Current Psychology (2026) 45:1386
https://doi.org/10.1007/s12144-026-09946-1

Cardiac and ocular correlates of mind wandering in meditators and non-meditators during a sustained attention to response task

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Received: 22 October 2025 / Accepted: 14 August 2026

Abstract

Mind wandering refers to spontaneous shifts of attention from ongoing tasks to unrelated thoughts. Evidence shows that such shifts are characterized by behavioral and physiological changes, such as heart rate and eye blinks. However, previous findings on cardiac changes during mind wandering are mixed, and little is known about whether mindfulness experience and acceptance-related traits are associated with distinct psychophysiological responses to mind wandering. To shed light on this topic, we investigated psychophysiological correlates of mind wandering in 26 experienced meditators and 24 non-meditating controls during a Sustained Attention to Response Task (SART) with thought probes. We recorded heart rate and eye blinks; mindfulness-related traits and mind wandering phenomenology were assessed through questionnaires. Results showed that, while mind wandering episodes were associated with more frequent eye blinks and slower reaction times in both groups, between-group differences emerged for heart rate. Indeed, only meditators showed a significant heart rate reduction during mind wandering, whereas controls did not. In addition, individual heart rate differences between mind wandering and on-task SART episodes were associated with self-reported levels of experiential acceptance. Overall, meditators reported higher levels of experiential acceptance and assessed their mind wandering episodes as more realistic and concrete than controls. These findings contribute to the literature by showing that, while eye blinks and reaction times may reflect the general attentional cost of mind wandering, heart rate may be more sensitive to individual differences in how these episodes are experienced and regulated, particularly in relation to meditation experience and experiential acceptance.

Keywords Mind Wandering · Mindfulness · Heart Rate · Eye Blinks · Sustained Attention to Response Task (SART)

Introduction

The human mind naturally tends to drift away from the present moment, ongoing tasks, or environmental stimuli to task-unrelated and stimulus-independent thoughts, a phenomenon commonly referred to as mind wandering (MW) (Feruglio et al. 2021a; Smallwood and Schooler 2006; Stawarczyk et al. 2011). Sometimes considered a failure of attention and executive control (McVay & Kane, 2010), MW is now recognized as a multidimensional construct whose complex phenomenology requires investigation through multiple methods (Christoff et al., 2016; Cantone et al., 2021; Sorella et al., 2025). Both subjective and objective measures, such as experience sampling (i.e., self-report thought probe) and attentional tasks (i.e., behavioral performance), have been used in experiments involving reading (Smilek et al., 2010) or sustained attention (Smallwood et al., 2004, 2008), including the Sustained Attention to Response Task (SART; Robertson et al., 1997). These studies differentiate between task-related and task-unrelated thoughts during task execution and consistently show that MW impairs performance. However, only recently the phenomenology of MW has been considered during tasks such as the SART, revealing

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Published online: 22 August 2026

that it often involves future-oriented thoughts, typically associated with inner speech, greater personal relevance, and concrete and structured cognition (Stawarczyk et al., 2011, 2013).

However, although MW has been widely studied behaviorally, its embodied correlates remain less clearly understood. Beyond behavior, the embodied markers of MW, such as ocular and autonomic measures during attentional tasks, may provide additional information about the psychophysiology of MW. For example, MW was associated with larger ocular movements (Matiz et al., 2019) during an instructed MW task, increased pupil dilation during a vigilance task (Pelagatti et al., 2020), and a higher number of blinks (Smilek et al., 2010) in comparison to focused-attention conditions. The authors of the latter study proposed that eye blinks (EB) may serve to modulate sensory input, thereby facilitating the internal redirection of attention.

Other research has considered cardiac markers of MW, such as heart rate (HR). This index has previously been linked to acute short-term stress (Schubert et al., 2009) as well as to task and situational features (Corcoran et al., 2025).

Smallwood et al. (2004) found that during the SART, HR increases in blocks with MW. However, a recent study by Corcoran et al. (2025) found that MW and mind-blanking were both associated with reductions in HR and pupil size, suggesting decreased autonomic arousal. Interestingly, MW showed smaller decreases than mind-blanking, and was associated with amplified cortical processing of interoceptive signals. They suggest that, as arousal decreases (from on-task, through MW, to mind-blanking states), there is an initial reallocation of attention toward internal processes (as in MW), followed by a more profound attentional withdrawal (as in mind-blanking). Whereas Corcoran et al. (2025) interpret MW as a state of attenuated autonomic arousal, Smallwood et al. (2004) found increased HR during MW, hypothesizing that such states may reflect physiological activation associated with the processing of personally salient internal information. The discrepancy between these studies may reflect differences in the features or intensity of MW episodes (Ottaviani et al., 2013), or in inter-individual factors such as mood or personality traits (Smallwood et al., 2007). However, this possibility has rarely been tested by combining cardiac indices, behavioral performance, and first-person phenomenological characterization within the same SART paradigm.

From a broader psychophysiological perspective, these cardiac findings can be interpreted within the interaction between cognitive-emotional processes and autonomic regulation. Psychological stress and negative emotional states activate neuroendocrine and autonomic response systems, producing changes in hemodynamic physiology, including HR (Vaccarino & Bremner, 2024). In particular, increases in HR may be compatible with sympathetic activation, which supports mobilization during stress or increased activity, together with reduced parasympathetic activity, which normally contributes to slowing HR during rest and recovery (Schneider & Schwerdtfeger, 2020). Within this framework, MW episodes may have different autonomic consequences depending on their phenomenological content, with anxiety, worry, or perseverative cognition potentially sustaining physiological arousal (Vaccarino & Bremner, 2024). This interpretation is consistent with the amplification hypothesis (Watkins, 2008), according to which MW may function as an amplifier of individual vulnerabilities, perpetuating cognitive risk factors associated with mental disorders, particularly when MW is characterized by repetitiveness, rigidity, inflexibility and abstract processing (Marchetti et al., 2016).

Marchetti et al. (2016) highlighted the potential of mindful awareness as an opposite construct of MW, not only in terms of frequency (where higher levels of MW imply lower levels of awareness), but also in terms of attitude, as mindful awareness is characterized by increased equanimity and acceptance of mental contents.

Indeed, mindfulness has been shown to reduce resting HR and sympathetic activation, and to regulate stress reactivity (Pascoe et al., 2017).

However, despite evidence linking MW to behavioral and physiological changes, and evidence linking mindfulness to changes in MW (Feruglio et al. 2021a), these lines of research have rarely been integrated.

Mindfulness can be defined as an intentional self-regulation of attention combined with a mental state of nonjudgmental awareness of present-moment experience (Feruglio et al., 2021a, b). Evidence from behavioral (Mrazek et al., 2013), physiological (Matiz et al., 2019) and neuroimaging studies (Malinowski, 2013) suggests that MW and mindfulness are associated with at least partially different mechanisms. Previous work has indeed examined mindfulness-related differences in MW, such as its phenomenology, reducing features such as its repetitiveness (Cantone et al. 2021; Feruglio et al. 2021b) and its

negative behavioral impact on different cognitive tasks (Feruglio et al. 2021a), an effect also observed in SART behavioral outcomes (Banks et al., 2019; Giannandrea et al., 2019). In addition, mindfulness-related differences were previously found when considering MW physiology (Matiz et al., 2019) and neural correlates (Matiz et al., 2021; Sorella et al., 2025). Despite the theoretical overlap with previous investigations, to the best of our knowledge, no study has adopted a comprehensive design to directly test whether experienced mindfulness meditators and meditation-naïve controls differ in the physiological correlates of MW during an attentional task, while also characterizing the phenomenological content of MW episodes.

To address these gaps, we conducted a comparative study between experienced mindfulness meditators and matched controls (without mindfulness experience), using a SART paradigm with thought probes.

The first aim of this study was to test whether mindfulness experience is associated with the behavioral, cardiac, and ocular correlates of MW during the SART, while also characterizing the phenomenological content of MW episodes through a post-task questionnaire. This design extends previous work by integrating group comparison, behavioral performance, cardiac and ocular indices, and phenomenological aspects of MW. This objective was motivated by previous evidence showing that MW is typically associated with decreased task performance (Smallwood et al., 2004) and increased number of EB (Smilek et al., 2010), whereas findings on HR are less consistent, with both increases (Smallwood et al., 2004) and decreases (Corcoran et al., 2025) reported during MW. Our study aims to clarify these discrepancies, investigating whether they might be associated with mindfulness experience (and MW phenomenology). Indeed, prior evidence on the effects of mindfulness training on MW shows HR reductions (Delgado-Pastor et al., 2015) and attenuated performance deterioration (Feruglio et al. 2021a), while EB are reduced in expert but not in novice meditators (Kruis et al., 2016). Based on these findings, we hypothesize that meditators will show better SART performance and lower HR during MW episodes, while EB may increase similarly in both groups, or to a lesser extent in meditators during SART with MW episodes.

Second, we aimed to investigate which mindfulness-related trait scores were associated with individual differences in SART performance and HR and EB indices during MW and on-task conditions. This aim was motivated by the idea that mindfulness may influence not only the occurrence of MW, but also the way internally generated mental contents are experienced and physiologically regulated (Feruglio et al. 2021a; Pascoe et al. 2017; Marchetti et al. 2016). In particular, we expected equanimity, a central mechanism of change in mindfulness practice that can promote an extinction response during unwanted experiences (Rogers et al., 2021), to be associated with changes in physiological regulation, as observed after mindfulness training (Delgado-Pastor et al., 2015). Third, given that the phenomenology of MW during the SART has received limited empirical attention (Stawarczyk et al., 2011, 2013), particularly in relation to mindfulness experience (Cantone et al., 2021), we explored potential group differences in the characteristics of MW during the SART.

Methods

Participants gave written, informed consent to participate in the research. The study was performed in accordance with the 1964 Declaration of Helsinki and its procedures were approved by the Institutional Review Board of the Department of Languages and Literatures, Communication, Education and Society of the University of Udine [CGPER-2022-12-22-02].

Participants

An a priori power analysis was performed using G*Power (version 3.1, Faul et al., 2009) to estimate the sample size needed to detect a medium-sized Group (Meditators vs. Controls) * Condition (on-task vs. MW) interaction in a repeated-measures analysis of variance (ANOVA). Based on prior studies showing behavioral and physiological moderate-to-large detrimental effects of MW on sustained attention in SART tasks (i.e., Smallwood et al., 2004, 2008; Stawarczyk et al., 2011, 2013; Mrazek et al., 2012), we conservatively set the expected effect size to $f = 0.25$. Assuming $\alpha = 0.025$ (Bonferroni correction for the two ANOVAs on physiological and behavioral data, 0.05/2), power = 0.80, and correlation among repeated measures = 0.5, the required sample was 42 participants. We initially recruited 56 participants (28 per group), exceeding this requirement and ensuring adequate statistical power. Even after exclusion of six participants (due to no MW self-reports or technical errors), our final sample ($N = 50$; 26 meditators and 24 controls) still exceeded the minimum required sample size, ensuring sufficient power.

Fifty-six volunteers (31 females, 25 males, age range 25–74 years, mean = 48.07, SD = 12.08) took part in the study. Twenty-eight were expert meditators (17 females, 11 males, age range 27–68 years, mean = 49.82, SD = 10.66), who had on average more than 5 years of experience in mindfulness meditation (mean = 5.45, SD = 4.22) and self-reported to have meditated on average 4271.54 min (SD = 3102.04) in the 6 months before the experiment. They also reported meditating on average 5 days per week (M = 5.00, SD = 1.94) for approximately 34 min per day (M = 34.14, SD = 15.05). Twenty-eight participants were naïve controls with no regular practice of meditation (14 females, 14 males, age range 25–74 years, mean = 46.32, SD = 13.31). The two groups were matched on age (t = -1.09, $p = .282$) and gender (chi-square = 0.65, $p = .420$). Due to technical errors, three participants were excluded from the analysis due to mismatches between physiological and behavioral timing data. Another three participants were excluded since they never reported MW episodes during the SART. The final sample thus included 26 meditators (15 females, 11 males, age range 27–68 years, mean = 49.77, SD = 11.03) and 24 controls (13 females, 11 males, age range 25–74 years, mean = 46.08, SD = 13.20).

Participants were recruited among individuals who had previously attended mindfulness-oriented meditation (MOM; Fabbro & Crescentini, 2017) courses organized by our research group, as well as through personal acquaintances. MOM is an 8-week mindfulness-based program, based on the Mindfulness Based Stress Reduction (MBSR) of Jon Kabat-Zinn, that trains participants in awareness of the breath, bodily sensations, and mental events. The program has been examined in previous studies using different methodological approaches and across both non-clinical and clinical samples (Campanella et al., 2014; Crescentini et al., 2014, 2015, 2018; Cantone et al., 2021). Although participants shared a common MOM training background, their subsequent individual practice varied in frequency, amount, and, in a few cases, specific meditation style, as reflected by the practice indices reported above. Nonetheless, the sample was relatively homogeneous with respect to the main reported meditation style: participants primarily practiced MOM, which consists of an integrated practice including breath- and body-focused attention components as well as open monitoring of mental events. In addition to MOM practice, two participants reported practicing Vipassana meditation and one participant reported practicing Zen meditation at home.

Control group was recruited through convenience sampling to match the meditator sample on demographic variables. Participants were excluded if they reported a diagnosis of a mental disorder, if they had less than one year of meditation experience (meditator group), or if they had any previous experience with meditation courses or regular meditation practice (control group).

Experimental design and paradigm

Experimental design

The study employed a mixed experimental design. Group (Meditators vs. Controls) was the between-subjects factor, while Condition (on-task vs. MW) was the within-subject factor. Age and Gender were added as covariates. The dependent variables (one for each analysis) were behavioral performance in the SART and physiological measures recorded during the task. Specifically, behavioral dependent variables included mean reaction times (RT) to correct go trials and response accuracy (proportion of correct responses across all trials). Physiological dependent variables included heart rate and eye blinks.

Sustained attention to response task (SART)

The SART paradigm was adapted from Smallwood et al. (2008), Stawarczyk et al. (2011), and Stawarczyk et al. (2013). The task requires pressing a response key following each presentation of a random series of single digits (numbers between 1 and 9), except for a no-go digit (number 3), to which no response has to be made. Stimuli were presented electronically using the E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA;https://support.pstnet.com/). The probability of number 3 presentatio n was 11%, the stimulus duration was 500 ms and the interstimulus interval was 2000 ms, during which an “X” was presented on the screen. Within each block of trials, the order of target and non-target probability was pre-randomized. Each session consisted of 30 randomized blocks, six blocks each with duration of 25s (10 stimuli), 35s (14 stimuli), 45s (18 stimuli), 55s (22 stimuli) or 65s (26 stimuli). The stimulus duration, interstimulus interval, no-go probability, block structure, and thought-probe schedule were selected to closely match the probe-caught SART implementation used by Stawarczyk et al. (2011, 2013), thereby facilitating comparability with previous MW studies. Participants were instructed to press the space bar as quickly and accurately as possible in response to every digit except the no-go digit (3). Responses could be emitted during either the digit presentation or the subsequent fixation interval (“X”). After each block, participants could decide when to begin the next one by pressing the space bar, allowing for variable-length breaks. In addition, at the end of each randomized block, participants were immediately probed whether their mind had wandered immediately prior to that moment (MW condition) or had remained focused on the task (on-task condition). Specifically, the question was “At the time when the sequence of numbers and X’s stopped and this screen appeared: (a) was your attention on the task at hand or (b) was your mind wandering?”. Responses were provided via keyboard press (“a” = on-task; “b” = distraction/MW), and the probe remained on screen until a response was made. Responses to the probes were coded dichotomously as on-task (“on-task”) or mind-wandering (“MW”) conditions. Thus, each SART block was assigned to one of two attentional-state categories: on-task or MW. Therefore, in the present study, MW was operationally defined as a self-reported attentional state in which participants indicated that, immediately before the probe, their attention had shifted away from the SART rather than remaining focused on the task.

In addition, when participants answered "b" (i.e., MW condition), they were prompted to write a brief description of the distraction in their own words on the keyboard. These words were used at the end of the task to complete, for each MW episode, a Thought Characteristics Questionnaire (TCQ; Cantone et al., 2021; Stawarczyk et al., 2013; Stawarczyk et al., 2011) and to classify, a posteriori by two experimenters, the MW episode as: environment-related (e.g., sounds), internal-stimulus-related (e.g., bodily sensations, tiredness) and cognitive MW including thoughts and mental images. The entire SART task lasted on average approximately 27.3 min (*M*=1637s, range=1502–1854 s).

Procedure

All participants were tested individually under standardized and controlled environmental conditions, in a quiet room at the University of Udine. Upon arrival, they were welcomed and informed about the general aims of the study without revealing its specific hypotheses. After providing informed consent and demographic information, participants were seated comfortably in front of a computer screen at a distance of approximately 60 cm. Then, physiological recording devices were set up and participants were asked to minimize movements throughout the sessions.

The first recording consisted of a 5-minute baseline with eyes open. Then, participants completed the experimental task (SART). Participants also performed a short training session of the SART (22 numbers and two thought-probes). Upon completion of the SART, these responses were presented back to participants to report MW features throughout the TCQ (Cantone et al., 2021), with the questions orally presented by the experimenter.

Afterward, participants filled out self-report questionnaires at home assessing personality, mindfulness and equanimity. The entire laboratory session lasted approximately one hour. Participants were debriefed at the end of the session and thanked for their time with a 15 euro gift card to spend in a local library.

Assessment tools and questionnaires

Baseline personality characteristics of the two groups of participants were assessed through the Italian version of the Temperament and Character Inventory (TCI; Delvecchio et al., 2016), completed at home, after participation in the SART experiment. The TCI is a 125 item questionnaire based on Cloninger's psychobiological model of personality (Cloninger et al., 1994) and includes four temperamental dimensions, which reflect automatic emotional responses to environmental stimuli: Novelty Seeking (ω=0.70, α=0.69 for the present sample), Harm Avoidance (ω=0.87, α=0.86), Reward Dependence (ω=0.53, α=0.58), and Persistence (ω=0.61, α=0.58). It also includes three character dimensions, which respectively relate to self-concept, interpersonal attitudes, and transpersonal identification: Self-directedness (ω=0.89, α=0.88), Cooperativeness (ω=0.46, α=0.57), and Self-transcendence (ω=0.79, α=0.78). None of these scales showed differences between the two groups (all p-values > 0.230).

In addition to the TCI, participants also completed questionnaires assessing mindfulness and equanimity.

Mindfulness traits were assessed using the Italian version (Giovannini et al., 2014) of the Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006). This 39-item instrument measures five distinct facets of dispositional mindfulness on a 5-point Likert scale: Observing (ω=0.78, α=0.77 in the present sample), Describing (ω=0.88, α=0.87), Acting with Awareness (ω=0.88, α=0.87), Non-judging (ω=0.92, α=0.92) and Non-reactivity (ω=0.83, α=0.83) to inner experience.

Equanimity was measured using the Equanimity Scale–16 (ES-16; Rogers et al., 2021), translated into Italian by the authors, designed to assess the capacity to maintain mental calm and balance in the face of emotional stimuli. The ES-16 evaluates Experiential Acceptance (ω=0.87, α=0.86) and Non-Reactivity (ω=0.90, α=0.90) on a 5-point Likert scale.

Moreover, the phenomenological qualities of self-reported thoughts during MW episodes were assessed using the TCQ (Cantone et al., 2021), which was adapted from the version used by Stawarczyk and colleagues (Stawarczyk et al., 2011, 2013). The TCQ was inspired by the Memory Characteristics Questionnaire (Johnson et al., 1988) and has been used to evaluate the subjective features of spontaneous thoughts sampled in daily life (e.g., Berntsen & Jacobsen, 2008; D'Argembeau et al., 2011; Cantone et al., 2021).

As mentioned above, at the end of each SART block, participants indicated whether their attention was on-task or their mind wandered. Each MW episode was evaluated through the TCQ at the end of the task (see Table S10 for the full list of items), which asked participants to rate their experience on distinct characteristics. Nine items were rated on a 7-point Likert scale (0 = "not at all", 6 = "completely") and included assessments of visual imagery (TCQ1), inner speech (TCQ2), intentionality (TCQ3), sequential structure (e.g., goal-directed thought chains; TCQ4), realism (TCQ5), concreteness (TCQ6), personal relevance (TCQ7), connection to personal goals (TCQ8) and emotional intensity (TCQ10). Two additional items captured frequency of recurrence of that specific thought in daily life (TCQ9; 0 = "never", 6 = "very frequently") and its emotional valence (TCQ11; -3 = "very negative", 0 = "neutral", 3 = "very positive").

For TCQ1–TCQ10, higher scores indicated greater endorsement of the corresponding characteristic. For TCQ11 lower scores indicated more negative emotional valence and higher scores indicated more positive emotional valence. Finally, participants indicated the temporal orientation of each thought (TCQ12: past, present, future, or no specific temporal orientation).

Physiological signal acquisition and analysis

Physiological data were collected using the BioGraph Infiniti system (Thought Technology Ltd.) with the Physiology Suite software (version 5.1.1). Data acquisition was performed via the ProComp Infiniti encoder, connected to the recording computer through a fiber optic cable and TT-USB interface, ensuring high signal fidelity and electrical isolation. The physiological analyses focused on mean HR and blink rate.

Baseline physiological activity was additionally recorded for 5 min, prior to the SART, during which participants were asked to remain quiet and avoid movements. Signal quality was visually monitored in real time to confirm a stable and artifact-free waveform before proceeding with the experimental task.

Because thought probes explicitly referred to the attentional state immediately preceding the probe, physiological indices were interpreted as reflecting activity in the pre-probe period rather than the entire inter-probe interval.

Accordingly, the intervals of interest to analyze physiological signals consisted in the 5s windows before the probes. This window for physiological signals preceding the thought probes (which were presented at the end of each block, i.e., 30 times during the SART), was selected to capture physiological activity as close as possible to the reported attentional state while still providing sufficient data for HR and blink-rate estimation. This choice was motivated by previous MW studies using short pre-probe windows for physiological indices such as eye blinks (e.g., 5s; Smilek et al., 2010), as well as by evidence that many MW episodes are brief, often lasting 5 s or less (Pelagatti et al., 2020). Because pre-probe windows vary across SART and related sustained-attention studies (e.g., Smallwood et al., 2004, 2008; Stawarczyk et al., 2011, 2013), and longer intervals have also been used for HR analyses in recent thought-probe studies (e.g., Corcoran et al., 2025), we additionally analyzed HR over a 10s pre-probe window as a literature-based sensitivity analysis.

Heart rate

HR data were recorded through a blood volume pulse (BVP) sensor (otherwise known as a photoplethysmographic -PPG- sensor), placed on the ring finger of the left (non-dominant) hand using a Velcro strap, ensuring optimal contact pressure to minimize motion artifacts. Data were acquired at 256 Hz through a Procomp Infiniti device connected to the recording computer through a fiber optic cable and TT-USB interface. HR and blood volume pulse amplitude (BVPA) values were calculated in real time by the Biograph Infiniti software (Thought Technology Ltd.). HR data were preprocessed and analyzed using the open-source Python package NeuroKit2 (Makowski et al., 2021; https://neuropsychology.github.io/NeuroKit/). The first 250 samples of the recorded signal were removed to avoid initial transients. The signal was then processed using the "nk.ppg_process" function. This function filters the signal using a 3rd-order zero-phase Butterworth bandpass filter (0.5–8 Hz), following Elgendi et al. (2013), to preserve the frequency range relevant to cardiac activity while minimizing baseline drift and high-frequency noise. In addition, this function optimizes peak detection in PPG signal (Elgendi et al., 2013) and the signal quality assessment through a template-matching approach (Orphanidou et al., 2015). After the preprocessing, events were defined using the "nk.events_create()" function, with onsets, durations (5s and 10s intervals), and conditions (on-task vs. MW) derived from experimental markers from the SART. These events were used to segment the continuous data into task-relevant epochs using the "nk.epochs_create" function. Finally, event-related features were extracted with the function "nk.ppg_eventrelated", resulting in a dataframe containing a range of physiological metrics for each event. The PPG preprocessing parameters followed the standard NeuroKit2 PPG-processing pipeline, including the Elgendi et al. (2013) filtering and peak-detection procedure. Among the extracted features, mean heart rate (HR; beats per minute) within each epoch was retained for the main statistical analysis, as HR has been used as an index of autonomic arousal and stress-related activation (Corcoran et al., 2025; Schneider & Schwerdtfeger, 2020; Delgado-Pastor et al., 2015; Schubert et al., 2009; Smallwood et al., 2004, 2007). Finally, these values were normalized to the participant's average heart rate recorded during the pre-SART 5-minute baseline and analyzed with NeuroKit2 (same pipeline of the signal during the SART). This was done to reduce inter-individual variability when considering task-related fluctuations.

Eye blinks

Ocular movement data were recorded using vertical and horizontal electro-oculograms, using two pairs of gold cup electrodes connected to two pre-amplified electroencephalograph sensors (EEG-Z sensors from Thought Technology Ltd.). One pair of electrodes was placed above and below the right eye, and the other pair at the outer canthi of each eye. A fifth electrode applied to the forehead was grounded at the two sensors. Data were acquired at 256 Hz.

Eye blinks in the electro-oculogram signals were initially detected using BLINKER (Kleifges et al., 2017), a MATLAB (24.1.0.2578822 (R2024a) Update 2; Natick, Massachusetts: The MathWorks Inc.https://www.mathworks.com) plugin for EEGLAB, and were subsequently confirmed through visual inspection. Automatic detections produced by BLINKER were visually inspected by the experimenter and false positives or missed blinks were corrected manually. To normalize data to a condition in which motor activity (i.e., keyboard presses) and visual stimuli (SART stimuli on the screen) were the same as those during the 5s intervals of analysis, the baseline was obtained by concatenating the initial 10 s of the 30 blocks. EB data used in the analysis were therefore the total number of blinks per second in the condition of interest (MW or on-task) divided by the total number of blinks per second during the baseline.

Statistical analyses

SART

Data analyses were conducted in R (version 4.5.0; R Core Team, 2024; https://www.R-project.org/) and RStudio (version 2024.12.1+563; RStudio Team, 2024; https://www.rstudio.com/), using mixed-design analyses of covariance (ANCOVAs) implemented via the "aov_ez" function from the R package *afex*. This approach allows the specification of within-subject factors, between-subject factors, and covariates. Specifically, four separate ANCOVAs were conducted with Condition (MW vs. on-task conditions in the SART) as the within-subject factor, Group (Controls vs. Meditators) as the between-subject factor, and Gender and Age included as covariates. Age was mean-centered to zero to improve interpretability and reduce collinearity in the models.

Age and gender were included as covariates because they may influence psychophysiological and behavioral measures, including heart rate, ocular activity, and sustained-attention performance. Although meditators and controls were matched on these variables, they were retained to control for residual inter-individual variability.

Two ANCOVAs targeted physiological measures collected during the SART: HR and EB. The other two ANCOVAs focused on behavioral outcomes, namely RT and response accuracy during the SART. Specifically, RT were calculated as the mean reaction times to correct go trials, while response accuracy was calculated as the proportion of correct responses across all trials. To control for multiple comparisons, Bonferroni correction was applied separately within the physiological ($\alpha=0.05/2$) and behavioral ($\alpha=0.05/2$) domains.

Since assumptions of normality were sometimes violated, robustness checks were performed using the "bwtrim" function from the *WRS2* package, which implements robust mixed-design ANOVAs on 20% trimmed means. This method is suitable for designs with one between-subject and one within-subject factors, providing a robust alternative to standard ANOVAs when assumptions are violated.

In cases where significant interactions between MW and Group emerged, post-hoc comparisons were conducted using estimated marginal means through the *emmeans* package, applying Bonferroni correction for multiple comparisons.

In addition, to address the heterogeneity of self-reported MW episodes, we conducted an exploratory analysis in which reports classified as mind blanking or perceptual MW were excluded, including both environment-related and internal-stimulus-related distractions, retaining only cognitive MW episodes and on-task episodes. In this case, only 46 participants (24 meditators and 22 controls) reported cognitive MW episodes and were included in the analysis. Overall, to assess the sensitivity of the findings to key analytical choices, we performed the following robustness checks: HR analyses were repeated using a longer 10-s pre-probe window; standard ANCOVA results were compared with robust ANOVAs based on 20% trimmed means; additional control ANCOVAs were conducted including baseline HR and TCI Harm Avoidance as covariates; and the HR analysis was repeated after excluding perceptual MW episodes, as described above.

Finally, to reduce interindividual variability we normalized HR and EB (dividing their values 5/10s before the probes in the SART respectively by their values during the baseline or during the beginning of each SART block). Given the lack of a baseline for behavioral measures, and considering the high within-participant variance in RT and response accuracy as well as the need to increase the precision of the per-participant estimate (Baker et al., 2021), we averaged behavioral performance across the entire blocks classified as MW or on-task. This approach minimizes the excessive variability that would result from restricting the behavioral analysis to only a few seconds before each probe.

Questionnaire scores

Questionnaires' analyses were performed in JASP (JASP Team, 2023, version 0.18, https://jasp-stats.org). Inde pendent samples two-tailed t-tests were conducted to compare questionnaire scores between meditators and controls.

Then, a linear multiple regression model with a step-wise elimination approach was conducted to assess whether questionnaire subscale scores from the FFMQ and ES-16 (used as independent variables) could predict individual variability in physiological and behavioral responses associated with MW in the SART. Specifically, we performed a regression for each dependent variable that showed significant differences as a function of MW condition (either main effect or interaction in the ANCOVAs): HR, EB and RT. For each regression, the dependent variable was computed as the difference between the mean value in SART conditions where participants reported MW and the mean value in on-task conditions. This operationalization reflects the within-subject change in physiological or behavioral responses associated with MW episodes in the SART. Bonferroni correction was applied for the three regression models ($\alpha = 0.05/3$).

These regressions aimed to test whether individual differences in mindfulness and equanimity traits are associated with the magnitude of MW-related physiological (HR, EB) and behavioral (RTs) changes in the SART. This directionality of prediction is theoretically motivated by the assumption that relatively stable psychological traits (i.e., trait questionnaire scores) influence how participants physiologically and behaviorally respond during task-related cognitive fluctuations characterized by MW, rather than the inverse.

Finally, as exploratory analyses, we used t-tests and correlations to examine differences in TCQ responses between groups at the trial level, rather than at the participant level. Specifically, we included all available TCQ responses from all MW episodes, acknowledging that the number of episodes and corresponding TCQ completions varied across participants. Group differences were tested using t-tests for the 11 continuous TCQ items and a chi-square test for the categorical temporal-orientation item (TCQ12). Multiple comparisons were controlled using Bonferroni correction across the 12 TCQ items/tests ($\alpha = 0.05/12 = 0.004$). Exploratory correlations were conducted separately in meditators and controls between TCQ items and HR in the 5-s pre-probe interval. These analyses were exploratory and clearly separated from the primary ANCOVA-based analyses. Bonferroni correction was applied across 22 correlations (11 TCQ items × 2 groups; $\alpha = 0.05/22 = 0.002$).

Results

For the four main ANCOVAs on SART outcomes, Bonferroni correction was applied separately within physiological outcomes (HR and EB; $\alpha = 0.025$) and behavioral outcomes (RT and accuracy; $\alpha = 0.025$). Accordingly, only effects with $p < .025$ were considered statistically significant in the main analyses.

Heart Rate (PPG signal)

For heart rate (see Table S1 and Table 1 for descriptives), the ANCOVA revealed a significant interaction between Group and MW condition ($F(1, 46) = 5.75$, $p = .021$, $\eta^2_p = 0.11$). No significant main effects were observed for Group ($F(1,46) = 0.19$, $p = .668$) or MW ($F(1,46) = 2.25$, $p = .140$). The covariate Gender had a significant main effect ($F(1,46) = 6.30$, $p = .016$, $\eta^2_p = 0.12$), showing higher HR values in males (1.03 ± 0.06) than in females (0.99 ± 0.06) during the SART, while Age did not (table S1 and Fig. 1).

Assumptions were checked: Levene's test for homogeneity of variances was non-significant ($F(3, 96) = 0.24$, $p = .870$); however, Shapiro-Wilk test indicated non-normal residuals ($W = 0.95$, $p < .001$). Therefore, a robust ANOVA was also computed and confirmed the Group*MW interaction effect ($W(1,26.6) = 4.98$, $p = .034$). In addition to this analysis on 5s intervals, the significant interaction was confirmed also when considering 10s intervals ($F(1, 46) = 7.28$, $p = .010$, $\eta^2_p = 0.14$). See Table S5.

Post-hoc comparisons (Bonferroni-corrected) that explored the Group x MW condition interaction revealed a significant MW effect within the meditators group ($t(46) = 2.81$, $p = .007$, Cohen's $d = 0.48$), but not in the control group ($t(46) = -0.63$, $p = .531$). These results indicate that, while HR remained stable across MW conditions (i.e., MW vs. on-task conditions) in controls, during episodes of MW HR was reduced in meditators (Fig. 1).

Consistent with the a priori power analysis, a post-hoc sensitivity analysis based on the observed Group × MW interaction effect sizes ($\eta^2 p$ = .10–0.14) indicated very high statistical power (>0.99) for the main physiological analyses.

As a control analysis, we repeated the HR ANCOVAs after excluding episodes classified as perceptual MW, namely environment-related and internal-stimulus-related distractions. The analysis therefore compared on-task episodes with cognitive MW episodes only. This analysis showed a pattern directionally consistent with the main findings, although the Group × State interaction did not reach significance in either the 5-s pre-probe window ($F(1, 44) = 2.15$, $p = .150$, $\eta^2 p = .047$), or the 10-s pre-probe window ($F(1, 44) = 3.52$, $p = .067$, $\eta^2 p = .074$), possibly due to the

Table 1 Descriptives of the dependent variables used in our study Data were collected during the SART; HR and EB were calculated in the 5s before the probe, at the end of each block, and were normalized respectively by their values during the baseline (acquired for 5 min before the SART) or during the beginning of each block. RT and response accuracy were calculated across the entire blocks classified as MW or on-task conditions. C=controls, M=meditators, HR=heart rate, EB=eye blinks, MW=mind wandering; RT=reaction time; ACC=accuracy

Group	HR: MW		HR: on-task		EB: MW		EB: on-task		RT: MW		RT: on-task		ACC: MW		ACC: on-task	
	C	M	C	M	C	M	C	M	C	M	C	M	C	M	C	M
Mean	1.016	0.994	1.010	1.013	1.100	1.147	0.938	0.938	363.932	367.174	350.469	364.683	0.995	0.993	0.998	0.998
Std. Deviation	0.071	0.056	0.062	0.062	0.392	0.459	0.239	0.229	37.521	53.835	31.210	49.341	0.009	0.016	0.003	0.003
Minimum	0.918	0.916	0.912	0.928	0.390	0.590	0.130	0.290	301.377	278.127	298.146	291.441	0.960	0.923	0.990	0.990
Maximum	1.239	1.132	1.142	1.182	2.080	2.570	1.290	1.310	432.400	538.528	415.283	535.691	1.000	1.000	1.000	1.000

reduced sample size (N = 46) and number of observations when excluding MW subtypes. However, exploratory post-hoc comparisons showed a significant HR reduction during cognitive MW compared with on-task episodes in meditators in both the 5-s window (p = .045), and the 10-s window (p = .045), but not in controls (respectively, p = .955 and p = .530). These results are reported in Tables S6–S7.

Additional ANCOVAs confirmed the main results also when considering TCI Harm Avoidance and Baseline HR as covariates (see Table S8 and Table S9).

Eye Blinks

The ANCOVA for Eye Blinks (see Table S2 and Table 1 for descriptives) revealed a significant main effect of MW (MW > on-task, $F(1, 46) = 11.80$, $p = .001$, $\eta^2_p = 0.20$) (table S2). Residuals violated normality ($W = 0.87$, $p < .001$), although Levene's test for homogeneity of variances was non-significant ($F(3, 96) = 1.86$, $p = .140$). Given the violation of normality, a robust ANOVA was also computed and confirmed the main effect of MW (W(1,23.7) = 6.69, p = .016).

Reaction Time (RT)

The ANCOVA for RTs (see Table S3 and Table 1 for descriptives) to correct go trials in the SART revealed a significant main effect of MW ($F(1, 46) = 9.67$, $p = .003$, $\eta^2_p = 0.17$), and a Group*MW interaction ($F(1, 46) = 6.04$, $p = .018$, $\eta^2_p = 0.12$). A significant effect of Age*MW interaction ($F = 9.13$, $p = .004$, $\eta^2_p = 0.17$) was also found (table S3).

Residuals violated normality ($W = 0.90$, $p < .001$), although Levene's test for homogeneity of variances was non-significant ($F(3, 96) = 0.66$, $p = .570$). Given the violation of normality, a robust ANOVA was also computed and confirmed the main effect of MW (W(1, 29.2) = 4.37, p = .045), but not the Group*MW interaction (W(1,29.2) = 1.12, p = .299) and thus this was not explored further. These results show that RTs are slower during MW (mean = 365.62 ms, SD = 46.28) than during on-task conditions (mean = 357.86 ms, SD = 41.84).

An exploratory correlational analysis was performed due to the significant Age*MW interaction (the robust ANOVA was not applied in this case since it does not support the inclusion of covariates). The relationship between age and RT was significant only in controls in blocks involving MW ($r = .63$, $p = .001$). These results suggest that in controls, SART blocks in which MW occurred were associated with increased RTs, and that older participants exhibited generally longer RTs than younger participants. However, this was not true for meditators ($r = .15$, $p = .460$), and for

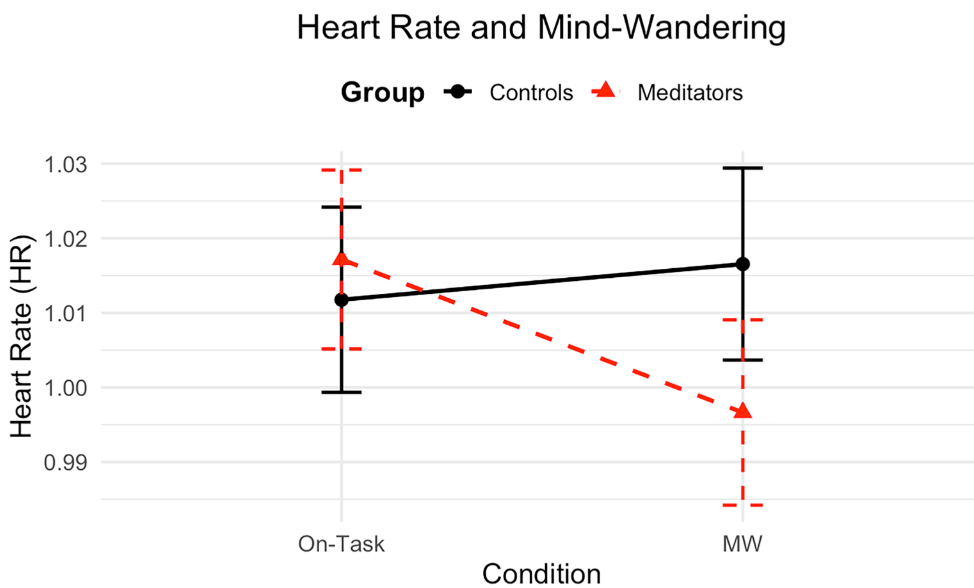

Fig. 1 Interaction between Group and Mind Wandering (MW) on heart rate (HR) measured via PPG signal. HR, expressed as the ratio between the average PPG signal in the 5 s preceding each thought probe and the baseline average PPG signal recorded before the SART, is shown as a function of MW condition (MW vs. on-task conditions in the SART) and group (Controls vs. Meditators). Error bars represent ± 1 standard error. A significant interaction between MW and group was found: while HR did not change in Controls, Meditators showed a significant reduction in HR in the MW compared to the on-task condition

blocks in which MW did not occur in both controls (r = .28, p = .185) and meditators (r = .14, p = .498).

Response Accuracy

For response accuracy (proportion of correct responses across all trials; see Table 1 for descriptives), the ANCOVA (Table S4) revealed a marginally significant result for the main effect of MW ($F(1, 46) = 4.15$, $p = .048$, $\eta^2_p = 0.08$); however, it did not survive Bonferroni correction or robust ANOVA (table S4). No other significant result was found.

Questionnaire scores

Descriptives of questionnaire scores are reported in Table 2. Independent samples two-tailed t-tests were conducted to compare questionnaire scores between meditators and controls. Assumptions of normality and homogeneity of variance were verified using the Shapiro-Wilk and Brown-Forsythe tests, respectively. Only the act with awareness subscale violated the normality assumption (W = 0.952, p = .043), for which Welch's test was applied. Results showed that meditators scored significantly higher than controls on the Experiential Acceptance subscale (t(47) = 3.314, $p < .002$, d = 0.95) and on the Non-Reactivity subscale (t(47) = 2.411, p = .020, d = 0.69) of the ES-16. Significant differences also emerged on the FFMQ Observe facet (t(48) = 2.382, p = .021, d = 0.67, Meditators > Controls). No significant differences were found for the describe (p = .192), act with awareness (p = .202), Non-Judging (p = .096) and Non-Reactivity (p = .069) facets of the FFMQ. Using a Bonferroni-corrected threshold for the 7 scales ($\alpha = 0.05/7 = 0.007$), these findings suggest that the meditator group was particularly characterized by higher levels of Experiential Acceptance (Table 2).

Moreover, in the exploratory analysis of TCQ responses, given the violation of normality assumptions, we applied Welch's t-test to compare the two groups. 344 MW episodes were included in the analyses; from the 30 probes for each participant, meditators reported 6.81 ± 3.97 episodes (min = 1; max = 17) while controls reported 7.74 ± 4.10 episodes (min = 1; max = 15), showing no significant difference between groups (t (48) = 0.81; p = .423). Using a Bonferroni-corrected threshold for the 12 TCQ tests ($\alpha = 0.05/12 = 0.004$), meditators reported significantly higher scores on TCQ items related to realism and concreteness, such as "*Was the content of the distraction realistic and plausible?*" (TCQ5: t = 3.47, $p < .001$, d = 0.38) and "*Was the content of the distraction related to something concrete and well-defined (e.g., a specific situation or a particular action)*?" (TCQ6: t = 3.97, $p < .001$, d = 0.43). No other significant group differences emerged.

To further explore the association between the phenomenological characteristics of MW and cardiac activity, exploratory Kendall's tau correlations (given violations of normality) were conducted between TCQ items and HR in the 5-s pre-probe interval, separately for meditators and controls (Bonferroni-corrected p-values are reported in Table S10, with uncorrected p-values additionally provided for transparency). In controls, HR was positively associated with visual imagery during MW (TCQ1: $\tau = 0.239$, pBonf = 0.022, uncorrected $p < .001$), and this association survived Bonferroni correction for 22 correlations ($\alpha = 0.05/22 = 0.002$). In meditators, emotional intensity showed a nominal negative association with HR (TCQ10: $\tau = -0.109$, pBonf = 1.000, uncorrected p = .048), but this effect did not survive correction for multiple comparisons.

Table 2 Descriptives and comparisons of questionnaire scores for the two groups

Age	Group	Valid	Missing[1]	Mean	Std.Deviation	Minimum	Maximum	Statistics	*p*-value[2]
	C	24	0	46.083	13.197	25.000	74.000	t = -1.08	0.288
Age	M	26	0	49.769	11.028	27.000	68.000		
Gender	C	24	0	13 F				$X^2 = 0.063$	0.802
Gender	M	26	0	15 F					
TCI-NS	C	24	0	9.750	3.442	5.000	17.000	t = 1.11	0.272
TCI-NS	M	26	0	8.654	3.521	2.000	15.000		
TCI-HA	C	24	0	9.667	5.247	2.000	18.000	W = 0.80	0.429
TCI-HA	M	26	0	8.538	4.709	1.000	18.000		
TCI-RD	C	24	0	8.125	2.626	4.000	13.000	t = -1.21	0.231
TCI-RD	M	26	0	9.038	2.690	3.000	14.000		
TCI-PS	C	24	0	2.500	1.588	0.000	5.000	W = -0.19	0.853
TCI-PS	M	26	0	2.577	1.301	0.000	5.000		
TCI-SD	C	24	0	17.750	6.173	5.000	24.000	W = -0.78	0.437
TCI-SD	M	26	0	19.000	4.980	5.000	24.000		
TCI-C	C	24	0	19.792	2.934	12.000	24.000	W = -1.04	0.302
TCI-C	M	26	0	20.615	2.624	15.000	24.000		
TCI-ST	C	24	0	7.917	3.400	3.000	14.000	t = -0.51	0.615
TCI-ST	M	26	0	8.423	3.679	1.000	14.000		
ES-experiential acceptance	C	24	0	3.065	0.625	2.130	4.380	t = -3.31	0.002
ES-experiential acceptance	M	25	1	3.658	0.627	2.000	4.630		
ES-16-non-react	C	24	0	3.226	0.818	2.130	4.630	t = -2.41	0.020
ES-16-non-react	M	25	1	3.762	0.738	2.000	5.000		
FFMQ-observe	C	24	0	3.165	0.701	1.880	4.630	t = -2.38	0.021
FFMQ-observe	M	26	0	3.560	0.458	2.500	5.000		
FFMQ-describe	C	24	0	3.559	0.600	2.250	4.500	t = -1.32	0.192
FFMQ-describe	M	26	0	3.800	0.682	2.500	5.000		
FFMQ-act-with-awareness	C	24	0	3.264	0.699	2.130	4.250	Welch = -1.30	0.202
FFMQ-act-with-awareness	M	26	0	3.498	0.566	2.250	4.500		
FFMQ-nonjudge	C	24	0	3.460	0.782	1.880	5.000	t = -1.70	0.096
FFMQ-nonjudge	M	26	0	3.843	0.813	2.250	5.000		
FFMQ-nonreact	C	24	0	2.982	0.580	2.140	4.140	t = -1.86	0.069
FFMQ-nonreact	M	26	0	3.297	0.616	2.140	4.860		
TCQ1-Visual	C	175	3	2.011	2.324	0.000	6.000	Welch = 1.194	0.233
TCQ1-Visual	M	160	6	1.719	2.164	0.000	6.000		
TCQ2-Speech	C	175	3	2.726	2.094	0.000	6.000	Welch = 0.679	0.497
TCQ2-Speech	M	160	6	2.569	2.130	0.000	6.000		
TCQ3-Intended	C	175	3	1.240	1.775	0.000	6.000	Welch = -0.69	0.490
TCQ3-Intended	M	160	6	1.375	1.797	0.000	6.000		
TCQ4-Structured	C	175	3	1.851	2.144	0.000	6.000	Welch = -1.89	0.059
TCQ4-Structured	M	160	6	2.281	2.010	0.000	6.000		
TCQ5-Realistic	C	175	3	4.011	1.900	0.000	6.000	Welch = -3.47	< 0.001
TCQ5-Realistic	M	160	6	4.662	1.525	0.000	6.000		
TCQ6-Concrete	C	175	3	4.051	2.066	0.000	6.000	Welch = -3.97	< 0.001
TCQ6-Concrete	M	160	6	4.844	1.572	0.000	6.000		
TCQ7-Important	C	175	3	1.349	1.800	0.000	6.000	Welch = -1.80	0.072
TCQ7-Important	M	160	6	1.706	1.828	0.000	6.000		
TCQ8-Goals	C	175	3	1.286	1.847	0.000	6.000	Welch = -0.66	0.510
TCQ8-Goals	M	160	6	1.419	1.841	0.000	6.000		
TCQ9-Repetitive	C	175	3	2.000	1.900	0.000	6.000	Welch = 1.90	0.059
TCQ9-Repetitive	M	160	6	1.612	1.836	0.000	6.000		
TCQ10-Affective	C	175	3	1.777	1.736	0.000	6.000	Welch = -0.574	0.566
TCQ10-Affective	M	160	6	1.881	1.584	0.000	6.000		
TCQ11-Affective2	C	175	3	-0.126	1.289	-3.000	3.000	Welch = 1.87	0.062
TCQ11-Affective2	M	160	6	-0.363	1.019	-3.000	3.000		

Table 2 (continued)

Age	Group	Valid	Missing[1]	Mean	Std.Deviation	Minimum	Maximum	Statistics	*p*-value[2]
	C	24	0	46.083	13.197	25.000	74.000	t = -1.08	0.288
TCQ12-Temporal collocation	C	175	3	Future: 26 Present: 123 Past: 16 No specific temporal orientation: 10				X^2=2.27	0.811
TCQ12-Temporal collocation	M	160	6	Future: 25 Present: 112 Past: 11 No specific temporal orientation: 12					

[1]Missing values indicate participants who did not complete the questionnaire; in case of the TCQ, they correspond to questions without answers (single trials were considered in the TCQ)

[2]uncorrected p-values are reported. For questionnaire scale comparisons, Bonferroni correction was applied across the 7 main questionnaire scales (α = 0.007). For TCQ comparisons, Bonferroni correction was applied across the 12 TCQ tests (α = 0.004). Bold p-values indicate effects surviving the relevant correction

Abbreviations: *C*=controls, *M*=meditators, *ES–16*=Equanimity Scale, *FFMQ*=Five Facets Mindfulness Questionnaire, *TCQ*=Thought Characteristics Questionnaire, *TCI*=Temperament and Character Inventory, *TCI-NS*=Novelty seeking, TCI-HA=Harm avoidance, TCI-RD=Reward dependence, *TCI-PS*=Persistence, *TCI-SD*=Self-directedness, *TCI-C*=Cooperativeness, *TCI-ST*=Self-transcendence, *t*=Student's t-test, *Welch*=Welch's t-test, *X²* = chi-square test

Relationships between HR and questionnaire scores

A linear multiple regression model (see Table S12) with a backward elimination approach was conducted to assess whether questionnaire subscale scores from the FFMQ and ES-16 (used as independent variables) could predict individual variability in physiological and behavioral responses associated with MW in the SART.

The regression analysis on HR returned a significant winning model (F (2, 46)=5.818, R2=0.202, Adjusted R^2 = 0.167; RMSE=0.036, p = .006). In this model, both the Experiential Acceptance subscale of the ES-16 (B = -0.036, SE=0.010, β = -0.622, t=-3.410, p = .001, 95% CI [-0.057, -0.015]) and the Observe subscale of the FFMQ (B=0.027, SE=0.012, β=0.420, t=2.304, p = .026, 95% CI [0.003, 0.050]) reached significance. However, only experiential acceptance was still significant after Bonferroni correction. Collinearity was not problematic (VIFs<2) and complete regression results are reported in Table S12 in the Supplementary Materials. The effect was negative, meaning that less experiential acceptance is associated with higher HR during MW; in other words, the more experiential acceptance, the greater the decrease in HR during MW (vs. on-task) episodes in the SART.

The regression analyses on EB and RTs did not retain any predictor variables after backward elimination, resulting in a null model including only the intercept (Model 0). This indicates that none of the questionnaire subscale scores significantly predicted the MW-related changes in EB and RTs during the SART.

Discussion

This study investigated the physiological and behavioral correlates of MW during a modified version of the SART, comparing experienced mindfulness meditators and non-meditating matched controls. The modified version of the SART incorporated thought probes to distinguish between self-reported MW and on-task conditions (Smallwood et al., 2008; Stawarczyk et al., 2011, 2013).

Regarding our first objective, results revealed a significant interaction between group and MW for HR: meditators showed a reduction in HR during MW episodes, while controls showed no significant change. EB and RT both increased during MW compared to on-task SART conditions, but these increases did not differ between groups. A similar pattern emerged for response accuracy (lower for MW vs. on-task conditions). But since this effect did not survive Bonferroni correction, accuracy was not included in subsequent regression analyses.

Regarding our second objective, results revealed that HR differences between MW and on-task SART conditions were predicted by experiential acceptance scores of the ES-16: the more experiential acceptance, the greater the decrease in HR during MW episodes in the SART. No significant associations were found when considering EB or RT.

Finally, exploratory analyses of MW phenomenology revealed that, compared to controls, meditators reported higher realism and concreteness within the TCQ.

HR was the only physiological marker that significantly differentiated between groups, with a reduction in HR during MW episodes only in meditators. To note, this result showed a trend, even if not statistically significant, when excluding perceptual MW episodes from the analysis, but was confirmed through both standard and robust ANOVAs, as well as in analyses conducted on both 5s and 10s time intervals preceding MW reports. These HR results contribute to a more nuanced understanding of heterogeneous findings in the literature, which linked both increases (Smallwood et al., 2004) and decreases (Corcoran et al., 2025) in HR to MW. To note, differences between these and our study should be outlined; first, participants in our study are older than in the other two studies; second, they measured HR through electrocardiography (ECG), while we recorded PPG signals and normalized them to the baseline; third, while Smallwood et al. (2004) considered HR during the last 30s of each block, Corcoran et al. (2025) relied on 10s intervals whereas we analyzed both 5s and 10s intervals; fourth, only Corcoran et al. (2025) distinguished between MW and mind-blanking; nevertheless, a posteriori, only 11 out of 344 MW episodes in our study were classified as mind-blanking (see Table S11); finally, our sample was of $N=50$, while Smallwood et al. (2004) relied on different experiments between $N=12$ and $N=41$, and Corcoran et al. (2025) relied on a sample of $N=65$. These methodological differences may partly explain why previous studies reported different directions of HR change during MW. Overall, these results suggest that MW is a heterogeneous process. Importantly, null results in the present study should not be interpreted as a general absence of MW effects. In fact, MW episodes were associated with slower RT and increased EB in both groups, indicating that the task successfully captured attentional disengagement. However, the cardiac findings were more selective, suggesting that in the present study behavioral/ocular markers may index the general attentional cost of MW in both groups, whereas HR may be more sensitive to the affective, motivational and regulatory quality of MW. Previous evidence suggested that both dispositional traits, such as dysphoria (Smallwood et al., 2007), and MW features, such as rigidity and inflexibility (Ottaviani et al., 2013) can explain HR increases during MW. Our results add to this evidence suggesting that the autonomic profiles across MW episodes may change according to mindfulness experience and experiential acceptance scores.

These effects may be interpreted within the Metacognitive Model of Mindfulness (Jankowski & Holas, 2014). According to this model, a conscious regulation of experiences and cognitive processes is reached through mindfulness-related metacognitive knowledge (specific beliefs about the transient and non-threatening nature of thoughts), experiences and skills. In this way, a person is able to consciously apply more adaptive coping strategies promoting acceptance to what he or she experiences, including MW. This perspective may help explain why HR reduction emerged specifically during MW in meditators. In samples not stratified by mindfulness expertise, MW has been associated with both increased (Smallwood et al., 2004) and decreased (Corcoran et al., 2025) HR, as reflecting, respectively, personally salient internal mentation or vigilance-related disengagement. These processes may coexist across different MW episodes, potentially explaining why controls in the present study did not show a significant HR difference between on-task and MW episodes. The present study contributes to this controversy by suggesting that the direction of HR change during MW may also depend on sample characteristics and mindfulness-related acceptance traits. Specifically, the lower HR observed in meditators during MW may be consistent with a more decentered and less reactive form of MW, possibly involving reduced engagement in tacit evaluative processes and higher-order cognitive elaboration, such as during rumination (Holas & Jankowski, 2013). This interpretation is supported by the regression analysis showing that experiential acceptance scores, which were higher in meditators, were associated with larger HR reduction during MW. Descriptively, Fig. 1 shows that meditators exhibited lower HR levels during MW than on-task conditions, whereas controls tended toward the opposite pattern. This group difference may be compatible with a regulatory profile associated with mindfulness experience during MW episodes (Feruglio et al. 2021a), although causal conclusions cannot be drawn from the present quasi-experimental design.

Nonetheless, we did not observe evidence that EB differed between meditators and controls. However, MW episodes in the SART were associated with a general increase in EB across both groups. This replicates earlier findings (Smilek et al., 2010) and supports the notion that increased EB may reflect a shift in the attentional orientation toward the inner world. While Kruis and collaborators (2016) found reduced blink rates in experienced meditators, their study focused on spontaneous EB during rest conditions. In addition, they did not find differences in novice meditators. It is possible that, when considering task-based MW episodes, both meditators and controls show higher EB, which may serve to modulate the sensory input and redirect attention to inner/outer world. Another possibility is that the level of mindfulness experience in our meditators sample (M = 5.69; SD = 4.27 years) is not sufficient to show significant differences in this measure. Future studies may clarify this point.

RTs were also significantly longer during MW episodes in the SART, consistent with behavioral costs of attentional disengagement (Stawarczyk et al. 2011, 2013; Feruglio et al. 2021a). However, no group differences emerged as main effect, and although a Group*MW interaction emerged in the classical ANCOVA, it did not survive robust statistical correction. Therefore, we did not perform post hoc analyses and did not further explore this finding.

Nevertheless, the above-mentioned differences between meditators and controls are further supported by exploratory correlational analyses conducted to clarify the significant MW*Age interaction in RTs during the SART. We observed a significant positive correlation between RTs and age during MW episodes, but only in the control group. Notably, this relationship was absent in meditators and in on-task trials, showing that only older non-meditators responded more slowly during MW episodes in the SART. Future studies could investigate whether mindfulness training is associated with reduced age-related attentional costs of MW during attentional task execution (Fountain-Zaragoza & Prakash, 2017), given the preliminary and correlational nature of these findings.

Taken together, the behavioral and physiological findings suggest that MW involves different cognitive and autonomic profiles depending on attentional and acceptance-based strategies related to mindfulness practice. Indeed, mindfulness experience may be associated not only with reduced frequency or cognitive/affective impact of MW (Feruglio et al. 2021a), but also with a different bodily response to such episodes, possibly through a more accepting and less reactive metacognition of internal processes (Jankowski & Holas, 2014).

This interpretation is also consistent with our exploratory phenomenological analysis, which showed that meditators rated their MW episodes as more realistic and concrete than controls. This may indicate a more grounded and less abstract form of MW that, together with the higher acceptance scores, is compatible with processes of detachment and cognitive defusion, as described in Acceptance and Commitment Therapy (Luoma & Hayes, 2009). Indeed, this is considered one of the key mechanisms supporting healing and coping with stressors (Holas & Jankowski, 2013), as opposed to identification and experiential avoidance, which characterize many forms of psychopathology, such as depression (Hayes et al., 1996).

Therefore, from a clinical perspective, the present findings may be relevant to conditions in which MW becomes repetitive, abstract, rigid, and difficult to disengage from. Watkins (2008) argued that abstract vs. concrete repetitive thoughts are respectively associated with unconstructive vs. constructive consequences of MW, in particular when considering mental disorders, such as major depression (Watkins et al., 2012).

In line with this view, Holas and Jankowski (2013) suggested that in individuals characterized by chronic negative affect or high neuroticism, metacognitive systems may be dominated by beliefs, goals, and strategies that hinder acceptance of experience, in contrast to the mindfulness-related meta-knowledge that supports a more decentered and accepting relationship with mental contents. In the same line, when considering physiological evidence, perseverative cognition has been associated with autonomic rigidity and altered brain–heart interactions (Ottaviani et al., 2013), and clinical conditions, such as post-traumatic stress disorder (PTSD), show altered autonomic functioning, including higher HR during stress (Schneider & Schwerdtfeger, 2020). Indeed, in clinical populations, MW is often marked by greater physiological arousal and rigidity, potentially reflecting altered perseverative cognition (Ottaviani et al., 2013; Marchetti et al., 2016). These alterations in MW, such as rumination in depression, severe worry in anxiety, heightened distractibility in attention-deficit/hyperactivity disorder (ADHD) and disorganized ideation in psychosis (Christoff et al., 2016), may be reflected in further changes in physiological balance. For instance, in depressed individuals, rumination and perseverative cognition have been associated with higher HR (Schumann et al., 2022) or reduced heart rate variability (Ottaviani et al., 2015).

More broadly, this interpretation is consistent with recent interdisciplinary perspectives emphasizing that mental disorders are closely linked to cardiovascular risk and outcomes, and calling for integrated approaches to mental and cardiovascular health within a "Whole Person Health" framework (Barlattani et al., 2026).

In this context, the association observed in the present study between mindfulness expertise, experiential acceptance, more concrete MW characteristics, and lower HR during MW may inform future research on mindfulness-based interventions targeting maladaptive MW and autonomic regulation in populations at increased psychiatric or cardiovascular risk. Evidence showing that mindfulness can reduce resting HR, decrease sympathetic activation, and regulate stress reactivity (Pascoe et al., 2017) supports this line of research. However, because the present sample was non-clinical and the study design was cross-sectional, these clinical implications remain tentative.

This study has different limitations. First, while the SART with thought probes provides insights into spontaneous MW, it remains a laboratory task that may not fully capture the complexity of MW in naturalistic settings. Moreover, MW episodes, thought characteristics, and mindfulness-related traits were assessed through self-report measures, which may be influenced by introspective accuracy and reportability. In addition, the present thought probes distinguished only between on-task and MW states. Although the TCQ was used to better characterize MW phenomenology, it remains a retrospective self-report measure. Future studies should more clearly distinguish between MW, perseverative cognition (Ottaviani et al., 2013; Feruglio et al., 2021b), mind-blanking (Corcoran et al., 2025) and other forms of spontaneous thought. In addition, they should combine these assessments with objective physiological and behavioral markers and individual-difference measures, since all these factors may explain different HR patterns of MW episodes found in the literature.

Second, the study employed a quasi-experimental design, as random assignment was not possible, which limits causal inference regarding mindfulness practice. Although our sample was adequately powered, and groups were matched on age and gender and did not differ on TCI personality dimensions, unmeasured pre-existing differences may have contributed to the observed results. Therefore, group differences should not be interpreted as causal effects of mindfulness practice, and future longitudinal and randomized studies, including pre-post mindfulness interventions, are needed to test causal effects.

Third, while the sample size exceeded the a priori requirements and provided high power for the main analyses, smaller effects may have gone undetected. Therefore, null findings should be interpreted cautiously and future studies with larger samples are needed to replicate these results.

Fourth, the physiological assessment has some limitations. HR was derived from PPG and normalized to a pre-task baseline, whereas previous studies often used ECG. Moreover, we did not concurrently assess respiration, electrodermal activity, pupillometry, or neural markers. Future studies should combine ECG with additional autonomic and neural measures to replicate our results and better disentangle sympathetic, parasympathetic, and attentional mechanisms during MW.

A further limitation concerns the dichotomous categorization of participants as meditators versus non-meditators. To facilitate group comparisons, we ensured that control participants had no meditation experience, while meditators reported regular meditation practice over the six months before the study and were relatively homogeneous with respect to their main reported practice style. However, this binary classification may lead to information loss regarding the multidimensional nature of meditation experience. The latter may indeed vary across several dimensions, including the specific contemplative tradition or practice style, such as focused attention, open monitoring or loving-kindness, as well as practice frequency, cumulative lifetime hours, retreat experience and maintenance of regular practice during the study period. Collapsing these dimensions into a single group variable may introduce within-group heterogeneity and limit construct validity. Although we reported the available practice indices descriptively, the present study was not designed to systematically disentangle these different dimensions of meditation experience, given the limited number of meditators and the absence of systematic assessment of relevant dimensions, such as cumulative lifetime hours and retreat experience. Future studies with larger samples should therefore characterize meditation expertise more comprehensively and test whether distinct dimensions of meditation experience predict MW-related behavioral, phenomenological, and physiological responses.

Finally, the generalizability of the findings is limited. The present results should be considered applicable primarily to non-clinical adults with or without pre-existing mindfulness meditation experience performing a laboratory SART with thought probes. They should not be generalized to clinical populations, younger samples, naturalistic MW contexts, or specific mindfulness-based interventions without further evidence. Future research should test these associations in larger and more diverse samples, including clinical groups characterized by maladaptive MW, and in longitudinal randomized intervention designs.

To conclude, the present work contributes to the psychophysiological literature on MW by showing that the autonomic correlates of MW may vary as a function of mindfulness experience and experiential acceptance. While both EB and RT increased during MW in both groups, the main difference emerged as a reduction in HR during MW in meditators, but not in controls, suggesting that MW should not be considered a unitary physiological state. These findings extend previous work by integrating behavioral, cardiac, ocular, and phenomenological measures within the same probe-caught SART paradigm, and by showing that the cardiac impact of MW appeared less pronounced in individuals with mindfulness experience, characterized by acceptance and metacognitive abilities. Although the present study was conducted in a non-clinical sample and does not allow causal conclusions, it provides a framework for future longitudinal and clinical research. In particular, future studies should examine whether mindfulness-based interventions are associated with changes not only in the frequency of maladaptive MW, but also in its phenomenological qualities and autonomic correlates. Phenomenological tools such as the TCQ may be especially useful for investigating how MW content and experiential qualities differ across clinical populations and whether they change following mindfulness-based treatments.

These implications align with broader interdisciplinary work linking mental health and stress-related processes to education, occupational functioning, and social well-being, including education on depression (Chookerd et al., 2025), the management of stress and burnout in promoting occupational well-being (Tran et al., 2025), and the multidimensional nature of social well-being, including health, education, and socioeconomic conditions (Geng & Hassan, 2025). Future studies should therefore examine whether mindfulness-based interventions targeting maladaptive MW may also support broader outcomes related to stress management and well-being.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12144-026-09946-1.

Acknowledgements We thank Dr. Susanna Feruglio, Stefania Pascut and Damiano Cantone for their assistance during data collection.

Author contributions Conceptualization: Sara Sorella, Alessio Matiz, Cristiano Crescentini; Methodology: Sara Sorella, Alessio Matiz; DataCuration: Sara Sorella, Alessio Matiz; Investigation: Sara Sorella, Alessio Matiz, Luca Chittaro, Peter Malinowski;Writing - original draft preparation: Sara Sorella; Alessio Matiz, Cristiano Crescentini; Writing - review and editing:Sara Sorella, Alessio Matiz, Luca Chittaro, Peter Malinowski, Cristiano Crescentini; Funding acquisition: Sara Sorella,Cristiano Crescentini; Software: Sara Sorella, Alessio Matiz, Luca Chittaro; Project Administration: Sara Sorella,Alessio Matiz, Cristiano Crescentini; Supervision: Luca Chittaro, Peter Malinowski, Cristiano Crescentini.

Funding Open access funding provided by Università degli Studi di Udine within the CRUI-CARE Agreement. The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the BIAL Foundation Grant for Scientific Research (No. 244/22).

Data availability The data supporting the findings of this study are available in the Open Science Framework (OSF) repository at the following link: [https://osf.io/r6vw7/overview?view_only=71861b4fc76841329b8d8f657ad6f66a].

Declarations

Ethics approval The study was performed in accordance with the 1964 Declaration of Helsinki and its procedures were approved by the Institutional Review Board of the Department of Languages and Literatures, Communication, Education and Society of the University of Udine [CGPER-2022-12-22-02].

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent to publish Informed consent for publish was obtained from all individual participants included in the study.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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