral arterial stiffness fluctuations. Our hypothesis regarding the CV and autonomic nerve activity is as follows. During rest, blood pressure regulation is supported by spontaneous bursts from muscle sympathetic nerves, causing variability in vascular stiffness and thus a higher CV. Conversely, in response to stimuli, heightened burst frequencies from both muscle and skin sympathetic nerves lead to increased and more consistent vascular stiffness, indicated by a lower CV. We propose that individuals with heightened interoceptive awareness are more adept at modulating this sympathetic nerve activity, enhancing their ability to respond to and recover from stress.

The relationship between EEG alpha power and IAw during recovery phase sheds light on the neurophysiological mechanisms underlying stress resilience. The increase in alpha power is interpreted as cortical idling or active inhibition of specific brain regions, reflecting a relaxed state of awareness or inward attention (Klimesch 1999, Klimesch 2012, Cohen 2017). This suggests that individuals with heightened IAw may have an enhanced capacity to modulate neural responses to stress, facilitating a swift return to baseline or calm states. This hypothesis is supported by findings that individuals with lower mental toughness scores experiencing significant alpha amplitude reductions as task difficulty increases, indicating that resilience is associated with stable alpha power (Zhozhikashvili, Zakharov et al. 2022). Further, studies have shown that focusing on breathing leads to higher average delta values and desynchronization of alpha in the temporo-central regions, indicating that engagement in interoceptive activities like breathing could influence brain activity (Angioletti and Balconi 2022). Additionally, a reduction in visual input, reflecting a transition from exteroceptive to interoceptive states, has been shown to increase alpha power and peak frequency compared to open-eye fixation states (Webster and Ro 2020). These results emphasize the role of alpha power in transitioning to a more inward-focused state, enabling more adaptive responses to stress and contributing to the resilience observed in individuals with high IAw.

Differential findings regarding the correlation between physiological resilience indices and two aspects of interoception, IAw and IAcc, provide a nuanced perspective on the role of body awareness in the stress recovery process. IAw refers to the metacognitive aspect of interoception, which includes an individual's perceived accuracy and awareness of internal body states (Suksasilp and Garfinkel 2022). In contrast, IAcc reflects the actual accuracy of detecting internal bodily signals (Ceunen, Vlaeyen et al. 2016). Our results, highlighting a correlation with IAw but not with IAcc, suggest that conscious recognition of bodily states may be more crucial for regulating physiological stress responses than the objective accuracy of such signals. The apparent discrepancy between the effects of IAw and IAcc on physiological recovery underscores the importance of subjective experience in stress response and recovery processes. This aligns with theories suggesting that the evaluation and interpretation of bodily signals play a significant role in emotional and stress-related processes (Craig 2009). Therefore, IAw, more than just accurate detection isolated from contextual understanding, may enable more effective stress adaptation by allowing individuals to contextualize and thus better manage bodily signals, fostering adjustment and recovery.

The observed relationships between IAw and both peripheral arterial stiffness and EEG oscillations, evident only over a one-month period, underscore the dynamic nature of these associations. This finding suggests that the relationship between IAw and physiological responses to stress is not static, but evolves over time, potentially influenced by a variety of factors, including changes in environmental stressors, individual experiences, and even practice of interoceptive skills. The longitudinal aspect of our study highlights the significance of time in understanding the impact of IAw on resilience and stress recovery processes.

Regarding the reliability of the heart rate discrimination task, we found moderate consistency with r = 0.42 for d' and r = 0.48 for AUC. An analysis focusing on same-day performance, by dividing data into first and second halves, showed a correlation of 0.69 (Ring and Brener 2018), whereas a study involving children reported a one-year retest reliability of 0.33 for the heart rate counting task (Koch and Pollatos 2014). This pattern suggests that while the heart rate task demonstrates some degree of stability, its reliability diminishes over longer intervals. These findings align with our observations that changes over a month significantly highlight the connection between IAw and physiological metrics, reinforcing the importance of considering temporal dynamics in such research.

Our findings indicate a positive correlation between MAIA scores and resilience scale, suggesting that individuals with a heightened interoceptive attention tend to exhibit greater resilience. Prior studies have established a connection between IAw and depressive tendencies, emphasizing the mediating role of resilience. Furthermore, the insular cortex-subcortical network has been highlighted as pivotal in associating IAw and resilience with depressive tendencies (Fermin et al., XXX). Our findings not only reinforce the essential role of IAw in fostering resilience but also spotlight the potential efficacy of targeted interventions aimed at improving IAw. Practices such as mindfulness, which focus on the body's sensory experiences, have been shown to increase IAw (Bornemann and Singer 2017, Fischer, Messner et al. 2017), offering essential tools for resilience training programs (Southwick and Charney 2012). These interventions present a promising strategy for strengthening psychological resilience, providing individuals with vital resources to address mental health challenges.

# Conclusion

## Acknowledgements

松浦さん，北広島町の人？，アドダイス？

This research was supported by the following grants: JST COI (grant nos. JPMJCE1311 and JPMJCA2208), JSPS KAKENHI (grant no. 22H00197), JST Moonshot Research and Development Program (grant no. JPMJMS2296).

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