CORTEX 194 (2026) 107–120

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Special Issue 'From Bodies to Spaces': a neurocognitive/neuropsychological...': Research Report

Impact of interoception and multisensory integration on functional and physical activities in aging

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ARTICLE INFO

Article history:
Received 30 November 2024
Revised 5 November 2025
Accepted 20 November 2025
Published online 27 November 2025

Keywords:
Interoception
Multisensory integration
Daily functioning

ABSTRACT

Aging affects the ability to process sensory input from the body (interoception) and integrate information from multiple sensory modalities. Interoception, which involves perceiving and interpreting internal bodily signals, undergoes significant changes with age, reducing the ability to recognize and respond to internal needs. Additionally, deficits in multisensory integration are known to predict declines in gait and stability, increasing the risk of falls and mobility issues in older adults. These changes impact physical health and hinder action planning and execution, yet the combined influence of interoception and multisensory integration on physical functioning remains underexplored. This study investigated how interoception and multisensory integration predict physical functioning in older adults compared to younger adults. Twenty-five young and twenty-eight older participants completed tasks assessing interoceptive dimensions (accuracy, sensibility, and awareness) and multisensory integration dimensions (temporal resolution and tactile acuity). Physical functioning was measured using the SF-36 questionnaire. In the older adult group, regression analyses revealed that interoceptive sensibility, interoceptive awareness, and multisensory temporal resolution significantly predicted physical functioning. Higher interoceptive sensibility and awareness were associated with better physical functioning, while reduced temporal resolution was linked to poorer functioning.

This article is part of a special issue entitled: From Bodies to Spaces published in Cortex.

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https://doi.org/10.1016/j.cortex.2025.11.010

These factors also predicted role limitations due to physical health: higher interoceptive awareness and sensibility were related to fewer limitations, whereas temporal resolution and tactile acuity were associated with greater limitations. These findings emphasize the critical role of interoceptive and multisensory processing in supporting physical functioning and managing perceived limitations in older adults, highlighting the importance of preserving these sensory capacities to maintain well-being in aging populations.

1. Introduction

According to Eurostat and North American statistics on functional and activity limitations, approximately half of the older adult population (aged 65 and over) reports experiencing difficulties with daily activities (Elgaddal & Kramarow, 2024). This highlights the profound impact of aging on physical and functional abilities, which often manifest as perceived restrictions in performing specific actions such as walking, climbing stairs, or lifting objects (Verbrugge & Jette, 1994). These functional limitations are not solely due to physical decline but are also shaped by age-related changes in sensory processing.

As individuals age, there is an unnoticed but significant increase in sensory thresholds across various modalities, including vision, hearing, smell, touch, temperature sensation, and pain perception (Humes et al., 2009). This means that stronger and more pronounced stimuli are required for sensory information to be consciously perceived (Low Choy et al., 2007). Such sensory changes impair the brain's ability to acquire, process, and integrate information from the body and the environment, creating significant challenges for movement autonomy and the performance of daily activities (Gescheider et al., 1994; Gibson & Farrell, 2004; Hurley et al., 1998). For instance, difficulties in detecting and interpreting sensory cues can reduce an individual's ability to navigate their surroundings safely and effectively.

The reliability of sensory signals plays a crucial role in multisensory integration, particularly in defining the time interval within which stimuli from different sensory modalities are perceived as simultaneous or causally connected, also known as the *temporal binding window* (McGovern et al., 2022). In older adults, the ability to select and integrate sensory signals diminishes, leading to less precise and more variable sensory processing. This reduced sensory reliability results in a broader temporal binding window, which can negatively impact coordination and perception (Basharat et al., 2018; Brooks et al., 2018; Cao et al., 2019). Research shows that older adults with a wider temporal binding window are more likely to experience falls, suggesting a direct link between multisensory integration and physical stability (Mahoney et al., 2019; McGovern et al., 2022; Setti et al., 2011).

Multisensory integration is also closely tied to motor skills and body awareness. Effective coordination of sensory inputs is essential for guiding everyday actions, from maintaining balance to executing precise movements. When sensory integration falters, the awareness of bodily states can become compromised, leading to impaired movement autonomy and difficulties in performing daily activities. These findings underscore the importance of multisensory processing and body awareness in maintaining functional independence in older adults. Recognizing this connection could inform interventions aimed at enhancing sensory reliability and improving quality of life for the aging population.

Bodily awareness, however, relies not only on proprioceptive and exteroceptive senses—those that detect stimuli originating from outside the body—but also on *interoception*, which refers to sensations arising from within the body, such as the heartbeat, breathing, hunger, and thirst (Cameron, 2001; Craig, 2002; Critchley et al., 2004; Damasio, 2003; Khalsa, Rudrauf, Sandesara, et al., 2009; Mayer, Naliboff, & Craig, 2006; Pollatos et al., 2007; Vaitl, 1996). Interestingly, aging has been linked to a decline in interoceptive accuracy and awareness (Khalsa, Rudrauf, & Tranel, 2009; Murphy et al., 2018; Nusser et al., 2021) and alterations in interoceptive brain networks (Dobrushina et al., 2024), highlighting significant changes in how the brain processes internal bodily signals.

Together, these changes in sensory and multisensory perception, as well as in interoceptive processing and awareness, likely impact daily life by influencing an individual's ability to recognize and respond to internal needs, as well as to plan and execute actions to meet those needs.

However, in aging the relationship between interoception, multisensory integration, and their impact on daily functional and physical activities remains largely underexplored.

Here, we investigated interoception and multisensory integration as distinct domains. Specifically, we focused on three aspects of interoception accuracy, sensibility, and awareness (Garfinkel et al., 2015) and selected specific components of multisensory integration related to temporal sensitivity and tactile spatial remapping (Keetels & Vroomen, 2009; Sternberg & Knoll, 1973). This choice reflects a functional distinction between internal bodily signal monitoring and the coordination of external sensory inputs, allowing us to explore their potentially distinct, but possibly interacting, contributions to perceived physical functioning in aging.

1.1. *Overview of the study*

This study aimed to investigate whether, and how, the quality of physical functioning in daily activities among healthy older adults, compared to a younger cohort, could be predicted by temporal sensitivity in multisensory perception as well as by interoceptive processing and awareness. To explore this, both young and older adult participants completed the Short Form Health Survey 36 questionnaire (SF-36; Apolone and Mosconi, 1998; Ware & Sherbourne, 1992), which includes eight subscales that assess various aspects of health-related quality of life, ranging from physical functioning to social and emotional well-being.

In addition, we assessed various interoceptive dimensions in the participants. According to Garfinkel et al. (2015), interoception can be divided into three distinct components: interoceptive accuracy, which refers to the objective ability to detect internal bodily sensations; interoceptive sensibility, which reflects the subjective evaluation or confidence in recognizing these internal bodily sensations; and interoceptive awareness, which pertains to metacognitive awareness of one's interoceptive abilities. To evaluate these dimensions, participants completed the Heartbeat Counting Task (also known as the Schandry Task; Schandry, 1981) and the Heartbeat Detection Task (also referred to as the Tapping or Tracking Task; Brener & Ring, 2016; McFarland, 1975). The Schandry Task primarily focuses on the perception of internal bodily signals, whereas the Tapping Task is designed to assess sensory and motor integration (Körmendi & Ferentzi, 2024). Previous studies have demonstrated age-related declines in interoceptive functioning using these tasks (Dobrushina et al., 2020; Herbert & Pollatos, 2018). Additionally, participants completed the multidimensional assessment of interoceptive awareness (MAIA) questionnaire (Calì et al., 2015; Mehling et al., 2012), a validated tool for assessing the interoceptive sensibility component across various age groups and body perception questionnaire (BPQ) that generally evaluates body awareness and autonomic symptoms (Poli et al., 2021; Porges, 1993).

Finally, to assess temporal sensitivity in multisensory perception, we employed two tasks widely used in the literature: the audio-tactile simultaneity judgment task (SJ) and the temporal order judgment task (TOJ) with both crossed and uncrossed hands (Allan, 1975; Barnett-Cowan & Harris, 2009, 2011; Love et al., 2013; Mitrani et al., 1986; Vatakis et al., 2008). The SJ task evaluates the ability to determine whether stimuli from different sensory modalities (auditory and tactile) occur simultaneously or at different times (Keetels & Vroomen, 2009). The TOJ task serves two distinct purposes: with uncrossed hands, it provides a baseline measure of the temporal resolution of the somatosensory system (Sternberg & Knoll, 1973), while with crossed hands, it assesses the multisensory representation of body space, particularly the integration of tactile signals with visuo-proprioceptive cues.

Although involving different sensory modalities, both SJ and TOJ tasks have been successfully employed in studies with older adults, consistently revealing a reduction in temporal sensitivity when distinguishing whether sensory stimuli occur simultaneously or sequentially (Basharat et al., 2018). Importantly, these tasks do not require rapid motor responses, allowing for a more accurate assessment of how perceptual processing evolves with age. This approach avoids the potential confound of motor-response speed, which can obscure the distinction between age-related changes in perceptual abilities and those in motor functions, as occurs in reaction-time-based tests.

We hypothesized that age-related declines in both multisensory perception and interoceptive processing and awareness would negatively impact the physical aspects of health-related quality of life. This effect may stem from changes in individuals' interoceptive representation of bodily needs and their multisensory representation of body space. In other words, since both interoception and multisensory integration deteriorate with age, we propose that these declines may serve as predictors of physical functioning in older adults.

2. Methods and materials

2.1. *Participant*

Twenty-five young (13 female; aged 21–38, mean = 28, SD = 6.81), twenty-eight old adults (17 female; aged 58–87, mean = 68, SD = 7.30), participated in the study after providing written informed consent. The younger adults were recruited through an online questionnaire. Older adults were recruited at UniTre Associazione Nazionale delle Università della Terza Età (National Association of Universities of the Third Age) – Chieti (Italy). The mini-mental state examination was used to evaluate the participants' cognitive function (Folstein et al., 1975; Grigoletto et al., 1999; Magni et al., 1996). Individuals who had a mini-mental state examination score that was lower than 26 were excluded. No participant had a history of neurologic, general medical or psychiatric conditions and/or medical conditions that could potentially affect cognitive functioning (e.g., Alzheimer's disease, multiple sclerosis, and Parkinson's disease). The experimental protocol was approved by the Institutional Ethics Committee at the University G. d'Annunzio, Chieti-Pescara. A sensitivity analysis (Perugini et al., 2018) was conducted to determine the minimum detectable effect size for our analyses. For the regression analyses, assuming a power of .80, $\alpha = .05$, and 28 participants, the analysis revealed that an effect size (Cohen's f) of at least 1.55 could be reliably detected, corresponding to an R^2 of .74. For the MANOVA, using the same power and alpha level but considering the full sample of 53 participants, the sensitivity analysis showed that the design could detect an effect size of $f(V) = .68$ and a Pillais' lambda of .31 (Alson, 1974; Ateş et al., 2019).

2.2. *Experimental procedure*

Participants completed the SF-36 questionnaire (Apolone & Mosconi, 1998) to evaluate physical functioning, as well as tasks assessing multisensory integration and interoception. While originally developed for adult populations, the SF-36 has been validated in younger cohorts, including adolescents and young adults, in various studies. Its robust psychometric properties make it suitable for evaluating health-related quality of life across age groups, providing reliable and comparable data on physical functioning, even in youth. To complement this assessment, multisensory integration was evaluated using the simultaneity judgment (SJ) and temporal-order judgment (TOJ) tasks. Interoception was assessed through four established measures: the Heartbeat Counting task (R. Schandry, 1981), the Heartbeat Detection task (Brener & Ring, 2016; McFarland, 1975), the multidimensional assessment of interoceptive awareness (MAIA) questionnaire (Mehling et al., 2012) and BPQ (Poli et al., 2021; Porges, 1993). The experiment lasts about 2 h (Fig. 1).

2.3. *Short Form Health Survey 36 questionnaire (SF-36)*

The SF-36 (Apolone & Mosconi, 1998) is a 36-item self-report questionnaire that measures perceived health across eight subscales, covering functional status, well-being, and overall evaluation of health (Brazier et al., 1992). The subscales are the following: Physical Functioning, Role Limitations Due to Physical Health, Role Limitations Due to Personal or Emotional Problems, Energy/Fatigue, Emotional Well-Being, Social Functioning, Bodily Pain and General Health. The scores for each subscale range from 0 to 100, where the lower scores are associated with negative health, while higher scores are associated with positive perceived health status. Each subscale can be used independently to investigate different dimensions of health and well-being. In the present study we focus on the subscales that mainly assess the physical health domain: Physical Functioning scale, which measures the perception of physical state; Role Limitations Due to Physical Health, which assesses how physical health issues interfere with daily activitiess; Energy/Fatigue, which evaluates the perceived levels of vitality and fatigue; and General Health, which measures a global assessment of overall health.

2.4. *Multisensory integration tasks*

2.4.1. *Simultaneity judgment (SJ)*

Simultaneity judgment (SJ) task was employed to evaluate Multisensory Temporal Resolution that refers to the principle that optimal multisensory integration occurs when stimuli from different senses are presented closely in time, diminishing as the temporal gap increases. SJ aims to measure temporal sensitivity in the integration of multisensory stimuli. Specifically, we focused on auditory and tactile stimuli (A-T). Auditory stimuli were delivered through headphones and consisted of a 3,500-Hz pure tone lasting 30 msec. Tactile stimuli were administered using two constant-current electrical stimulators (Digitimer DS7A), which controlled two pairs of neurological electrodes attached to the participant's right and left middle fingers. Tactile stimuli were single, constant voltage, rectangular monophasic pulses lasting 100 μs During the task, participants were blindfolded and comfortably seated at a table, with their index fingers resting on separate keys of a response box. The intensity of the stimuli was adjusted to each participant's detection threshold, set at 100 % for both auditory and tactile stimuli. In each trial, two stimuli were presented in opposite hemispaces, with stimulus pairs randomly interleaved at various stimulus onset asynchronies (SOAs): ±450, ±350, ±200, ±120, ±70, ±40, ±15, and 0 msec. Participants had to indicate whether the two stimuli were presented simultaneously or not using the response box. The AT-SJ task comprised two blocks, each consisting of 120 trials, resulting in a total of 240 trials (16 trials per SOA). The association between the side of presentation (right or left) and the modality (auditory or tactile) was balanced across trials, and the stimulus–response association was counterbalanced between blocks.

2.4.2. *Temporal order judgment task (TOJ, uncrossed hands)*

The temporal order judgment (TOJ) task was employed to evaluate Temporal Tactile Acuity that refers to the ability to perceive and discriminate temporal aspects of tactile stimuli.

During TOJ, participants were blindfolded and seated at a table with their hands placed palm down on the table surface. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli (i.e., stimulus onset asynchrony SOA) was randomly assigned from 22 intervals. In the uncrossed condition, it ranged from −450 to 450 msec (±450, ±300, ±200, ±150, ±100, ±75, ±50, ±40, ±30, ±15, ±5 msec). Negative and positive intervals indicated whether the left or right hand was stimulated first. The inter-trial intervals varied between 2000 and 4000 msec. Each condition comprised 176 trials, with 8 trials per SOA19. Tactile stimuli were delivered using two constant-current electrical stimulators (Digitimer DS7A), which controlled pairs of neurological electrodes attached to the dorsal surface of the middle fingers. The stimuli were supra-threshold vibrotactile stimuli oscillating at 100 Hz, with a total duration of 30 msec. They were instructed to make two-alternative forced-choice judgments regarding the order of stimulation by pressing the button under the index finger of the hand they believed was stimulated earlier or later than the other. The two response strategies (earlier and later) were counterbalanced. Trials with response times exceeding 3000 msec or without a response were re-presented at the end of the corresponding block, ensuring an equal number of trials

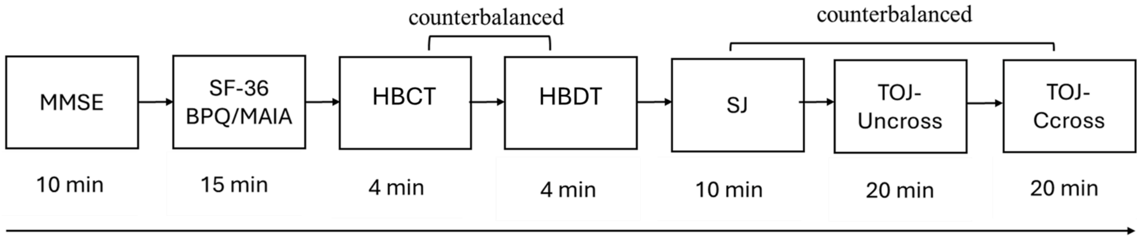

Fig. 1 – Example of experimental flow of the procedure. MMSE = mini-mental state examination; SF-36 = Short Form Health Survey 36 questionnaire; BPQ = body perception questionnaire; MAIA = multidimensional assessment of interoceptive awareness; HBCT = heartbeat counting task; HBDT = heartbeat detection task; SJ = simultaneity judgment; TOJ = temporal order judgment.

across all experimental conditions. No feedback was provided to the participants.

2.4.3. *Temporal order judgment task (TOJ, crossed hands)*

To perceive the location of touch in space, the brain combines information about the touched skin location with information about the location of that body part in space. When the two hands are crossed, this integration is impaired, affecting the ability to judge the order of touches on both hands (Azañón et al., 2016). This crossed-hand posture creates a conflict between how tactile senses represent external space. Consequently, the same cues must be remapped using an external reference frame. This remapping process becomes necessary to accurately judge the temporal order of the tactile stimuli in the crossed-hand condition (Ferri et al., 2016).

In the crossed condition participants were instructed to cross their arms over their wrists. The two possible arm positions (right over left and vice versa) were counterbalanced across participants, and the order was randomly assigned to each participant. Two tactile stimuli were presented in rapid succession, with one stimulus delivered to each hand. The time interval between the two stimuli ranged from −900 to 900 ms (±900, ±600, ±400, ±300, ±200, ±150, ±100, ±80, ±60, ±30, ±10 msec).

2.5. *Interoceptive tasks*

2.5.1. *Data acquisition*

During both heartbeat detection and heartbeat counting tasks, an electrocardiogram (ECG) was recorded. ECG data were obtained from three ECG electrodes (Ag/AgCl) placed in a three-lead configuration: two electrodes were placed on the left and right sides of the participant's lower abdomen, and a third electrode was located beneath the right collarbone. Cardiac signals were recorded with a BIOPAC MP160 System (BIOPAC System, Inc., Goleta, CA, USA) (low-pass filter: 35 Hz; high-pass filter: .05 Hz; notch filter: 50 Hz; sampling rate: 2000 Hz) using the AcqKnowledge software (version 5.0.5, BIOPAC System, Inc., Goleta, CA, USA). The occurrence of the R-peaks in the ECG signal was identified online through a Digital Trigger Unit (DTU100, BIOPAC System, Inc., Goleta, CA, USA).

2.5.2. *Heartbeat detection task*

Heartbeat Detection task, also known as the Tapping or Tracking task (Brener & Ring, 2016; McFarland, 1975), is used to assess participants' ability to accurately perceive and count their own heartbeats. It was employed to measure the interoceptive dimensions (i.e., Interoceptive accuracy, sensibility and awareness). During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and to press a button on a device each time they felt a heartbeat. The task consisted of two time periods, each lasting 2 min, with a pause between them. Following each time interval, participants were required to verbally report their level of confidence in their perceived accuracy of heartbeat detection. This confidence rating was recorded using a scale from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

2.5.3. *Heartbeat counting task*

The Heartbeat Counting task (Schandry, 1981), or Schandry task, is used to assess participants' ability to accurately perceive and count their own heartbeats. This task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals (Garfinkel et al., 2015). During the task, participants were seated comfortably in a chair with both legs on the ground. They were instructed to focus their attention on their bodily sensations and count the number of heartbeats they feel. The task consists of four different time periods: 25 sec, 30 sec, 45 sec, and 100 sec (Pollatos et al., 2008). These time periods are presented in a random order to avoid predictable patterns. During each time interval, participants were instructed to focus their attention on their heart activity and bodily sensations. They were specifically asked to count and keep track of their felt heartbeats without engaging in any physical manipulations, such as taking their pulse or using external cues. Participants were also discouraged from using the duration of the time interval as a basis for estimating the number of heartbeats. The task begins with a 10-s introductory phase to allow participants to settle into the task. Each period is presented separately, with a pause between each trial. Following each time interval, participants were required to verbally report the counted number of heartbeats they perceived. These responses were manually recorded by the experimenter for later analysis. At the end of each trial, participants were immediately asked to indicate their level of confidence (Garfinkel et al., 2015; Khalsa et al., 2018) regarding the accuracy of their responses on a scale ranging from 1 “Total guess/No heartbeat awareness” to 9 “Complete confidence/Full perception of heartbeat”. The evaluation of confidence levels was manually conducted by recording the participants' responses.

2.5.4. *Multidimensional assessment of interoceptive awareness (MAIA)*

The MAIA (Mehling et al., 2012) is composed of 32 items on a 6-point Likert scale, in which the participant must rate “how often each statement applies to you generally in daily life,” with ordinal responses coded from 0 (“never”) to 5 (“always”). According to Trevisan et al. (2023), the MAIA captures interoceptive awareness in its adaptive form, emphasizing mindful attention to bodily sensations and their relevance for self-regulation. This multidimensional instrument measures Interoceptive sensibility on eight scales: (1) Noticing, the awareness of one's body sensations; (2) Not-distracting, the tendency not to ignore or distract oneself from sensations of pain or discomfort; (3) Not-worrying, the tendency not to experience emotional distress or worry with sensations of pain or discomfort; (4) Attention regulation, the ability to sustain and control attention to body sensation; (5) Emotional awareness, the awareness of the connection between body sensations and emotional states; (6) Self-regulation, the ability to regulate psychological distress by attention to body sensations; (7) Body listening, the tendency to actively listen to the body for insight; and (8) Trusting: the experience of one's body as safe and trustworthy.

2.5.5. *Body perception questionnaire (BPQ)*

The body perception questionnaire (BPQ) is a self-report questionnaire that generally evaluates body awareness and autonomic symptoms (Poli et al., 2021; Porges, 1993). It is composed of 22 items and a three-factor structure including a body awareness factor, a supradiaphragmatic factor, and a subdiaphragmatic/body awareness factor. The body awareness (BOA) factor consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) involved in regulating of the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), which includes items related to subdiaphragmatic issues. Importantly, recent studies have suggested that the BPQ may capture aspects of maladaptive interoceptive attention, such as somatization, worry, or hypervigilance, rather than adaptive bodily awareness (Clemente et al., 2024; Trevisan et al., 2020, 2023).

2.6. *Data analysis*

2.6.1. *Simultaneity judgment (SJ)*

We calculated two parameters from SJ: the point of subjective equality (PSE), providing an estimate of the interval between stimuli at which there is the highest probability of the perception of simultaneity and the ‘just noticeable difference’ (JND-sj), reflecting the subject's sensitivity to changes in temporal intervals between the stimuli. The JND value denotes the minimal temporal interval at which the change between the perceived temporal relation stimuli can be observed (Binder, 2015). The analysis of participants' responses allowed us to measure temporal sensitivity in the integration of multisensory stimuli. All descriptive statistics (means and standard deviations) for younger and older adults across tasks and questionnaires are summarized in Table 1.

2.6.2. *Temporal-order judgment task (TOJ – uncrossed/cross hands)*

From TOJ, we measured both the JND for uncrossed and cross conditions (JND-toju; JND-tojc), which represents the smallest interval at which participants can reliably determine which of the two presented sensory inputs came first (Kostaki & Vatakis, 2018), and the Sum of Confusions (SC-toj), that indicates the sum of differences in the response functions between crossed and uncrossed conditions.

The mean response times (RT) and participant responses were calculated by considering the temporal distance between stimuli (SOA).

2.6.3. *Heartbeat detection task*

To calculate the accuracy during the Heartbeat Detection task (Acc-d), the recorded R-peaks and the corresponding tapping times were compared (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). The analysis involves categorizing the tapping responses based on the participant's heart rate (HR) (Fittipaldi et al., 2020; García-Cordero et al., 2017; Yoris et al., 2017). Three categories are used: HR < 69.75, 69.75 < HR < 94.25, and HR > 94.25. For each recorded heartbeat, the difference between the tapping time and the nearest R-peak is calculated. If the HR falls into one of the predefined categories, the tapping response within a specific time window is considered correct. The number of correct tapping responses is tallied for each HR category. The total correct responses for HR < 69.75, 69.75 < HR < 94.25, and HR > 94.25 are denoted as corr_69, corr_betw, and corr_94, respectively.

Table 1 – Descriptive statistics (means and standard deviations) for all tasks and questionnaire measures, reported separately for younger and older adult participants.

	Young adults N = 25		Older adults N = 28	
	M = 12	F = 13	M = 11	F = 17
	Mean	SD	Mean	SD
Age (y.o.)	31.12	6.95	67.43	5.64
SF-36				
Physical functioning	98.92	2.48	81.61	16.28
Role limitations due to physical health problems	88.04	18.92	80.00	33.07
Role limitations due to personal or emotional problems	57.33	43.59	83.33	33.33
Energy/fatigue	52.80	15.55	56.43	19.24
Emotional well-being	63.04	18.95	67.29	18.76
Social functioning	69.00	25.29	71.43	18.59
Bodily pain	82.20	19.99	73.13	19.90
General health	67.40	21.07	60.18	18.33
MAIA				
M 1	2.92	1.04	2.16	1.31
M 2	2.35	.66	2.10	.88
M 3	2.40	.99	2.69	.87
M 4	2.84	1.03	2.82	.97
M 5	3.43	.75	3.43	.89
M 6	2.56	1.02	2.91	1.16
M 7	2.65	1.25	2.63	1.36
M 8	3.16	.97	3.94	.96
Heartbeat detection task				
Acc-d	.80	.14	.76	.10
Con-d	5.42	1.64	6.52	1.44
Aw-d	.80	.14	.79	.16
Heartbeat counting task				
Acc-c	.79	.11	.72	.16
Con-c	6.54	1.16	6.96	1.29
Aw-c	.83	.11	.73	.20
BPQ				
BOA	13.40	4.22	15.75	3.44
SUB	10.68	2.25	10.96	3.08
BOA/SUP	13.28	2.73	15.07	3.09
Multisensory temporal resolution				
JND-sj	119.18	36.88	197.70	71.17
Temporal tactile acuity				
JND-tojun	.00	.96	−.30	.42
JND-tojcr	66.33	31.63	119.874	82.23

We evaluated the sensibility through the score of confidence in interoceptive accuracy during the performance of the Heartbeat Detection task (Con-d). This confidence rating was assessed using a scale ranging from 1 to 9, with 1 indicating low confidence (total guess/no heartbeat awareness) and 9 indicating high confidence (complete perception of heartbeat).

2.6.4. *Heartbeat counting task*

The Heartbeat Counting task measures cardiac interoceptive accuracy by evaluating participants' performance in silently counting their felt heartbeats during specific time intervals

(Garfinkel et al., 2015). Following each time interval, participants were required to verbally report the count or estimated number of heartbeats they perceived. Next, the accuracy score (Acc-c) was calculated by comparing the recorded heartbeats and the counted heartbeats (Koch et al., 2014). The participants' interoceptive accuracy score was computed according to the formula: Accuracy = 1/4 Σ [1 − (|recorded heartbeats − counted heartbeats|/recorded heartbeats)].

At the end of each trial, participants were immediately asked to indicate their level of confidence (also referred to as interoceptive “sensibility”) (Garfinkel et al., 2015; Khalsa et al., 2018) regarding the accuracy of their responses on a scale ranging from 1 “Total guess/No heartbeat awareness” to 9 “Complete confidence/Full perception of heartbeat”.

The awareness was calculated by comparing the accuracy and the confidence through the absolute difference between the rescaled (min–max normalization) measures of interoceptive accuracy and confidence (Mattioni et al., 2024).

2.6.5. *Multidimensional assessment of interoceptive awareness (MAIA)*

The MAIA generally evaluates multiple dimensions of interoceptive sensibility. From the MAIA we obtained a score for each subscale: Noticing (1 M), Not-Distracting (2 M), Not-Worrying (3 M), Attention Regulation (4 M), Emotional Awareness (5 M), Self-Regulation (6 M), Body Listening (7 M), Trusting (8 M).

The score for each scale is calculated by averaging the scores of its individual items and thus can vary in the 0–5 range.

2.6.6. *Body perception questionnaire (BPQ)*

From BPQ evaluates body awareness and autonomic symptoms. From the BPQ we obtained a score for each factor: the body awareness (BOA) that consists of items related to the upper parts of the body, the supradiaphragmatic (SUP) that is involved in regulating the functions of organs situated above the diaphragm and additionally, the subdiaphragmatic/body awareness factor (BOA/SUB), includes items related to subdiaphragmatic issues.

2.7. *Statistical Analysis*

To capture age-specific differences (young versus older adults), separate multiple regression analyses using a stepwise forward method were performed to examine the relationships between physical health dimensions, interoceptive measures (both objective and subjective), and multisensory integration.

The dependent variables were the mean scores (0–100) of the subscales of the SF-36 questionnaire related to the physical domain: Physical Functioning, Role Limitations Due to Physical Health, Energy/Fatigue, and General Health. Independent variables included *subjective* interoceptive measures (Con-c, Con-d, the eight dimensions of the MAIA questionnaire and the three factors of BPQ), *objective* interoceptive measures (Acc-c, Acc-d), *metacognitive* interoception (Aw-c, Aw-d) and multisensory integration indices (JND-sj, JND-tojc). Only statistically significant findings are reported, focusing on the most relevant predictors for understanding physical functioning and health in young and older adult populations. Moreover, to assess the influence of age on the significant predictors identified in the regression analyses, a MANOVA was performed with age group (young versus older adults) as a between-subjects factor. Univariate ANOVAs were then conducted to examine the effect of age on each variable.

3. Results

3.1. *Regression analysis*

In the older adults group, the multiple regression analyses with *Physical Functioning* (SF-36) as criterion showed a model with 9 predictors: F (11, 13) = 20.264, $p < .00001$, $R = .97$, $R^2 = .95$. To illustrate the goodness of the model, a graph comparing the observed and predicted values is presented in Fig. 2, where the clustering of data points near the red line suggests a strong predictive capacity.

The predictors Aw-c, Aw-d, and M3, M4, M5, M6 (MAIA), the Acc-c (heartbeat counting accuracy), BOA/SUB (BPQ) and JND-sj contributed significantly to the model (see Table 2). Subjective interception indices, such as sensibility and awareness (Aw-c, Aw-d, M3, M4, M5, M6), predict perceived physical functioning differently. Specifically, greater attention to bodily sensations (M4) and greater interoceptive metacognitive awareness (Aw-c, Aw-d, BOA/SUB), predicted higher levels of perceived physical functioning. Furthermore, lower tendency to ignore physical pain and discomfort (M3) predicted higher levels of perceived physical functioning. It is interesting to note that lower awareness of the relationship between emotional and physical states (M5) and lower ability to regulate emotional distress (M6) predict higher physical functioning. Overall, these results suggest a potential dissociation between emotional and bodily interoceptive awareness and physical self-evaluation.

Regarding objective interoception, higher accuracy in the heartbeat counting task (Acc-c) was associated with lower perceived physical functioning. Finally, poorer multisensory integration, as indicated by higher scores in multisensory

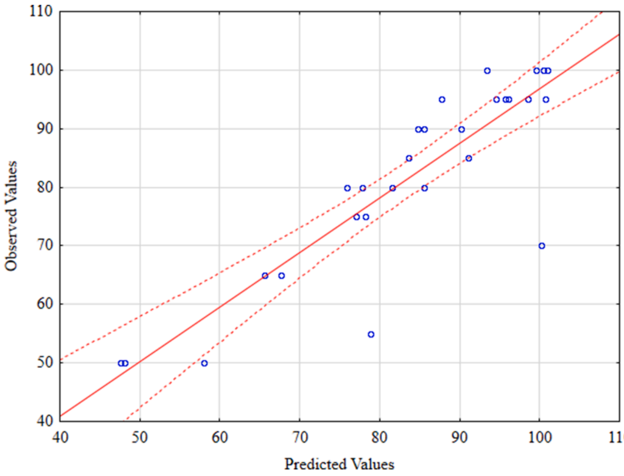

Fig. 2 – Graph shows observed versus predicted values from the stepwise forward regression model with physical functioning as a criterion.

Table 2 – The table shows the effect of predictors that contributed significantly to the model in relation to physical functioning as a criterion.

Physical Functioning	β	Std. Err.	t	p
Aw-c	.46	.11	4.110	.001***
Aw-d	.30	.09	3.135	.007*
M3	−.29	.12	−2.421	.030*
M4	1.12	.11	9.966	.000***
M5	−.41	.12	−3.362	.005*
M6	−.48	.14	−3.395	.004*
BOA/SUB	.22	.08	2.577	.022*
Acc-c	−.30	.07	−3.718	.002*
JND-sj	−.25	.11	−2.571	.023*

*** p < .001; ** p < .01; * p < .05. Aw-c = awareness in heartbeat counting task; Aw-d = awareness in heartbeat detection task; M3 = not-worrying MAIA scale; M4 = attention regulation MAIA scale; M5 = emotional awareness MAIA scale; M6 = self-regulation MAIA scale; BOA/SUB = subdiaphragmatic/body awareness factor of BPQ; Acc-c = accuracy in heartbeat counting task; JND-sj = just noticeable difference in simultaneity judgement task.

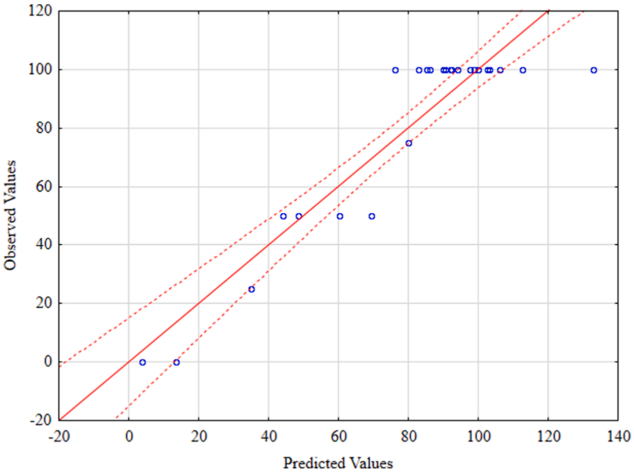

Fig. 3 – Graph shows observed versus predicted values from stepwise forward regression model with Role limitations due to physical health as a criterion.

Table 3 – The table shows the effect of predictors that contributed significantly to the model in relation to Role limitations due to physical health as a criterion.

Role limitations due to physical health	β	Std. Err.	t	p
M3	−1.02	.24	−4.306	.000***
M4	1.18	.17	7.110	.000***
M5	−.67	.23	−2.959	.011*
BOA	.58	.15	3.903	.001***
Con-d	.49	.14	3.382	.004**
Acc-c	−.50	.14	−3.640	.002**
JND-sj	−.37	.13	−2.750	.016*

*** p < .001; ** p < .01; *p < .05.
M3 = not-worrying MAIA scale; M4 = attention regulation MAIA scale; M5 = emotional awareness MAIA scale; BOA = body awareness BPQ factor; Con-D = confidence in heartbeat detection task; Acc-c = accuracy in heartbeat counting task; JND-sj = just noticeable difference in simultaneity judgement task.

temporal resolution (JND-sj), was linked to reduced perceptions of physical functioning.

In the young group, the multiple regression analyses with *Physical Functioning* (SF-36) as criterion showed a model with 1 predictor: F (6, 18) = 3.010, p < .00001, R = .70, R^2 = .50. The predictor Aw-c contributed significantly to the model (β = -.70; SE = .20; t = −3,462; p < .002), indicating lower levels of subjective interoception awareness were associated to higher levels of perceived physical functioning. No significant effects for both young and older adults for the Energy/Fatigue and General Health emerged.

Moreover, in the older adult group, the multiple regression analysis with *Role limitations due to physical health* (SF-36) as criterion resulted in a significant model with 7 predictors: F (11, 13) = 7.058, p = .0007, R = .93, R^2 = .86. To illustrate the model, a graph comparing the observed and predicted values is presented in Fig. 3, where the alignment of points near the red line suggests a strong predictive ability of the model.

The predictors M3, M4, M5 (MAIA), BOA (BPQ), Con-d (Detection), Acc-c (Counting), and JND-sj contributed significantly to the model (see Table 3): high levels of subjective interoception, such as *sensibility* and *awareness* (BOA, Con-d, M3, M4, M5), were associated with lower perceived physical limitations (i.e., high scores on the SF-36 scale). Specifically, higher attention to bodily sensations (M4) and increased metacognitive interoceptive awareness (Con-d, BOA) predicted lower perceived physical limitations. Interestingly, lower awareness of the connection between bodily and emotional states (M5) was also associated with fewer perceived limitations, suggesting that reduced emotional interoception may attenuate physical self-assessment. Conversely, a greater tendency to ignore physical pain (M3) was linked to higher perceived physical limitations. In contrast, higher objective interoceptive indices, such as accuracy, predicted higher perceived physical limitations. In fact, the results suggest that a greater ability to detect one's own beats (Acc-c) leads to the perception of greater physical limitations.

Lastly, reduced *multisensory integration,* defined by higher JND-sj scores (i.e., poorer multisensory temporal resolutions), was also associated with increased perceptions of physical limitations.

On the other side, in the young group, the multiple regression analysis with *Role limitations due to physical health* (SF-36) as criterion showed a model with 1 predictor: F (5, 19) = 2.931, p = .03, R = .70, R^2 = .44. The predictor JND-sj contributed significantly to the model (*β* = .41; SE = .18; t = 2,306; p < .03), indicating that higher *multisensory integration,* defined by lower JND-sj scores (i.e., better multisensory temporal resolutions), was associated with lower perceived physical limitations. No significant effects were found for both young and older adults on the Energy/Fatigue and General Health subscales.

3.2. MANOVA analysis

The MANOVA showed a significant overall effect of the experimental condition on the cognitive performances, Pillais' Lambda = .50, F (11, 41) = 3,780, $p < .0008$, multivariate $\eta^2_p = .50$. The Univariate analyses showed significant differences between the two groups for several interoceptive measures, as well as multisensory integration variables (see Table 4).

As shown in Table 5, subjective interoception (Con-D, BOA, BOASUB) were higher in the older group compared to the younger group. However, the components assessing metacognitive interoception were better in the younger group than in the older group (Aw-c), and objective interoception (Acc-c) tended to be better in the younger group than in the older group ($p = .06$). Finally, multisensory integration processes were higher in the younger group compared with the older group.

4. Discussion

Functional and physical limitations in aging are risk factors for future disability and institutionalization (Onder et al., 2005; Paterson et al., 2004). Given the increasing proportion of older adults in the Western countries, understanding what factors may contribute to predicting such limitations is an important public health endeavour, and a goal for maintaining an independent lifestyle for as long as possible.

To address this issue, we assessed the daily life functioning of a group of young and older adults by means of the Short Form Health Survey 36 questionnaire (SF-36; Ware et al., 1992; Apolone and Mosconi, 1998). To assess interoceptive dimensions, participants completed the MAIA and BPQ questionnaires, followed by the COUNTING AND Detection tasks. Finally, to assess multisensory integration, participants performed the simultaneity judgment (SJ) task and the temporal order judgment (TOJ) task, with crossed and uncrossed hands (Pasciucco et al., 2025; Sarko, Nidiffer, et al., 2012; Sarko, Eisenhut, et al., 2012; Laasonen et., al, 2001).

Table 4 – The table shows the effect of univariate results to examine the effect of age on each variable.

Variables	F	*p*
Aw-c	5.295	**.025***
Acc-c	3.670	.061
Con-d	6.748	**.012***
BOA	4.978	**.030***
BOA/SUB	4.962	**.030***
JND-sj	24.518	**.000*****

*** p < .001; ** p < .01; *p < .05.
Aw-c = awareness in heartbeat counting task; Acc-c = accuracy in heartbeat counting task; Con-D = confidence in heartbeat detection task; BOA = body awareness BPQ factor; BOA/SUB = subdiaphragmatic/body awareness factor of BPQ; JND-sj = just noticeable difference in simultaneity judgment task.

Table 5 – The table shows the descriptive analysis on tasks and questionnaire.

Variables	Mean $_{Young}$	SD $_{Young}$	Mean $_{Old}$	SD $_{Old}$
Aw-c	.83	.11	.73	.20
Acc-c	.79	.11	.72	.16
Con-d	5.42	1.64	6.52	1.44
BOA	13.40	4.22	15.75	3.44
BOA/SUB	13.28	2.73	15.07	3.09
JND-sj	119.18	36.88	197.70	71.17
PF	98.92	2.48	81.61	16.28
RLPH	88.04	18.92	80.00	33.07

Aw-c = awareness in heartbeat counting task; Acc-c = accuracy in heartbeat counting task; Con-D = confidence in heartbeat detection task; BOA = body awareness BPQ factor; BOA/SUB = subdiaphragmatic/body awareness factor of BPQ; JND-sj = just noticeable difference in simultaneity judgement task; PF = physical functioning; RLPH = role limitations due to physical health.

Our findings indicate that, in older adults, different dimensions of interoception and multisensory integration show distinct relationships with perceived physical functioning. In more details higher attention to bodily sensations (M4, BOA/SUB) and metacognitive interoceptive awareness (Aw-c, Aw-d) were associated with higher perceived physical functioning. Furthermore, lower tendency to ignore physical pain and discomfort (M3) predicted higher levels of perceived physical functioning. Conversely, lower awareness of the relationship between emotional and physical states (M5) and lower ability to regulate emotional distress (M6) predict higher physical functioning. These aspects could reflect a compensatory response to perceived physical functioning. Overall, these findings suggest that accurate monitoring of bodily sensations, combined with less processing of emotional and regulatory aspects, may promote a more positive assessment of one's physical abilities. This indicates a potential dissociation between interoceptive and emotional body awareness in the perception of physical functioning, in line with previous studies that emphasise the crucial role of interoceptive awareness in shaping the perception of physical well-being (Wallman-Jones et al., 2021). Finally, the reduction of emotional and regulatory aspects could represent an adaptive strategy implemented in conditions of reduced physical efficiency. Rather than indicating a maladaptive profile, this finding might reflect the use of interoceptive attention to manage distress or preserve autonomy in the face of functional decline. Consistently, older adults with higher levels of objective interoception, reported lower perceived physical functioning, which could indicate that a greater ability to accurately monitor bodily cues accentuates awareness of one's functional limitations.

At the same time, this ability could help explain why some elderly people, even in the face of inevitable decline in sensory and physical abilities, still perceive relatively higher levels of functioning, probably due to adaptive use of interoceptive information.

Although interoceptive accuracy generally tends to decline with age, and older adults often show reduced interoceptive awareness (Khalsa, Rudrauf, & Tranel, 2009; Ulus & Aisenberg-Shafran, 2022), we found instead that preserved interoceptive awareness may promote better perceived physical health. However, our findings revealed an interesting dissociation between the reduction of interoceptive emotional and physical regulatory aspects and high perception of physical functioning. Overall, this could reflect the adoption of different adaptive strategy in response of reduced physical efficiency. Conversely, reduced multisensory integration (as indicated by JND-sj scores, where higher scores represent poorer performance) were associated with lower perceived physical functioning, Difficulties in processing and integrating sensory information from the external environment can adversely impact physical performance and overall health perception. Multisensory integration is crucial for accurately perceiving and responding to external stimuli, playing a fundamental role in daily activities (de Dieuleveult et al., 2017). Impairments in this area can negatively impact physical capabilities in older adults. In line with this, previous studies have shown that age-related deficits in multisensory integration can contribute to physical limitations and a diminished sense of functional ability (Diaz & Yalcinbas, 2021; Seghier, 2013). For instance, impaired multisensory integration can increase the risk of falls among older adults (Mahoney et al., 2019; Zhang et al., 2020), further highlighting the importance of sensory processing for maintaining physical functioning in aging populations.

In young people, results show that lower interoception (Aw-c) predicts higher physical functioning, suggesting that interoceptive perception could also play an adaptive role in relation to bodily functioning in this age group. Indeed, a study by Fischer et al showed that individuals with a high physical activity tend to show lower scores on the heart rate counting task, leading them to “ignore” bodily sensations to optimize performance. Similarly, research on healthy youth populations suggests that excessive interoception can increase the perception of fatigue and limit physical activity (Herbert & Pollatos, 2018). Overall, these data suggest that, in youth, lower body awareness may be a functional advantage, facilitating better physical functioning. Similarly, it also emerged how different dimensions of interoception and multisensory integration show distinct relationships with role limitations due to physical health. Particularly in the older adults, higher attention to bodily sensations (M4, BOA) and higher confidence in interoceptive capacity (Con-d) were associated with lower perceived physical limitations, suggesting a stronger connection with internal bodily signals fosters a more positive perception of their physical state. In contrast, the tendency to ignore physical discomfort (M3) and emotional awareness (M5) were linked to greater perceived limitations in physical functioning, indicating that focusing on physical discomfort and difficulties in recognise emotion leads to a worse perception of physical functioning and increased awareness of limitations. Consistently, older adults with higher levels of objective interoception (Acc-c) reported higher perceptions of physical limitations, which could reinforce the idea that a greater ability to accurately monitor body signals heightens awareness of one's functional limitations. Finally, difficulties in processing external sensory information and integrating it effectively (JND-sj) are found to be associated with a worse perception of physical functioning. In contrast, in young people, a greater capacity for multisensory integration is associated with a better perception of one's physical functioning. Taken together, these results are consistent with existing models of successful ageing, which propose that older adults are less likely to maintain good functionality in daily life when they perceive significant motor or sensory limitations (Lowry et al., 2012). This highlights the critical role of sensory processing in shaping older adults' subjective experiences of physical health and their ability to adapt to age-related changes.

In this perspective, the differences between the elderly and the young in the dimensions of interoception and multisensory integration, which emerged from the MANOVA, are particularly relevant. Indeed, univariate ANOVAs showed that although the elderly report higher levels of subjective interoception, this result may reflect primarily a compensatory or reassuring perception, rather than real functional superiority. In contrast, metacognitive, objective, and multisensory integration components are found to be more efficient in the young, suggesting an age-related decline in more complex interoceptive abilities and a subsequent reorganization of processing strategies in the elderly. These data could indicate that, with advancing age, interoceptive perception tends to shift from more analytical and accurate forms to more subjective and compensatory modes. This reorganization, while not providing the same level of efficiency observed in the young, may still play an adaptive role, helping to preserve the perception of well-being despite functional decline.

From a neurocognitive and neurofunctional view, examining the brain regions involved in these processes provides insight into the compensatory strategies that older adults employ to maintain performance despite age-related declines in multisensory and interoceptive processing, For instance, neuronal loss, microinfarcts, and white matter alterations have been linked to daily physical activity in older adults, with the integrity of regions such as the insula, precentral and postcentral gyri, and white matter tracts strongly associated with physical activity levels near the end of life (Buchman et al., 2018). Although older and younger adults demonstrate similar behavioural responses to multisensory stimuli, neuroimaging reveals distinct patterns of brain activity, Younger adults show greater activation in sensory-specific regions like the superior temporal gyrus and calcarine fissure, whereas older adults increasingly rely on dorsal frontal and parietal areas, indicating compensatory recruitment of regions involved in executive functions and attention (Diaz and Yalcinbas, 2021), Additionally, the angular gyrus plays a pivotal role in multisensory integration in older adults, serving as a hub for sensory convergence (Hirst et al., 2021; Seghier, 2013).

Interoceptive processing, critical for physical functioning, engages regions such as the insula, anterior cingulate cortex, and medial prefrontal cortex, with the Salience Network playing a key role in prioritizing interoceptive signals (Ueno et al., 2020; Wu et al., 2024). The insula emerges as a central structure linking interoception with daily functioning, while frontal, parietal, and angular gyrus regions support compensatory multisensory strategies. This intricate interplay reflects the adaptive complexity of sensory and interoceptive systems in aging, underscoring the brain's ability to reallocate resources to maintain functional performance.

To sum up, aging-related changes in multisensory interoceptive processing are accompanied by an increase in physical limitations, such as self-reported autonomic movement difficulties. These changes can have a significant impact on the ability to perform daily activities, reducing overall quality of life (Mullen et al., 2012; Rejeski & Mihalko, 2001; Stuifbergen et al., 2006). Indeed, our study highlights the critical interaction between exteroceptive dimensions and multisensory temporal processing, demonstrating their significant role in influencing the perception of physical well-being.

The integration of contributions from different aspects of exteroceptive and interoceptive dimensions in examining physical functioning in different age groups represents a novel aspect of this study. This approach provided a more comprehensive and detailed understanding of how these factors interact to shape perceptions of physical functioning, particularly in older adults.

These findings highlight the critical interaction between exteroceptive and interoceptive dimensions in shaping perceptions of physical functioning. While the present study provides valuable insights, some methodological considerations should be noted. Performance on the Heartbeat Counting Task may reflect not only interoceptive processes, but also other factors, such as prior knowledge or beliefs about heart rate (e.g. Desmedt et al., 2018; Flynn & Clemens, 1988; Montgomery & Jones, 1984; Ring et al., 2015; Zamariola et al., 2018). Moreover, the lack of an objective physical assessment does not allow us to determine whether altered interoceptive or multisensory processing leads to reduced physical functioning, or whether functional decline itself contributes to sensory processing deficits. Future studies will be needed to clarify the directionality and underlying mechanisms of these associations. Finally, the older adult group included a broad age range (58–87 years), and future studies could explore whether the observed associations vary across narrower age ranges. This would help to strengthen and generalize the present findings. It should be noted that the study was powered to detect only large effects, and smaller associations may have gone undetected. Further studies will be needed with larger samples to better characterize the strength and generalizability of these associations. These findings highlight the potential importance of fostering interoceptive abilities to support well-being in later life.

CRediT authorship contribution statement

M.R. Pasciucco: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Nunziata:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **S. Iuliano:** Writing – original draft, Methodology, Formal analysis. **M.G. Perrucci:** Validation, Software, Resources, Data curation. **M. Costantini:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **G. Ruggiero:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **F. Ferri:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Acknowledgments

This research paper was supported by Boosting Ingenium for Excellence (BI4E) project, funded by the European Union' s HORIZON-WIDERA-2021-ACCESS-05-01-European Excellence Initiative under the Grant Agreement No. 101071321.

-The PRIN 2022 – Interception and Active Aging (InterActing) - Prot, 2022JS4SY2.

-The Departments of Excellence 2023–2027″ initiative of the Italian Ministry of University and Research for the Department of Neuroscience, Imaging and Clinical Sciences (DNISC) of the University of Chieti-Pescara.

We would like to thank Uni Tre Associazione Nazionale delle Università della Terza Età (National Association of Universities of the Third Age) – Chieti (Italy) for their collaboration and support in participant recruitment.

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