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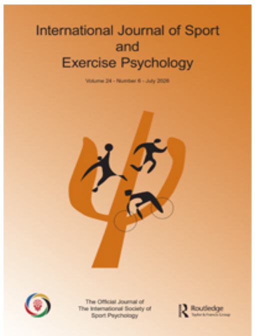


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# Associations between physical activity intensity and experience, self-regulation, and self-reported interoceptive accuracy and attention

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**ABSTRACT**

Interoception may play a key role in promoting healthy lifestyles, but its determinants are largely unknown. This study examines how (1) regular engagement in physical activity (PA), (2) years of PA experience, and (3) self-regulation are associated with interoceptive accuracy and attention. Included were 1178 participants (age = 52.13 ± 16.78). The Interoceptive Accuracy Scale and Interoceptive Attention Scale were used, along with the International Physical Activity Questionnaire to determine physical activity, with in-depth questions to determine years of experience. Self-regulation was assessed using the Short Self-Regulation Questionnaire. Results indicated that PA experience (M = 13.39 ± 15.39, β = −0.021, CI = [−0.036, −0.006]) was negatively associated with interoceptive attention, but not accuracy. Self-regulation (M = 109.36 ± 13.50, β = 0.262, CI = [0.210, 0.315]) was positively associated with interoceptive accuracy, but not attention. Different PA intensities were not associated with either interoceptive accuracy nor attention (all β < |0.022| and *p* > 0.07). More years of PA experience may result in adaptive habituation effects where well-developed internal models reduce the need for monitoring of bodily signals. Self-regulatory skills negatively associated with interoceptive attention, potentially reflecting greater bodily trust. Adaptive interoceptive processing may be crucial for PA engagement.

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Interoception; Self-report; Exercise; Health; Lifestyle

## Highlights

- Interoception is key in healthy lifestyles, but its determinants are largely unknown.
- Adaptation to physical activity develop internal interoceptive models.
- Improved self-regulation results in greater processing efficiency and bodily trust.
- Adaptive interoceptive processing may be crucial for physical activity engagement.

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Physical activity is an important factor in maintaining cardiovascular and musculoskeletal health, promoting mental health, and reducing the risk of non-communicable disease. However, only one in five adolescents and adults worldwide meet aerobic and muscle strengthening activities guidelines (Garcia-Hermoso et al., 2023). Interoception, the perception of internal bodily signals, may play a key role in promoting a healthy lifestyle, specifically in engaging in physical activity (Mulder, Boelens, et al., 2025). When interoceptive signals are insufficiently or excessively perceived during physical activity, this may lead to adverse health behaviour. For example, when there is a mismatch between perceived fatigue and the actual physiological state during physical activity, this can result in hypoactivity (i.e., reduced participation in physical activity, which may lead to problems related to sedentary behaviour such as obesity) or hyperactivity (i.e., continuation of physical activity resulting in fatigue and injuries; Wallman-Jones et al., 2021). Because these mismatches could damage the body, the brain intervenes by modulating or terminating physical activity in order to prevent physiological harm (McMorris et al., 2018). This highlights the importance of studying the determinants of interoception, and understanding these can provide insights into how physical activity is initiated, regulated, and maintained.

There is a possible bi-directional relationship between physical activity and interoception. Participation in physical activity helps to tune internal models (i.e., the brain's ability to predict and control movements based on prior experiences and sensory feedback), and better tuned internal models allow for better management of exertion (Seabury et al., 2023). Here, interoceptive accuracy and attention may relate differently with various physical activity intensities. At lower intensities, individuals may be able to accurately predict internal states as attention can be solely put toward bodily signals, but with increasing exertion attentional resources have to be shared with other competing signals (Marshall et al., 2018; Wallman-Jones et al., 2023). During interoceptive accuracy tasks, such as heartbeat tracking, brain activation is not only found in the insular cortex, anterior cingulate cortex, and prefrontal cortex, but also in the primary motor cortex and supplementary motor area (Critchley et al., 2004; Zarza Rebollo et al., 2019). The overlap in brain activation during interoceptive and motor tasks implies that engaging in physical activity could potentially improve interoception, or vice versa.

Additionally, an individual's physical activity background and experience may influence interoceptive responses: prior experience in physical activity may moderate interoceptive reactions to physical activity, increasing accuracy of perceiving internal bodily signals (Wallman-Jones et al., 2022). This relates to a central command network and ratings of perceived exertion: during physical activity, signals from the brain, accompanied by memories of prior experiences, help to manage energy expenditure and the intensity of physical exertion through interoceptive predictions. Ratings of perceived exertion are generated by interoceptive processes that compare the expected sensations with incoming bodily signals (Brevers et al., 2024; McMorris et al., 2018). During lower intensity physical activities, these cognitive control strategies are easier to maintain, future interoceptive states are easier to predict, and there are fewer interoceptive prediction errors. This allows for better interoceptive regulation and the adaptation to physical activity intensities so homeostasis is not threatened (McMorris et al., 2018; Seabury et al., 2023). It is expected that those who are more frequently physically active, and have been for a longer period during their lives, are better able to engage in and maintain physical activity because of reduced errors between expected sensations and incoming interoceptive signals (Brevers et al., 2024; McMorris et al., 2018).

Current research on the relation between engagement in physical activity and interoception is limited. That is, prior studies focused on single interoceptive domains, such as interoceptive accuracy (Abrams et al., 2018; Herbert et al., 2007; Kosa et al., 2021; Koteles et al., 2020; Machado et al., 2019; Teng et al., 2018). Interoceptive accuracy refers to the ability to adequately interpret interoceptive signals, while interoceptive attention refers to the extent to which one pays attention to interoceptive signals. Furthermore, studies often look at only one modality of interoception, such as perception of heartrate (Abrams et al., 2018; Herbert et al., 2007; Kosa et al., 2021; Koteles et al., 2020; Machado et al., 2019). Other interoceptive modalities can, for example, include the perception of respiratory sensations or digestive processes. Interoceptive domains and modalities relate in different ways to several disorders, showing the need for research that includes both domains and several essential modalities (Heim et al., 2023; Schoeller et al., 2025). Finally, current research mainly focuses on acute exercise protocols (Wallman-Jones et al., 2022; Wallman-Jones et al., 2023), while interoceptive responses may differ when intensity of physical activity changes. These findings underscore the need for more comprehensive research on how different physical activity intensities, backgrounds, and levels of experience associate with various domains of interoception. Therefore, the current study focuses on the determinants of multiple domains of interoception, in relation to various intensities of physical activity.

One possible determinant that may be important both in physical activity and interoception is self-regulation. Self-regulation plays a key role in initiating, sustaining, and adapting to (regular) physical activity (van Genugten et al., 2017). General self-regulation commonly refers to cognitive and behavioural strategies that facilitate behaviour adaptation, and comprises of meta-cognitive functions such as the ability to reflect, plan, monitor, and evaluate a goal-directed process as well as aspects of motivation and self-efficacy (Menting et al., 2019). In physical activity, self-regulation is relevant not only for managing fatigue in people with long-term conditions (e.g., chronic pain conditions, cardiovascular diseases, neurological conditions, arthritis, cancer, and gastrointestinal conditions) and promoting sustained physical activity, but also for improving health-related quality of life (Barakou et al., 2023).

Individuals with better self-regulatory behaviour may be better equipped to perceive and interpret bodily signals, allowing them to identify what requires immediate regulation. Self-regulation involves monitoring one’s thoughts, emotions, and impulses, a process that depends on cognitive functions like attention, working memory, and inhibition (Hofmann et al., 2012). These introspective skills overlap with the ability to tune into subtle internal sensations, which may be key to good interoception. Regions of the brain involved in self-regulation, like the prefrontal cortex, also help process interoceptive signals. In essence, these individuals’ executive functions and body monitoring functions are well integrated. Conversely, those with lower interoceptive accuracy may struggle with self-regulation, as they lack awareness of the most urgent physiological needs (Füstös et al., 2013; Georgiou et al., 2015; Herbert et al., 2007; Marshall et al., 2018). Thus, it could be that individuals with better self-regulatory skills also display better self-reported interoceptive accuracy, supporting engagement in sufficient physical activity.

The purpose of this study is to examine how varying intensities of physical activity (e.g., walking, moderate intensity, and vigorous intensity), physical activity experience, and self-regulation are associated with both self-reported interoceptive accuracy and attention. Our hypotheses are that (1) greater participation in walking, moderate intensity, and vigorous intensity activities are related to better self-reported interoceptive accuracy and attention; (2) more years of experience in physical activity are associated with better self-reported interoceptive accuracy and attention scores; and (3) better self-regulation is related to better self-reported interoceptive accuracy.

## Methods

### Population

Participants in the current study were from the general Dutch population, recruited through a Dutch internet panel administered by research agency Flycatcher (www.flycatcher.eu). Through Flycatcher's "double-active-opt-in" participants voluntarily and actively indicated their willingness to participate in this study. Flycatcher's panel consists of 20,000 members from the Dutch general population, giving a fair representation based on sex, age, region, and socio-economic status (SES). Flycatcher meets high quality standards and is ISO-certified, and offers participants points to be spent on (charity) gift vouchers for completing surveys. Participants had to meet the following criteria to participate in the study: (1) the subject was at least 18 years old, and (2) the subject had a clear understanding of the Dutch language. Sample size calculations for linear multiple regression analyses using G*Power 3.1 (Faul et al., 2009) suggested a minimum sample size of 1240 participants, based on an effect size of 0.02, alpha of 0.005 (0.05 divided by 10 predictors in the original study protocol), and a power of 0.8. Participants were contacted via email to take part in the study.

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The local research committee (reference number WSC-2024-26/ SP) and local ethics committee (METC number N24.072) approved this study as non-WMO.

### Measures

#### Demographic information

Demographic data that were collected by Flycatcher included age at the time of filling in the questionnaires, sex (male, female, or other), education category (low, middle, or high based on the Dutch education system), and income category (below average, average, or above average). Education and income were used to calculate SES, resulting in low (i.e., low education plus below average income, middle education plus below average income, or low education plus average income) or high (i.e., high education plus average income, middle education plus above average income, or high education plus above average income) SES.

#### Self-reported interoceptive accuracy

The Interoceptive Accuracy Scale (IAS; Murphy et al., 2020) is a questionnaire constructed to include items relating to physical sensations that have either been described as interoceptive or are associated with activation in the insula, an area commonly associated with the processing of interoceptive signals. The questionnaire was developed as part of a $2 \times 2$ factorial structure of interoception (Murphy et al., 2019), a model that is based on dimensions of interoception proposed by Garfinkel (Garfinkel et al., 2015). An example of a question in this questionnaire is "I can always accurately perceive when my heart is beating fast." The scale includes 21 items rated on a scale from strongly agree (5) to strongly disagree (1), with total scores ranging from 21 to 105. Higher scores show greater self-reported interoceptive accuracy. A Dutch version of the IAS (IAS-D; Appendix A) was used (Mulder, Elferink-Gemser, et al., 2025). Previous research has shown that the IATS demonstrates good to excellent consistency across languages. The internal consistency of the IAS-D in the current sample was $\alpha = 0.90$.

### *Self-reported interoceptive attention*

The Interoceptive Attention Scale (IATS; Gabriele et al., 2022) is a questionnaire constructed to quantify the extent to which internal signals are the object of one's attention. The signals exactly match the signals included in the IAS. The questionnaire was developed as part of a $2 \times 2$ factorial structure of interoception (Murphy et al., 2019), a model that is based on dimensions of interoception proposed by Garfinkel (Garfinkel et al., 2015). An example of a question in this questionnaire is "Most of the time my attention is focused on whether my heart is beating fast." The IATS comprises 21 items rated from strongly agree (5) to strongly disagree (1), with total scores ranging from 21 to 105. Higher scores indicate greater self-reported attention to internal signals. A Dutch version of the IATS (IATS-D; Appendix B) was used (Mulder, Elferink-Gemser, et al., 2025). The scale has shown good to excellent internal consistency in prior validation work. The internal consistency of the IATS-D in the current sample was $\alpha = 0.96$.

### *Physical activity*

The International Physical Activity Questionnaire (IPAQ; Booth, 2000) covers four domains of physical activity: work-related, transportation, housework/gardening, and leisure-time activity. Additionally, the questionnaire includes questions about time spent sitting as an indicator of sedentary behaviour. In this study, the fourth domain ("Physical activities related to sports and leisure") was used to determine the time spent on physical activity. Number of days per week and time spent per day in walking, moderate, and vigorous intensity physical activities were recorded. Hours per week reported in walking-, moderate-, and vigorous-intensity activities were used as outcome measures. Additionally, participants were asked about their years of experience in physical activities they primarily participate in.

### *Self-regulation*

The Short Self-Regulation Questionnaire (SSRQ; Carey et al., 2004) is a 31-item measure of the ability to regulate behaviour in order to achieve desired future outcomes. The SSRQ is a short form of the original Self-Regulation Questionnaire. Response options range from strongly disagree (1) to strongly agree (5), with total scores ranging from 31 to 155. Example of questions in this questionnaire are "I usually keep track of my progress towards my goals" and "I have trouble making up my mind about things." Higher scores indicate better self-regulatory skills. Since the SSRQ was not available in Dutch, the questionnaire was first translated from English to Dutch by a professional organisation specialised in medical translations. After this, think-aloud interviews were conducted in which participants speak their thoughts while completing the questionnaire, providing insights into their reasoning, decisions, and problem-solving processes. These insights were then used to revise the translated questionnaire where necessary, in accordance with established guidelines for cross-cultural health research (Sousa & Rojjanasrirat, 2011). See Appendix C for the specific items of the SSRQ-D. The internal consistency of the SSRQ-D in the current sample was $\alpha = 0.91$.

### *Statistical analyses and software*

All analyses were performed using a custom script written in Python (version 3.12), using the SciPy (version 1.14) and statsmodels (version 0.14) packages. Normality of data for all measures was checked beforehand, by visually examining the distribution of data using histograms and Q-Q plots, and performing the Shapiro–Wilk test. For variables with missing data (i.e., SES), analyses indicated that data were missing at random (MAR > 0.5). Missing values were imputed using the Multiple Imputation by Chained Equations with random forests (MICEforest version 6.0) package in Python, generating ten imputed datasets and running 20 iterations. Given the substantial data loss and evidence supporting MAR assumptions, we report the imputed analysis as our primary results, with complete case analysis provided in supplementary materials (Supplemental file 1).

Given a sample skewed toward older adults, we expected the vigorous intensity activities variable to be non-normally distributed. Following data cleaning, vigorous intensity activity (skewness = 2.80) showed positive skew and leptokurtosis, with a zero-inflated distribution (median = 0.00). To address these distributional issues and improve model assumptions of linearity and homoscedasticity, multivariate regression analyses with log-normalisation were adopted, with the IAS-D and IATS-D as dependent variables, and the three IPAQ categories (hours of walking, moderate, and vigorous intensity activities), years of experience in the physical activity primarily participated in, and SSRQ-D as independent variables. All dependent, independent, and covariate variables were transformed (i.e., a log–log model). This means coefficients should be interpreted as elasticities: a 1% increase in the dependent variable is associated with a β% change in the independent variable. For example, if walking hours per week has a coefficient of 0.25 in the IAS model, this means a 1% increase in walking hours per week is associated with a 0.25% increase in IAS scores. While multicollinearity after normalisation caused a potentially concerning variance inflation factor in the self-regulation variable (VIF > 20), this variable did not show elevated correlation coefficients ($r < 0.3$ at most). Given this suggested compound rather than problematic multicollinearity, and the theoretical importance of self-regulation as a potential mediator, this variable was retained in the log-normalised regression analyses.

First, univariate regression analyses were performed to analyse the relation between the dependent and independent variables separately. Next, Model 1 was built as a regression analysis with all independent variables entered into the model. Finally, the covariates age, sex, and SES were entered into the final regression model to check for potential confounding effects using a stepwise method and keeping only those confounders in the final model that improved the model based on R-squared, adjusted R-squared, AIC, and BIC. When significant associations were found between the dependent and independent variables, interaction terms were explored. Interaction terms were not explored for confounding variables. To assess the robustness of our findings and explore potential differences in relationships across levels of self-regulation, we explored sensitivity analyses with groups split on the median of the self-regulation scores (Supplemental File 2, Tables 1 and 2). Coefficients were interpreted using Cohen's $f^2$:

**Table 1.** Descriptive statistics for continuous variables in mean ± SD and categorical variables in count (%), in 1178 Dutch adults from the general population.

| | Total (n = 1178) |
|---|---|
| Age | 52.13 ± 16.78 |
| Dutch Interoceptive Accuracy Scale total score | 81.66 ± 9.62 |
| Dutch Interoceptive Attention Scale total score | 57.63 ± 16.63 |
| Walking activities (hours per week) | 3.75 ± 4.17 |
| Moderate intensity activities (hours per week) | 2.01 ± 3.29 |
| Vigorous intensity activities (hours per week) | 1.33 ± 2.52 |
| Total active hours per week | 7.10 ± 6.92 |
| Physical activity experience (years) | 13.39 ± 15.39 |
| Dutch Short Self-Regulation Questionnaire total score | 109.36 ± 13.50 |
| Sex | |
| Female | 612 (52%) |
| Male | 566 (48%) |
| SES | |
| Low | 539 (46%) |
| High | 639 (54%) |

Data was collected between July 2024 and August 2024.

**Table 2.** Regression analyses with log-normalisation for the Dutch Interoceptive Accuracy Scale, in 1178 Dutch adults from the general population.

| Variable | Univariate Beta (95% CI) | Model 1 Beta (95% CI) | Final Model Beta (95% CI) |
|---|---|---|---|
| Walking (Hours per week) | 0.009* (0.001–0.017) | 0.004 (−0.004–0.013) | 0.005 (−0.004–0.014) |
| Moderate intensity activities (Hours per week) | 0.005 (−0.004–0.013) | 0.002 (−0.007–0.010) | 0.001 (−0.008–0.010) |
| Vigorous intensity activities (Hours per week) | 0.002 (−0.007–0.011) | −0.006 (−0.015–0.003) | −0.007 (−0.016–0.003) |
| Physical activity experience (years) | 0.003 (−0.002–0.008) | −0.002 (−0.007–0.004) | −0.003 (−0.009–0.003) |
| Self-regulation | 0.282** (0.232–0.332) | 0.284** (0.233–0.335) | 0.262** (0.209–0.314) |
| Sex | −0.034* (−0.067 to −0.001) | | −0.010 (−0.042–0.023) |
| Age | 0.024* (0.005–0.043) | | 0.026* (0.005–0.046) |
| SES | 0.071** (0.038–0.104) | | 0.050* (0.015–0.084) |
| **Model fit statistics** | | | |
| R-squared | | 0.096 | 0.105 |
| Adjusted R-squared | | 0.092 | 0.099 |
| F-statistic | | 24.796 | 17.161 |
| F-statistic *p*-value | | <0.001 | <0.001 |
| AIC | | −1817.920 | −1824.270 |
| BIC | | −1787.490 | −1778.630 |
| RMSE | | 0.111 | 0.111 |
| MAE | | 0.083 | 0.083 |

Note: Data was collected between July 2024 and August 2024.
Significant findings are marked with *, and significant findings after Bonferroni corrections are marked with **. Model fit statistics are presented for model 1 and the final model.

coefficients of 0.02 were considered small, 0.15 medium, and 0.35 large (Cohen, 2013). Both a priori alpha ($p < 0.05$) and adjusted significance based on Bonferroni corrections ($p < 0.0071$) were considered during analyses.

## Results

### *Descriptive statistics*

Responses from 1242 participants were collected. The physical activity experience variable had 159 (12.8%), and the SES variable 416 (33.5%) missing values. After imputation and removal of outliers (values outside 3SD for the interoception, hours of physical activity, and years of physical activity experience variables), 1178 participants remained. The average age of the participants was 52.13 ± 16.78, and 52% were female. In the current sample, about 28% of the participants did not meet Dutch physical activity guidelines, which is lower than the national average of 56%. Furthermore, only a small percentage (about 6%) of the participants indicated generally participating in team sport activities. Additional descriptives of the participants are presented in Table 1.

### *Hypotheses testing*

Self-regulation was found to be significant in the final IAS model (β = 0.262, CI = [0.210, 0.315]), with medium to large effect sizes (Table 2). This means that a 1% increase in

**Table 3.** Regression analyses with log-normalisation for the Dutch Interoceptive Attention Scale, in 1178 Dutch adults from the general population.

| Variable | Univariate Beta (95% CI) | Model 1 Beta (95% CI) | Final Model Beta (95% CI) |
|---|---|---|---|
| Walking (Hours per week) | 0.001 (−0.021 to −0.022) | 0.016 (−0.008–0.040) | 0.021 (−0.002–0.043) |
| Moderate intensity activities (Hours per week) | −0.012 (−0.034 to −0.010) | −0.002 (−0.026–0.022) | −0.003 (−0.026–0.021) |
| Vigorous intensity activities (Hours per week) | −0.003 (−0.027 to −0.021) | 0.004 (−0.021–0.029) | 0.014 (−0.011–0.039) |
| Physical activity experience (years) | −0.016* (−0.029 to −0.003) | −0.018* (−0.033 to −0.003) | −0.021** (−0.036–0.006) |
| Self-regulation | −0.147* (−0.285 to −0.010) | −0.139 (−0.279–0.002) | −0.071 (−0.212–0.069) |
| Sex | −0.177** (−0.263 to −0.091) | | −0.183** (−0.271 to −0.096) |
| Age | 0.095** (0.046–0.145) | | 0.034 (0.020–0.088) |
| SES | −0.318** (−0.403 to −0.233) | | −0.304** (−0.396 to −0.211) |
| **Model fit statistics** | | | |
| R-squared | | 0.009 | 0.068 |
| Adjusted R-squared | | 0.005 | 0.062 |
| F-statistic | | 2.177 | 10.706 |
| F-statistic *p*-value | | 0.046054 | <0.001 |
| AIC | | 562.174 | 495.773 |
| BIC | | 592.603 | 541.417 |
| RMSE | | 0.306 | 0.296 |
| MAE | | 0.245 | 0.234 |

Note: Data were collected between July 2024 and August 2024.
Significant findings are marked with *, and significant findings after Bonferroni corrections are marked with **. Model fit statistics are presented for model 1 and the final model.

self-regulation scores is associated with a 0.262% increase in interoceptive accuracy scores. The confounders age (β = 0.026, CI = [0.005, 0.046] and SES (β = 0.050, CI = [0.015, 0.085]) were found to be significant determinants in the final model. No significant interaction terms were found.

Physical activity experience was a significant determinant of interoceptive attention (Table 3) in the final model (β = −0.021, CI = [−0.036, -0.006]), with small effect sizes. This indicates that with a 1% increase in years of physical activity experience, there is a 0.021% decrease in interoceptive attention scores. Sex (β = −0.183, CI = [−0.271, -0.096]) and SES (β = −0.304, CI = [−0.396, -0.211]) were significant in the final model. No significant interaction terms were found.

## Discussion

The current study looked into physical activity and self-regulation as determinants of interoception, as this may be important for initiating, regulating, and maintaining physical activity. Therefore, we examined how varying intensities of physical activity (e.g., walking, moderate intensity, and vigorous intensity physical activity) are associated with self-reported interoceptive accuracy and attention. Additionally, this study investigated the influence of individual (i.e., years of physical activity experience and self-regulatory skills) factors on self-reported interoceptive accuracy and attention. Results showed that higher levels of self-regulation scores were associated with higher self-reported interoceptive accuracy, while more physical activity experience and higher levels of self-regulation were associated with lower levels of interoceptive attention. Walking, moderate, and vigorous physical activity hours per week were not associated with self-reported interoceptive accuracy and attention in the final models, but walking hours per week did significantly determine interoceptive accuracy in the univariate model.

We expected that individuals who participate more in walking, moderate, and vigorous intensity activities would have better self-reported interoceptive accuracy and attention, because physical activity refines central command-driven interoceptive predictions, enabling individuals to better anticipate, attend to, and interpret internal bodily states during exertion (Brevers et al., 2024; McMorris et al., 2018). However, as the results from the final regression model show, this was not the case. For walking and moderate intensity physical activity, this may be explained by adaptation or habituation effects related to adaptive (i.e., balanced bodily awareness beneficial for health-promoting behaviour) forms of interoception (Aaron et al., 2020; Trevisan et al., 2023). Habituation means growing accustomed to situations or stimuli, and while it can serve as an adaptive function by conserving mental and physical resources, not all habituation is adaptive. Adaptive habituation involves a calibrated, functionally beneficial reduction in responses to stimuli. For example, becoming more accustomed to bodily changes induced by physical activity reduces the perceived sensitivity to arousal signals, which allows more attentional resources to be directed towards external stimuli (Marshall et al., 2018; Wallman-Jones et al., 2023). These findings suggest that, instead of enhancing self-reported interoceptive accuracy and attention, regular engagement in low-intensity physical activity may facilitate adaptive habituation to internal bodily signals through repeated exposure.

The finding that hours per week engaged in vigorous intensity physical activity did not significantly determine self-reported interoceptive accuracy and attention scores might be the result of higher internal noise during these types of physical activity (Koteles et al., 2020; Wallman-Jones et al., 2022). In contrast to lower intensity activities, during vigorous intensity physical activity it becomes more difficult to make top-down interoceptive predictions: cognitive control strategies become less effective, future states are harder to predict, and interoceptive prediction errors become more prevalent (Seabury et al., 2023). When physical activity intensifies, interoceptive cues call for more attention, decreasing the availability of attentional resources (Razon et al., 2014; Wallman-Jones et al., 2022). Instead, attention may shift towards associative imagery (e.g., increasing engagement with physical movement and bodily experiences, and enhancing motivation to cope with effort perceptions) in order to adapt to physiological sensations and extend task performance and duration (Razon et al., 2010). Additionally, intense physical activity can negatively impact emotional well-being due to the body's physical state (Ekkekakis, 2003). These emotions (i.e., affective responses) combined with other internal physiological noise, compete with interoceptive signals, and make it harder to distinguish these feelings and sensations from one another. This may explain why in the current study, hours per week participated in vigorous intensity physical activity did not determine scores on the IAS-D and IATS-D.

The finding that years of physical activity experience was negatively associated with interoceptive attention, but showed no significant relationship with interoceptive accuracy, did not support our hypotheses. We expected increases in interoceptive accuracy and attention with more years of physical activity experience, as physical activity participation refines central command-driven interoceptive predictions and enhances the brain's ability to predict and control exercise using prior experiences and sensory feedback (Seabury et al., 2023). However, our findings align with evidence suggesting that physical activity background moderates interoceptive responses, with experienced individuals showing diminished benefits from acute physical activity interventions (Wallman-Jones et al., 2022). These adaptive habituation effects, similar to those observed for specific activity intensities, support the idea that with extensive physical activity experience, internal models become more developed, allowing for more accurate anticipation of bodily states during exertion without requiring increased attention (Brevers et al., 2024; McMorris et al., 2018). When internal models are well-tuned through repeated exposure, fewer interoceptive prediction errors occur, reducing the need for active monitoring of internal signals. This may suggest increased efficiency in interpreting internal bodily signals. In other words, with more experience in perceiving internal signals during physical activity, individuals may start to trust their body more and shift their attentional focus from internal to external.

In line with previous studies (Füstös et al., 2013; Georgiou et al., 2015; Herbert et al., 2007; Marshall et al., 2018), the current study found a positive significant association between self-regulatory skills and interoceptive accuracy. While speculative and based on cross-sectional data, it may be that individuals with higher self-regulation scores do not need to allocate as much attention to accurately perceive internal signals, reflecting greater processing efficiency. Affective responses to physical activity come from the combination of cognitions originating in the frontal cortex, such as self-regulation, and interoceptive signals about the physiological state of the body

(Ekkekakis, 2009). Increased interoceptive accuracy improves self-regulatory skills, which in turn allows better management of attention and emotions (Seabury et al., 2023). For example, individuals who are good at perceiving and interpreting bodily signals may also be good at self-regulation. Or vice versa: if bodily signals are not interpreted correctly, it becomes more difficult to self-regulate. It could be that with better interoceptive accuracy and self-regulation comes more trust in one's bodily signals, resulting in less attention paid to those sensations.

The novelty of the current study is that it investigated time spent in multiple intensities (i.e., walking, moderate, and vigorous) of physical activity in two separate interoceptive domains (i.e., accuracy and attention), providing more information by tapping into different aspects of interoception (Schoeller et al., 2025). To the best of our knowledge, previous research has mainly focused on the effect of acute exercise protocols on interoception in a lab-setting, as well as in single interoceptive domains. Thus, the current study adds to existing information by investigating the association between the intensity and amount of physical activity individuals participate in during their leisure time and several interoceptive domains, which might result in a better comprehension of how interoception is used in daily physical activities.

There were some limitations to this study. First, we should note that conclusions on the relation between hours per week spent on different intensities physical activity and self-reported interoception should be interpreted with caution. The questionnaires we used are of a more general nature and were not directly linked to different physical activity intensities (i.e., we did not ask participants to take specific physical activities or intensities in mind when filling out the questionnaires). Therefore, our conclusions may indicate possible mechanisms, but we are not able to mention causal relations. However, the outcomes of this explorative study may provide a starting point for future research on the associations between physical activity intensities, self-regulation, and interoceptive accuracy and attention. Second, participants aged 18 years and older from the general Dutch population were included in the study, which led to the participants ranging in age from 18 to 96 with a mean of 52. This, on average, middle-aged sample has a different physical activity profile compared to, for example, young adults, which means they took part less in vigorous intensity activities than their younger counterparts. Moreover, since the sample consisted of older individuals, it should be noted that years of physical activity experience is likely related to age. Therefore, complete statistical separation of these predictors is difficult, and overlapping variance may have influenced regression parameters. Future research would benefit from modelling age of physical activity onset or residualizing physical activity experience on age. This approach would more clearly distinguish the effects of aging from those of accumulated experience and could reveal whether the timing of physical activity adoption differentially influences interoception. Finally, the current study relied solely on self-report measures. There are known limitations to self-report measures, such as cultural differences, recall bias, and misinterpretation of questions (Corder & van Sluijs, 2010). There is also a tendency to overestimate actual physical activity levels with the IPAQ (Steene-Johannessen et al., 2016). Additionally, because of the complexity of interoception, relationships between self-report and objective interoceptive measures must also be considered in order to paint a complete picture of the association between physical activity and interoception (Schoeller et al., 2025). However, the current results do provide insight into the association between interoception and physical activity, and can be used as a starting point for further experimental research.

More research is needed to better understand the complex relations between physical activity, self-regulation, and interoception. Based on the results of the current study, this research should focus on possible mechanisms underlying these relations. An interesting next step for research would be to investigate whether individuals with better self-regulatory skills are more physically active because of these skills, whether this leads to them being able to more accurately perceive their internal bodily signals, and subsequently pay less attention to internal bodily signals because of improved bodily trust. Insights into these relations and mechanisms are extremely relevant for promoting health behaviour, as it may help individuals filter the most relevant interoceptive information and engage in more adaptive forms of interoception (i.e., balanced bodily awareness beneficial for health-promoting behaviour). Additionally, future research should pay more attention to the association between different physical activity types (e.g., cardio versus strength, team versus individual, or organised versus non-organised) and different interoceptive domains and modalities, considering how different populations associate with specific interoceptive profiles (Schoeller et al., 2025). Insights into these differences could allow for optimisation of specific physical activity and interoception interventions for specific target populations. Finally, to understand how knowledge on the relation between different physical activity intensities and interoceptive domains can be used to inform lifestyle interventions, more longitudinal research is needed. Longitudinal research may allow us to investigate the timing of physical activity and interoceptive interventions (i.e., how long it takes for these interventions to show effects) as well as examine the bidirectional, causal relationships between physical activity and interoception, for example using more complex analyses such as Structured Equation Modelling (SEM).

## Conclusion

Walking hours per week associated with an increase in interoceptive accuracy, while more years of PA experience decreased interoceptive attention. At lower intensity physical activity, adaptation or habituation effects reduce perceived sensitivity to internal signals, meaning attention is shifted more towards external stimuli. Similar adaptations may occur over longer periods of time, resulting in interoceptive attention decreasing with more years of physical activity experience. Better self-regulatory skills were associated with increased interoceptive accuracy, and decreased interoceptive attention. It could be that with better interoceptive accuracy and self-regulation comes more trust in one's bodily signals, resulting in less attention paid to those sensations. Being able to filter relevant interoceptive information may be extremely important in health behaviour. An interesting next step for researchers is to investigate whether individuals with better self-regulation are therefore more physically active, resulting in increased interoceptive accuracy and decreased interoceptive attention.

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## Data availability

Data will be made available by the corresponding author upon reasonable request. Analysis code is available at: https://github.com/JesperMulder/interoception-physical-activity


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# Appendices

## *Appendix A: IAS-D*

### *Omschrijving*

Hieronder staan een aantal stellingen over hoe nauwkeurig u bepaalde lichaamssensaties waarneemt. Wij willen u vragen om aan te geven hoe goed u denkt elke specifieke sensatie waar te nemen. Als u bijvoorbeeld vaak voelt dat u moet plassen, maar eenmaal op het toilet u eigenlijk toch niet hoeft, dan geeft u aan dat uw nauwkeurigheid voor deze lichaamssensatie laag is.

Het is de bedoeling dat u alleen aangeeft hoe goed u deze sensaties waarneemt zonder externe signalen. Als u bijvoorbeeld alleen kunt nagaan hoe snel uw hart klopt door uw pols op te nemen, dan geldt dit niet als een nauwkeurige interne waarneming.

| Nr. | Nederlands | English |
|---|---|---|
| 1 | Ik kan altijd nauwkeurig waarnemen wanneer mijn hart snel klopt | I can always accurately perceive when my heart is beating fast |
| 2 | Ik kan altijd nauwkeurig waarnemen wanneer ik honger heb | I can always accurately perceive when I am hungry |
| 3 | Ik kan altijd nauwkeurig waarnemen wanneer ik snel ademhaal | I can always accurately perceive when I am breathing fast |
| 4 | Ik kan altijd nauwkeurig waarnemen wanneer ik dorst heb | I can always accurately perceive when I am thirsty |
| 5 | Ik kan altijd nauwkeurig waarnemen wanneer ik moet plassen | I can always accurately perceive when I need to urinate |
| 6 | Ik kan altijd nauwkeurig waarnemen wanneer ik moet poepen | I can always accurately perceive when I need to defecate |
| 7 | Ik kan altijd nauwkeurig waarnemen wanneer ik verschillende smaken proef | I can always accurately perceive when I encounter different tastes |
| 8 | Ik kan altijd nauwkeurig waarnemen wanneer ik moet overgeven | I can always accurately perceive when I am going to vomit |
| 9 | Ik kan altijd nauwkeurig waarnemen wanneer ik moet niezen | I can always accurately perceive when I am going to sneeze |
| 10 | Ik kan altijd nauwkeurig waarnemen wanneer ik moet hoesten | I can always accurately perceive when I am going to cough |
| 11 | Ik kan altijd nauwkeurig waarnemen wanneer ik het warm of koud heb | I can always accurately perceive when I am hot/cold |
| 12 | Ik kan altijd nauwkeurig waarnemen wanneer ik seksueel opgewonden ben | I can always accurately perceive when I am sexually aroused |
| 13 | Ik kan altijd nauwkeurig waarnemen wanneer ik een wind moet laten | I can always accurately perceive when I am going to pass wind |
| 14 | Ik kan altijd nauwkeurig waarnemen wanneer ik een boer moet laten | I can always accurately perceive when I am going to burp |
| 15 | Ik kan altijd nauwkeurig waarnemen wanneer ik spierpijn heb | I can always accurately perceive when my muscles are tired/sore |
| 16 | Ik kan altijd nauwkeurig waarnemen wanneer ik een blauwe plek krijg | I can always accurately perceive when I am going to get a bruise |
| 17 | Ik kan altijd nauwkeurig waarnemen wanneer ik pijn heb | I can always accurately perceive when I am in pain |
| 18 | Ik kan altijd nauwkeurig waarnemen wanneer mijn bloedsuiker laag is | I can always accurately perceive when my blood sugar is low |
| 19 | Ik kan een liefdevolle aanraking altijd nauwkeurig onderscheiden van een niet-liefdevolle aanraking | I can always accurately perceive when someone is touching me affectionately rather than non-affectionately |
| 20 | Ik kan altijd nauwkeurig waarnemen wanneer iets mij een kietelgevoel geeft | I can always accurately perceive when something is going to be ticklish |
| 21 | Ik kan altijd nauwkeurig waarnemen wanneer iets mij jeuk geeft | I can always accurately perceive when something is going to be itchy |

## Appendix B: IATS-D

### Omschrijving

Hieronder staan een aantal stellingen over hoeveel aandacht u schenkt aan bepaalde lichaamssensaties. Wij willen u vragen om aan te geven hoeveel aandacht u denkt te schenken aan elke specifieke sensatie. Het is belangrijk om te denken aan wat u voelt in de meeste situaties in uw dagelijks leven, in plaats van op een specifiek moment. Als u bijvoorbeeld vaak denkt aan uw hartslag, uw hongergevoel of uw aandrang om naar het toilet te gaan, dan geeft u aan dat uw aandacht voor deze sensaties hoog is. Maar als u bijvoorbeeld niet vaak denkt aan uw hartslag, uw hongergevoel of uw aandrang om naar het toilet te gaan, dan geeft u aan dat uw aandacht voor deze sensaties laag is.

Het is de bedoeling dat u alleen aangeeft hoeveel **aandacht** u schenkt aan deze sensaties, **ongeacht hoe goed u denkt deze sensaties waar te nemen**. Als u bijvoorbeeld vaak aandrang voelt om naar het toilet te gaan, maar eenmaal op het toilet u eigenlijk niet hoeft, dan is uw aandacht voor deze sensatie toch hoog. U hoeft niet te denken aan hoe vaak de sensatie **daadwerkelijk** plaatsvindt in uw lichaam; wat wij willen weten is hoe vaak u aandacht aan deze sensaties schenkt.

De vragen hebben betrekking op uw aandacht voor gevoelens die van **binnenuit** uw lichaam komen. Als de vraag bijvoorbeeld gaat over temperatuur, dan betreft het de sensaties die u intern waarneemt zonder dat u uw hand gebruikt om te voelen hoe warm uw huid is, en als de vraag gaat over uw hartslag, dat betreft het de sensaties die u in uw lichaam waarneemt zonder dat u uw pols opneemt.

*Vragenlijst*

| Nr. | Nederlands | English |
|---|---|---|
| 1 | Meestal is mijn aandacht gericht op het gevoel of mijn hart snel klopt | Most of the time my attention is focused on whether my heart is beating fast |
| 2 | Meestal is mijn aandacht gericht op het gevoel of ik honger heb | Most of the time my attention is focused on whether I am hungry |
| 3 | Meestal is mijn aandacht gericht op het gevoel of ik snel ademhaal | Most of the time my attention is focused on whether I am breathing fast |
| 4 | Meestal is mijn aandacht gericht op het gevoel of ik dorst heb of uitgedroogd ben | Most of the time my attention is focused on whether I am thirsty or dehydrated |
| 5 | Meestal is mijn aandacht gericht op het gevoel of ik moet plassen | Most of the time my attention is focused on whether I need to urinate |
| 6 | Meestal is mijn aandacht gericht op het gevoel of ik moet poepen | Most of the time my attention is focused on whether I need to defecate |
| 7 | Wanneer ik eet, is mijn aandacht meestal gericht op verschillende smaken | Most of the time when I am eating, my attention is focused on different tastes |
| 8 | Meestal is mijn aandacht gericht op het gevoel of ik misselijk ben of moet overgeven | Most of the time my attention is focused on whether I am nauseated or need to vomit |
| 9 | Meestal is mijn aandacht gericht op het gevoel of ik moet niezen | Most of the time my attention is focused on whether I need to sneeze |
| 10 | Meestal is mijn aandacht gericht op het gevoel of ik moet hoesten | Most of the time my attention is focused on whether I need to cough |
| 11 | Meestal is mijn aandacht gericht op mijn lichaamstemperatuur (of ik het koud of warm heb) | Most of the time my attention is focused on the temperature of my body (feeling hot or cold) |
| 12 | Meestal is mijn aandacht gericht op het gevoel of ik seksueel opgewonden ben | Most of the time my attention is focused on whether I am sexually aroused |
| 13 | Meestal is mijn aandacht gericht op het gevoel of ik een wind moet laten | Most of the time my attention is focused on whether I need to pass wind |
| 14 | Meestal is mijn aandacht gericht op het gevoel of ik een boer moet laten | Most of the time my attention is focused on whether I need to burp |
| 15 | Meestal is mijn aandacht gericht op het gevoel of ik spierpijn heb | Most of the time my attention is focused on whether my muscles are tired or sore |
| 16 | Meestal is mijn aandacht gericht op het gevoel of ik pijn heb wanneer ik mij bezeerd heb of gewond ben | Most of the time my attention is focused on whether I am in pain after I am hurt or injured |

(*Continued*)

Continued.

| Nr. | Nederlands | English |
|---|---|---|
| 17 | Meestal is mijn aandacht gericht op het gevoel of ik pijn heb (die niet veroorzaakt is door letsel) | Most of the time my attention is focused on whether I am in pain (that is not caused by injury) |
| 18 | Meestal is mijn aandacht gericht op het gevoel of mijn bloedsuiker laag is | Most of the time my attention is focused on whether my blood sugar is low |
| 19 | Wanneer iemand mij aanraakt, is mijn aandacht meestal gericht op het gevoel of die aanraking fijn of liefdevol is | Most of the time when someone is touching me, my attention is focused on whether it is pleasant/ affectionate |
| 20 | Meestal is mijn aandacht gericht op het gevoel of mijn lichaam een kietelgevoel ervaart wanneer ik word aangeraakt, of bepaalde materialen draag | Most of the time my attention is focused on whether touch or materials feel ticklish on my body |
| 21 | Meestal is mijn aandacht gericht op het gevoel of ik jeuk heb | Most of the time my attention is focused on whether my body feels itchy |

## Appendix C: SSRQ-D

### Omschrijving

Beantwoord de volgende vragen door het antwoord te omcirkelen dat het best beschrijft hoe u bent. Onthoud: er zijn geen goede of foute antwoorden.

*Vragenlijst*

| Nr. | Nederlands | English |
|---|---|---|
| 1 | Ik houd meestal de voortgang van mijn doelen bij | I usually keep track of my progress towards my goals |
| 2* | Ik heb moeite met het nemen van besluiten | I have trouble making up my mind about things |
| 3* | Ik raak snel afgeleid van mijn plannen | I get easily distracted from my plans |
| 4* | Ik merk de gevolgen van mijn acties pas wanneer het te laat is | I don't notice the effects of my actions until it is too late |
| 5 | Het lukt mij om de doelen die ik mijzelf gesteld heb, te behalen | I am able to accomplish goals I set for myself |
| 6* | Ik stel het nemen van beslissingen uit | I put off making decisions |
| 7* | Ik vind het moeilijk om bij mijzelf na te gaan wanneer ik "genoeg heb gehad" (bijvoorbeeld bij alcohol, eten, snoep) | It's hard for me to notice when I've "had enough" (alcohol, food, sweets) |
| 8 | Als ik zou willen veranderen, dan heb ik er alle vertrouwen in dat mij dat ook lukt | If I wanted to change, I am confident that I could do it |
| 9* | Als het aankomt op het nemen van beslissingen over verandering, voel ik mij overweldigd door de keuzes | When it comes to deciding about change, I feel overwhelmed by the choices |
| 10* | Ik heb moeite om dingen op te pakken wanneer ik besloten heb om iets te doen | I have trouble following through with things once I've made up my mind to do something |
| 11* | Ik lijk niet te leren van mijn fouten | I don't seem to learn from my mistakes |
| 12 | Ik kan mij houden aan een plan dat goed werkt | I can stick to a plan that's working well |
| 13 | Ik hoef meestal maar één keer een fout te maken om ervan te leren | I usually only have to make a mistake one time in order to learn from it |
| 14 | Ik heb persoonlijke normen en waarden, en probeer mij daaraan te houden | I have personal standards, and try to live up to them |
| 15 | Zodra ik een probleem of uitdaging zie, begin ik te zoeken naar mogelijke oplossingen | As soon as I see a problem or challenge, I start looking for possible solutions |
| 16* | Ik vind het moeilijk om doelen voor mijzelf te stellen | I have a hard time setting goals for myself |
| 17 | Ik heb veel wilskracht | I have a lot of willpower |
| 18 | Wanneer ik iets wil veranderen, let ik op hoe ik mij daarbij voel | When I'm trying to change something, I pay attention to how I'm doing |
| 19* | Ik heb moeite met het maken van plannen die mij helpen mijn doelen te behalen | I have trouble making plans to help me reach goals |
| 20 | Ik kan verleidingen goed weerstaan | I am able to resist temptation |
| 21 | Ik stel doelen voor mijzelf en houd mijn voortgang bij | I set goals for myself and keep track of my progress |

(*Continued*)

Continued.

| Nr. | Nederlands | English |
|---|---|---|
| 22* | Meestal sta ik niet stil bij wat ik doe | Most of the time I don't pay attention to what I'm doing |
| 23* | Ik doe vaak hetzelfde, ook wanneer het niet werkt | I tend to keep doing the same thing, even when it doesn't work |
| 24 | Ik kan meestal verschillende mogelijkheden bedenken wanneer ik iets wil veranderen | I can usually find several different possibilities when I want to change something |
| 25 | Wanneer ik een doel heb, lukt het mij meestal om een plan op te stellen om dit doel te behalen | Once I have a goal, I can usually plan how to reach it |
| 26 | Als ik besluit iets te veranderen, let ik heel goed op hoe ik mij daarbij voel | If I make a resolution to change something, I pay a lot of attention to how I'm doing |
| 27* | Meestal heb ik niet in de gaten wat ik doe, totdat iemand mij hierop wijst | Often I don't notice what I'm doing until someone calls it to my attention |
| 28 | Ik denk meestal na voordat ik handel | I usually think before I act |
| 29 | Ik leer van mijn fouten | I learn from my mistakes |
| 30 | Ik weet hoe ik wil zijn | I know how I want to be |
| 31 | Voordat ik een beslissing neem, ga ik na wat er waarschijnlijk gebeurt als ik deze keuze maak | Before making a decision, I consider what is likely to happen if I do one thing or another |

Questions with a * are reverse scored.