When your heart isn't in it anymore: Cardiac correlates of task disengagement

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Abstract

Neuroscience is beginning to uncover the role of interoceptive feedback in perception, learning, and decision-making; however, the relation between spontaneous visceral and cognitive dynamics has received surprisingly little scrutiny. Here, we investigate how subjective, physiological, and behavioural indicators of arousal and attentional state vary as a function of cardiac activity and brain-heart coupling. Combined electroencephalogram, electrocardiogram, and pupillometric records were obtained from 25 healthy human adults during the performance of a sustained attention to response task (SART). Thought-probes were intermittently administered during the SART to collect subjective reports of attentional state (i.e., on-task, mind-wandering, mind-blanking) and vigilance level (i.e., alertness). Mind-wandering and mind-blanking reports increased in frequency with time-on-task, but were associated with distinct behavioural profiles. Mind-blanking was further characterised by more profound decreases in heart-rate and pupil size than mind-wandering, and late modulation of the heartbeat-evoked potential. Besides attentional state, lower heart-rate predicted decreased vigilance and pupil size, while heart-rate variability predicted more impulsive behaviour and pupil dilation. Together, these findings reveal that cardiac parameters afford complementary information about arousal states and attentional dynamics, illustrating the complexity of task disengagement from a cognitive and physiological perspective.

Keywords: Arousal; Attention; Brain-body interaction; HEP; Heart-rate variability; Mind-blanking; Mind-wandering; Pupillometry; SART; Vigilance

Introduction

Interoceptive processing of visceral dynamics is essential for homeostasis, and conditions the way we perceive and act in the world (Critchley and Garfinkel, 2018; Khalsa et al., 2018; Azzalini et al., 2019; Skora et al., 2022; Engelen et al., 2023). Visceral afferent signals generated by the heartbeat modulate the sensation (Saxon, 1970; Sandman et al., 1977; Edwards et al., 2009; Wilkinson et al., 2013; Motyka et al., 2019), learning, and memory of external stimuli (Garfinkel et al., 2013, 2021; Fiacconi et al., 2016), coincide with the initiation of voluntary actions (Kunzendorf et al., 2019; Galvez-Pol et al., 2020; Palser et al., 2021), and are regulated to optimise perceptual decision-making (Corcoran et al., 2021). Moreover, cortical processing of cardio-afferent feedback (indexed by the heartbeat-evoked potential [HEP]; Schandry et al., 1986; Schandry and Montoya, 1996) predicts stimulus detection (Park et al., 2014; Al et al., 2020, 2021), interoceptive attention (Petzschner et al., 2019; Fló et al., 2023), and decision-making (Azzalini et al., 2021) in healthy individuals, and may harbour diagnostic information in disorders of consciousness (Candia-Rivera et al., 2021, 2023).

While this growing body of evidence demonstrates the involvement of cardio-afferent signals in shaping conscious experience and behaviour, the underlying mechanisms that explain how these effects occur remain unclear. One possibility is that tonic cardiac activity affords contextual information about bodily and environmental states, whereby the brain integrates successive heartbeats to make inferences on arousal level that inform perception and decision-making (Garfinkel and Critchley, 2016; Pezzulo et al., 2018; Allen et al., 2022; Hsueh et al., 2023; Biddell et al., 2024). In addition, phasic cardiac activity may provide fine-grained information about evolving environmental dynamics. Such transient fluctuations might impact cognition and behaviour by stimulating neuromodulatory pathways regulating cortical arousal (Allen et al., 2016; Hulsey et al., 2017; Collins et al., 2021; Munn et al., 2021), potentially promoting the allocation of attentional resources towards external stimuli (Villena-González et al., 2017; Al et al., 2020; Barber et al., 2020; Corcoran et al., 2021; Kritzman et al., 2022).

To assess the contribution of tonic and phasic heartbeat fluctuations to spontaneous cognitive dynamics, we examined how cardiac activity relates to subjective, physiological, and behavioural indices of arousal and attention. Specifically, we investigated whether cardiac parameters indexing phasic and tonic cardiac activity encode information distinguishing episodes of task-focused attention (‘on-task’ state) from task disengagement.

We distinguished between two modes of task-disengagement – task-unrelated thought ('mind-wandering') and the absence of thought ('mind-blanking') – because of their distinct signature in terms of behaviour and arousal, with mind-blanking being associated with lower levels of arousal and more sluggish responding than mind-wandering (Andrillon et al., 2021; Boulakis et al., 2024).

Previous work has linked mind-wandering with increased heart-rate during the performance of laboratory-based tasks (Smallwood et al., 2004a, 2004b, 2007; Ottaviani et al., 2013). However, this association was not evident in a 24-hr experience sampling study (Ottaviani et al., 2015a, 2015b). Short-term heart-rate fluctuations (i.e., heart-rate variability; HRV) have also been identified as a potential biomarker of mind-wandering, although differences in HRV have thus far only been reported for perseverative, negatively-valenced thoughts (Ottaviani et al., 2013, 2015a, 2015b). Given the paucity of data on the relation between cardiac activity and task disengagement (in contrast to the rich literature linking mind-wandering and pupillometry; Smallwood et al., 2011; Franklin et al., 2013; Mittner et al., 2014; Unsworth and Robison, 2016, 2018; Andrillon et al., 2021), and extending beyond recent studies investigating brain-heart interactions under resting-state conditions (e.g., Boulakis et al., 2024; Sargent et al., 2024), we sought to identify the cardiac signatures of attentional state dynamics during task performance.

Materials and Methods

Participants

We analysed a previously published dataset (Andrillon et al., 2021) featuring electroencephalogram (EEG), electrocardiogram (ECG), and pupillometric recordings obtained from 26 healthy adults during the performance of a sustained attention to response task (SART; Robertson et al., 1997). One participant was excluded from analysis due to a poor-quality ECG. The remaining sample consisted of 15 males and 10 females aged 23-38 years (M = 29.6, S.D. = 4.2). All individuals provided written informed consent prior to participating in the study. The study protocol was approved by the Monash University Human Research Ethics Committee (Project ID: 10994).

Stimuli and experimental design

Task instructions and stimuli were presented using the Psychophysics Toolbox (v3.0.14; Brainard, 1997) for MATLAB R2018b (The MathWorks Inc., Natick, MA, USA). Participants viewed task stimuli while seated in a dimly-lit room with their head stabilised on a support positioned approximately 60 cm from the computer screen.

Participants performed two versions of a modified SART: one featuring face stimuli, another featuring numerical digits (Figure 1). Face stimuli were sampled from the Radboud Face Database (Langner et al., 2010). Eight faces (4 female) featuring a neutral expression were selected as Go stimuli; one image of a smiling female served as the NoGo stimulus. Stimuli for the Digit SART were computer-generated integers ranging from 1 to 9, with “3” serving as the NoGo stimulus. All digits were presented at a uniform font size.

In order to induce steady-state visual evoked potentials (SSVEPs) in the EEG, the left and right halves of each presented face stimulus were flickered at different frequencies (12 and 15 Hz; laterality counterbalanced across blocks). Digit stimuli were embedded within a Kanizsa illusory square, the left and right parts of which were likewise flickered. Analysis of this component of the experimental design is postponed to future work. Please note, flicker frequencies were sufficiently high that participants did not report any impact on their capacity to perform the SART.

Stimuli were presented continuously at the centre of the screen, with successive trial onsets occurring at intervals of 750 to 1250 ms (randomly sampled from a uniform distribution). All 9 stimuli within the stimulus set were present once in a pseudo-randomised order, before the set was randomly permuted for the next 9 trials (with the constraint that the same stimulus never appeared twice in succession). The probability of a NoGo trial was thus fixed at p = .11. Participants were instructed to pay attention to each presented stimulus and respond via button-press each time a Go stimulus appeared. Conversely, they were told to withhold their response whenever a NoGo stimulus was presented. Participants were advised to prioritise accuracy over speed of response, in line with evidence that this strategy improves the precision of SART errors as an index of attentional lapses (Seli et al., 2012).

The SART was intermittently interrupted by the presentation of the word “STOP” and an accompanying sound, followed by a sequence of 7 or 8 thought probes. The present study focuses on participants’ subjective reports of the content of their attentional focus “just before the interruption”. Participants responded to this probe by selecting one of the

following options: (1) “task-focused” (i.e., on-task), (2) “off-task” (i.e., focused on something other than the SART; mind-wandering), (3) “mind-blanking” (i.e., focused on nothing), (4) “don’t remember”. In the analyses that follow, responses (3) and (4) were collapsed into a single “mind blanking” category. Data from the final probe, which asked participants to rate their level of vigilance “over the past few trials” on a 4-point Likert scale (1 = “Extremely Sleepy”; 4 = “Extremely Alert”), are also reported.

Prior to commencing the experiment, participants performed two blocks of practice trials (1 block of 27 trials for each variant of the SART). Performance feedback (proportion of correct responses, average response time) was provided at the end of each practice block. Participants then performed 3 blocks of each SART (block order randomly permuted per participant) for a total of 6 blocks. Blocks lasted approximately 12–15 min each and were separated by self-paced breaks (total duration: M = 95.10 min, S.D. = 10.40). Each block comprised 10 sets of thought probes separated by intervals ranging 40–70 s (randomly sampled from a uniform distribution).

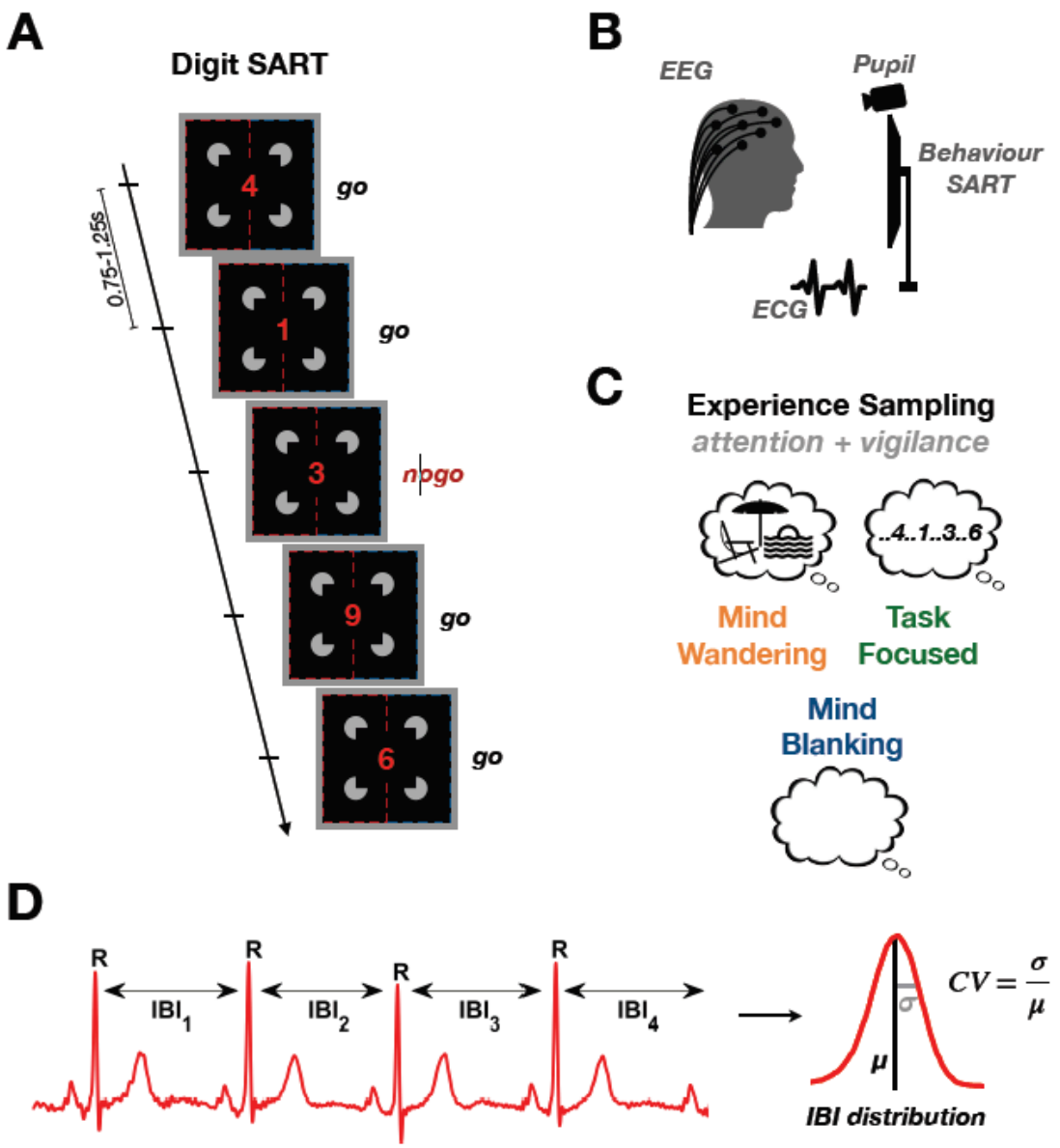

Figure 1: Tracking the neural and cardiac correlates of task disengagement

A: Participants were instructed to perform a modified version of the Sustained Attention to Response Task (SART), a Go/NoGo task involving either face or digit stimuli (block design). Participants had to respond to all stimuli (Go trials) except when presented with a specific target stimulus (smiling face or digit '3'; NoGo trials). B: For each participant, EEG and ECG signals, pupil size, and behavioural data on the SART were continuously recorded. C: Participants were interrupted every 40-70 s (10 times per block) and asked to report their attentional state (on-task, mind-wandering, or mind-blanking) and vigilance level (alertness). D: In ECG recordings, we automatically detected R-peaks and computed the duration of successive interbeat intervals (IBIs) during SART performance. The IBI time-series was used to calculate the IBI distribution from which we derived the mean IBI duration (i.e., average

heart period; inverse of heart-rate) and coefficient of variation (CV; i.e., heart-rate variability) during epochs preceding thought probes.

Psychophysiological signal acquisition and preprocessing

Electroencephalography and electrocardiography

High-density EEG was acquired using 63 EasyCap-mounted active electrodes. A ground electrode placed over FPz; AFz served as the online reference. The ECG was acquired from electrodes on either shoulder; the electro-oculogram (EOG) was recorded from electrodes placed above and below the left and right canthi. All signals were sampled at 500 Hz using a BrainAmp system (Brain Products GmbH) in conjunction with BrainVision Recorder (v1.21.0402; Brain Products GmbH).

Offline processing of the raw EEG and ECG was performed in MATLAB R2022a (v9.12.0.1884302) in conjunction with the EEGLAB (v2019.1; Delorme & Makeig, 2004) and Fieldtrip (v20220810; Oostenveld et al., 2011) toolboxes. All filters were implemented via the 'pop_eegfiltnew' function of the 'firfilt' plugin (v2.4). Data were high-pass filtered (passband edge = 1 Hz, transition width = 1 Hz) and downsampled to 250 Hz prior to removal of 50 and 100 Hz frequency line noise via the 'cleanLineNoise' function from the 'PrepPipeline' plugin (v0.55.4; Bigdely-Shamlo et al., 2015).

EEG data were re-referenced to the average of TP9 and TP10. Non-task-related periods (i.e., segments between trial blocks and during experience sampling) were excluded prior to bad channel detection (flatline criterion = 5 s; channel criterion = .8; median number of rejected channels = 1; range = 0–8) and artifact subspace reconstruction (burst criterion = 20; Mullen et al., 2015) as implemented via the 'clean_rawdata' plugin (v2.4; Kothe et al., 2019). Rejected channels were interpolated prior to re-referencing to the common average. EEG data were then low-pass filtered (passband edge = 40 Hz, transition width = 10 Hz) and decomposed into independent components using the (extended) 'binica' implementation of the logistic infomax algorithm (Bell and Sejnowski, 1995). Components were automatically classified using ICLabel (v1.3; Pion-Tonachini et al., 2019); those classed as ocular, cardiac, or line noise artefacts with > .90 probability were subtracted from the dataset (median number of rejected components = 2; range = 1–4).

The ECG was low-pass filtered (passband edge = 40 Hz, transition width = 10 Hz) and R-wave peaks automatically extracted using the QRS beat-detection algorithm implemented by the 'ConvertRawDataToRRIntervals' function of the PhysioNet Cardiovascular Signal Toolbox (v1.0; Vest et al., 2018). Resolved R-peaks were visually inspected (and where necessary, manually corrected) with the aid of the HEPLAB plugin (v1.0.1; Perakakis, 2019). Corrected peak latency information was appended to the stimulus event structure associated with the EEG recording.

Pupillometry

Eye-movements and pupil size of one eye were sampled at 1000 Hz via an EyeLink 1000 eye-tracking system (SR Research Ltd., Mississauga, Canada). The eye-tracker was calibrated at the beginning of each experimental session using the EyeLink acquisition software. Pupil size data were preprocessed using custom-built MATLAB functions, based on procedures previously reported by van Kempen and colleagues (2019) and Corcoran and colleagues (2023). Blink timings (automatically identified by the EyeLink acquisition software) were corrected via the linear interpolation of the average pupil size spanning [-200, -100] ms before and [100, 200] ms after the blink period. The corrected signal was then low-pass filtered below 6 Hz using a 2-pass, 4th-order Butterworth filter. Blinks exceeding 2000 ms were marked as missing data, as were data points spanning 100 ms before and after the blink period.

Data analysis

Signal detection theoretic measures

Responses on Go trials were classed as 'hits'; failures to respond (errors of omission) were classed as 'misses'. Responses during NoGo trials (errors of commission) were classed as 'false alarms'; withheld responses were classed as 'correct rejections'. Hit rate was calculated as the proportion of Go trials that elicited a response within both a 10 and 30 s time window (preprobe epoch) preceding the onset of experience sampling; false alarm rate was analogously calculated as the proportion of NoGo trials that elicited a response (loglinear correction for extreme values applied following Hautus, 1995). Please note, correct rejections preceded and followed by misses were excluded from analysis on the basis that sustained absence of responding across Go-NoGo-Go trial sequences suggests a period of task disengagement (rather than selective response inhibition).

Sensitivity to trial type (Go vs. NoGo) was quantified with the discriminability index *d'*, which was obtained by subtracting z-scored false alarm rates from corresponding z-scored HRs. A *d'* of 0 indicates chance-level discrimination of Go trials from NoGo trials; more positive values indicate increasing sensitivity. Response bias (decision criterion) was quantified as *c*, the mean of z-scored hit and false alarm rates. A *c* of 0 indicates no bias towards either stimulus category; more positive values indicate greater bias towards responding (i.e., liberal criterion), while more negative values indicate greater bias towards not responding (i.e., conservative criterion).

Response speed

Response speed was calculated by inverting response times obtained from Go trials. Responses registered within 300 ms of trial onset were discarded, since they conflate fast responses to the present trial with (very) slow responses to the preceding trial (see, e.g., Cheyne et al., 2009). Mean response speed (RS_{μ}) was obtained by averaging response speed estimates for each set of preprobe epochs per participant.. Response speed time-series were then linearly interpolated to impute missing or withheld trial responses, and the coefficient of variation (RSc_v) for each preprobe epoch obtained by dividing the standard deviation of the interpolated series by the corresponding RS_{μ}. A minimum of 5 and 15 response speed estimates was required to calculate summary statistics for the 10 and 30 s preprobe epochs, respectively.

Pupil diameter

Trial-level pupil size estimates were averaged over trial duration (750–1250 ms). Estimates within the 30 s preprobe epoch were z-transformed on the subject-level; scores exceeding +/- 4 z.u. were excluded from analysis. Remaining z-scores were averaged to yield an estimate of mean pupil size for each preprobe epoch. Similar to the response speed data, 10 s (30 s) epochs containing fewer than 5 (15) trial-level pupil size estimates were excluded from analysis.

Cardiac parameters

Interbeat intervals (IBIs; heart period) were calculated as the difference between successive R-peaks. IBIs <300 ms or >2000 ms in duration were excluded as physiologically implausible. IBIs were z-transformed on the subject-level, and scores exceeding +\- 5 z.u. excluded from analysis. The corrected IBI time-series (i.e., tachogram) was then upsampled to 5 Hz and cubic-spline interpolated. Analogous to the reaction speed analysis, mean IBI

(IBI_{μ}) and natural log-transformed coefficient of variation ($IBIc_v$) estimates were calculated for each individual's set of preprobe epochs.

Heartbeat-evoked potentials

Heartbeat-evoked potentials (HEPs) were extracted by first applying lowpass filters to the EEG and ECG signals (passband edge = 30 Hz, transition width = 10 Hz) and then aligning the ECG and EEG data (for each channel) to the detected R-peaks. We used epochs of -0.5 s to 1 s around each R-peak. We then averaged the epochs for each attentional state (on-task, mind-wandering, and mind-blanking) or vigilance level (1-4) and computed the Global Field Potential (GFP) across EEG electrodes at the single-subject level. The GFP was computed by extracting the root-mean-square (RMS) values of the EEG potentials across all electrodes for each sample of the ERP window. Following these operations, we obtained ERP-ECG and GFP-EEG time-courses for each attentional state and vigilance level reported by each participant.

To estimate the effect of attention and vigilance on extracted time-courses, we applied mixed-effect models with either a fixed-effect of attentional state (on-task, mind-wandering, or mind-blanking) or vigilance and random-intercepts for subject identity on each sample. To correct for multiple comparisons, we implemented a cluster permutation approach inspired by (Maris and Oostenveld, 2007), in which we applied the same mixed-effects models on permuted datasets (permutation of attentional state or vigilance levels across participants, total number of permutations: 250). The effect of attention and vigilance was estimated by running an analysis of variance (ANOVA) on the linear mixed-effects models and retrieving the F-values and p-values of the attention and vigilance effect for each sample of the real and permuted data. We then selected clusters of continuous time samples crossing a statistical threshold of .05 (two-tailed) and extracted the sum of the F-values over these clusters. A similar procedure was applied to all the permuted datasets. Finally, we compared the values from the clusters obtained in the original (real) data compared to those obtained in the permuted datasets and derived a Monte-Carlo p-value for each cluster. A cluster was considered significant if the Monte-Carlo p-value was < .05 (one-tail test on the F-value distribution).

Mutual information between cardiac and brain signals

Coupling between the EEG and IBI time-series was quantified using mutual information (MI), an information-theoretic measure of the statistical relationship between two random variables (Shannon, 1948; Cover and Thomas, 2005). MI was estimated using the

Gaussian-Copula technique (see Ince et al., 2017) as implemented via v0.4 of the open-source MATLAB code available from https://github.com/robince/gcmi.

EEG records were bandpass filtered into the following frequency bands: 1.070-1.448 Hz, 1.463-1.979 Hz, 1.999-2.705 Hz, 2.733-3.697 Hz, 3.735-5.053 Hz, 5.105-6.907 Hz, 6.978-9.440 Hz, 9.537-12.903 Hz. The detrended IBI and filtered EEG time-series were resampled to 50 Hz and Hilbert-transformed to obtain bivariate sequences of complex numbers, which were copula-normalised using the 'copnorm' function. The normalised time-series were then segmented into 10 s epochs according to the scheme outlined below and the MI between each epoch pair estimated via the 'mi_gg' function.

To assess the extent to which coupling dynamics were driven by top-down (brain-heart) or bottom-up (heart-brain) connectivity, epoched signals were offset from one another such that one signal corresponded to the 10 s preprobe period while the other preceded this period by an arbitrary time constant. IBI estimates led the EEG time-series by 16 linearly-spaced intervals spanning 50-800 ms; EEG estimates led the IBI time-series by 16 linearly-spaced intervals spanning 100-1600 ms. Longer latencies were favoured when estimating fluctuations in brain-heart coupling due to time delays in the modulation of cardiac pacing incurred at the sino-atrial node.

We adopted a mass linear mixed-effects modelling approach ('lmeEEG'; Visalli et al., 2024) to evaluate whether MI systematically varied across attentional states. Linear mixed-effects models were fitted to MI estimates from each channel x frequency x time-point combination in each set of time-lagged epochs. Attentional state (on-task, mind-wandering, mind-blanking) was included as a fixed-effect; subject identity was included as a random intercept. Marginal estimates of MI were extracted from these models and subjected to mass univariate regression analysis ('lmeEEG_regress'). T-values extracted from these regression models were then compared against those generated from 2000 random permutations of the design matrix ('lmeEEG_permutations') using threshold-free cluster enhancement (Smith and Nichols, 2009; Mensen and Khatami, 2013; implemented via 'lmeEEG_TFCE').

Statistical analysis

Statistical analysis of behavioural, pupillometric, and cardiac parameters was performed in *R* (v4.2.1 [2022-06-23 ucrt]; R Core Team, 2019) using the *RStudio Desktop* IDE (v2022.07.2+576; RStudio Team, 2015) in conjunction with the 'tidyverse' package (v1.3.2; Wickham et al., 2019). All analyses were conducted under a generalised additive

mixed-effects model framework (a semiparametric extension of linear mixed-effects modelling) implemented via the 'mcgv' package (v1.8-40; Wood, 2011, 2017). Model diagnostics were assessed using functions from the 'itsadug' (v2.4.1; van Rij et al., 2017) and 'mgcViz' (v0.1.9; Fasiolo et al., 2020) packages; model visualisation was accomplished with the aid of 'cowplot' (v1.1.1; Wilke, 2020), 'emmeans' (v1.7.5; Lenth, 2020), 'ggeffects' (v1.1.2; Lüdecke, 2018), and 'ggh4x' (v0.2.8; van den Brand, 2024).

All models were fitted using restricted maximum likelihood via the 'gam' function. Attentional state reports were modelled as unordered categorical data using multinomial logistic regression; vigilance reports were modelled as ordered categorical data. Uncorrected hit and false alarm rates were modelled using the logit-linked beta distribution; response speed variability was modelled using the inverse-linked gamma distribution. All other models assumed Gaussian-distributed errors. Dependent variables were regressed onto a covariate encoding stimulus type (Face vs. Digit) and the independent variable of interest (except in the case of IBI_{μ} and $\mathrm{IBI}c_{v}$, which were included together as orthogonal predictors). Models were additionally equipped with a by-participant factor smooth on probe number to control for time-on-task and reduce the temporal autocorrelation of residuals (see Baayen et al., 2017).

Analyses involving attentional state reports were conducted using estimates derived from 10 s preprobe epochs; all other analyses included summary statistics calculated from 30 s preprobe epochs.

Data and code availability

The datasets analysed in this report can be accessed from the Open Science Framework repository: https://osf.io/ey3ca/ (Andrillon et al., 2020). The code used to perform these analyses has been archived on GitHub: https://github.com/corcorana/WIM_HB/ (Corcoran and Andrillon, 2024).

Results

Impact of mind-wandering and mind-blanking on behavioural performance

This section replicates previous findings on the same dataset (Andrillon et al., 2021). On average, participants reported being on-task 49.2% of times probed, consistent with previous experience-sampling research (Seli et al., 2013). Mind-wandering and mind-blanking were reported on 39.1% and 12.7% of probes, respectively. Mind-wandering and mind-blanking states were reported more frequently with time-on-task (MW: $\beta = 0.46$, s.e. = 0.06, $z = 7.16$, $p < .001$; MB: $\beta = 0.35$, s.e. = 0.09, $z = 3.79$, $p < .001$), and were associated with lower vigilance ratings (i.e., increased sleepiness; MW: $\beta = 0.81$, s.e. = 0.11, $z = 7.64$, $p < .001$; MB: $\beta = 1.20$, s.e. = 0.16, $z = 7.66$, $p < .001$) and smaller pupil diameter (MW: $\beta = -0.31$, s.e. = 0.10, $z = 2.99$., $p = .003$; MB: $\beta = -0.48$, s.e. = 0.14, $z = 3.39$, $p < .001$), than on-task reports.

Using signal detection theory (Green and Swets, 1966; Macmillan and Creelman, 2005), we calculated measures of sensitivity (*d'*) and response bias (*c*) in trial epochs preceding thought probes. Sensitivity was significantly decreased in epochs preceding mind-wandering ($\beta = -0.25$, s.e. = 0.04, $t = 5.81$, $p < .001$) and mind-blanking ($\beta = -0.32$, s.e. = 0.06, $t = 5.10$, $p < .001$) as compared to on-task reports. Bias was significantly increased in epochs preceding mind-wandering ($\beta = 0.09$, s.e. = 0.02, $t = 4.33$, $p < .001$), but not mind-blanking.

Mean response speed (1/Response Time; RS_{μ}) on Go trials preceding mind-wandering reports did not significantly differ from on-task reports ($\beta = 0$, s.e. = 0.01, $t = 0.01$, $p = .993$); however, mind-blanking was associated with significant response slowing ($\beta = -0.05$, s.e. = 0.02, $t = 2.52$, $p = .012$). Response speed variability (RSc_{v}) was significantly increased prior to both mind-wandering ($\beta = -0.38$, s.e. = 0.14, $t = 2.69$, $p = .007$) and mind-blanking ($\beta = -0.67$, s.e. = 0.20, $t = 3.41$, $p < .001$) relative to on-task epochs. Overall, these results confirm previous reports on the same and different datasets (Ward and Wegner, 2013; Unsworth and Robison, 2018; Andrillon et al., 2021; Boulakis et al., 2024) showing distinct signatures of mind-wandering and mind-blanking on cognitive performance.

Cardiac measures afford complementary information about arousal, attentional, and behavioural states

Having confirmed the expected differences in behavioural and pupillometric measures across attentional and vigilance state reports, we next sought to examine whether cardiac parameters derived from epochs preceding thought probes predict attentional and arousal states and their behavioural correlates.

Mixed-effects modelling revealed a positive association between mean interbeat interval (IBI_{μ}) and off-task attentional states: increased IBI_{μ} (i.e., lower heart-rate) significantly increased the probability of mind-blanking reports ($\beta = 0.54$, s.e. = 0.16, $z = 3.39$, $p < .001$); a similar (albeit non-significant) relationship was noted for mind-wandering ($\beta = 0.22$, s.e. = 0.12, $z = 1.84$, $p = .066$). Moreover, increased IBI_{μ} was associated with more sleepiness ($\beta = 0.30$, s.e. = 0.15, $z = 1.99$, $p = .046$) and smaller pupil diameter ($\beta = -0.07$, s.e. = 0.03, $z = 2.14$, $p = .032$), consistent with a global shift towards parasympathetic dominance and hypoarousal (Joshi and Gold, 2020; Matuz et al., 2021). HRV (interbeat interval coefficient of variation; $IBIc_v$) did not significantly predict attentional state nor vigilance ratings but did predict pupil dilation ($\beta = 0.04$, s.e. = 0.01, $z = 2.55$, $p = .011$; see Figure 2).

Turning next to behavioural performance during the SART, a negative association was observed between IBI_{μ} and *d'* ($\beta = -0.09$, s.e. = 0.04, $t = 2.22$, $p = .027$). This effect was driven by a reduction in hit rate as IBI_{μ} increased ($\beta = -0.11$, s.e. = 0.05, $t = 2.21$, $p = .027$). False alarm rate, *c*, RS_{μ} and RSc_v were not associated with IBI_{μ}. $IBIc_v$ was also negatively associated with *d'* ($\beta = -0.07$, s.e. = 0.03, $t = 2.48$, $p = .013$) but this effect was driven by an increase in false alarm rate ($\beta = 0.14$, s.e. = 0.05, $z = 3.02$, $p = .003$). $IBIc_v$ also covaried with *c* ($\beta = 0.03$, s.e. = 0.01, $t = 2.65$, $p = .008$) and RS_{μ} ($\beta = 0.02$, s.e. = 0.01, $t = 3.13$, $p = .002$), but not RSc_v.

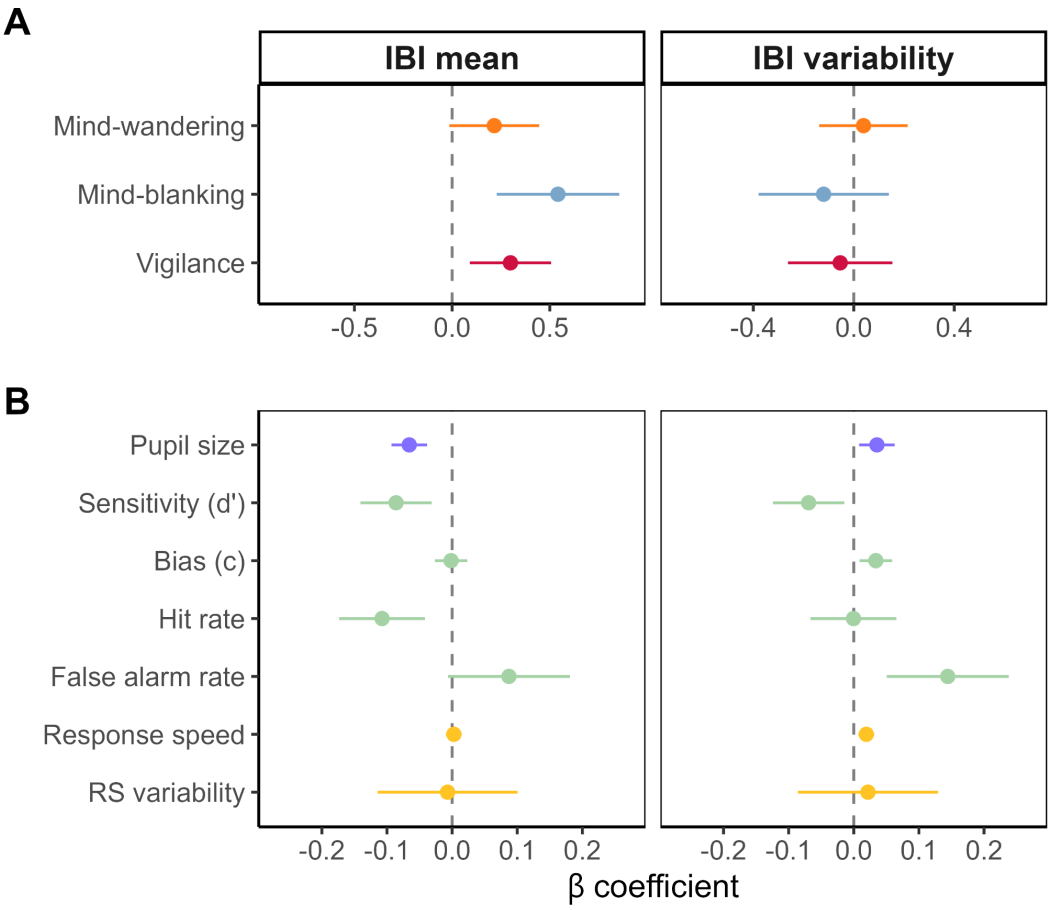

Figure 2: Summary of modelled relationships between cardiac parameters and attentional, arousal, and behavioural state variables

A: Estimated effect of a z-unit increase in interbeat interval (IBI) duration (left) and coefficient of variation (right) on subjective reports of attentional state and vigilance level. Mind-wandering and mind-blanking coefficients encode differences relative to the on-task state. B: Estimated effect of a z-unit increase in IBI duration (left) and coefficient of variation (right) on mean pupil size, signal detection theoretic measures, mean response speed, and response speed coefficient of variation. Error bars represent 95% confidence intervals.

Brain-heart coupling across attentional states

To assess whether differences in attentional state are accompanied by altered neural processing of cardiac signals, we investigated two complementary measures of heart-brain interaction: (1) time-locked neural responses captured by the HEP; and (2) the mutual information (MI) shared between heartbeat and low-frequency EEG activity.

HEPs were estimated for R-peaks captured within the 10 s epoch preceding each thought probe. To avoid any bias in electrode selection, we first computed the Global Field Power of the HEPs. We also compute the ERPs of the ECG signal locked to R-peaks. Then, we examined the impact of vigilance ratings and attentional states on the time course of the ECG-ERP (Figure 3A) and HEP-GFP (Figure 3B) with linear mixed-effects models at each sample with either the attentional state or vigilance report for the corresponding probe as a predictor and random intercepts for participants. To correct for multiple comparisons, we applied a cluster permutation approach across samples ($\alpha_{cluster} = 0.05$, $p_{Monte\text{-}Carlo} < .05$).

We found a modulation by the attentional state reports of the HEP-GFP (cluster: [0.524-0.728]s, t = 350.7). No significant cluster was observed for vigilance level. We averaged the HEP over the time window of this cluster for each electrode and fitted linear mixed-effects models across electrodes. Figure 3C shows the topographies of the attentional state effect and between-state contrasts. The attentional state effect appears driven by the mind-blanking vs. on-task contrast, with significant electrodes showing a centro-occipital dipole. These results suggest that cortical processing of cardiac inputs is enhanced during mind-blanking compared to on-task episodes, potentially accounting for the reduced responsivity to external inputs observed in this state.

Finally, we computed the MI index between heartbeat and low-frequency EEG to test for the influence of cardiac activity on ongoing brain dynamics (in addition to evoked responses). MI between phases of the IBI time-series and bandpass-filtered EEG (8 logarithmically-spaced frequency bins spanning ~1-13 Hz) was estimated at 16 time-lags, such that the 10 s cardiac signal led the 10 s EEG signal preceding probe report (heart-brain coupling) or vice-versa (brain-heart coupling). Linear mixed-effects modelling and permutation-testing were again deployed to ascertain whether MI differed across attentional states. No significant clusters were identified. Hence, although spontaneous changes in attentional state were associated with altered responses to cardiac inputs, time-evolving patterns of cardiac and cortical dynamics did not systematically deviate across states.

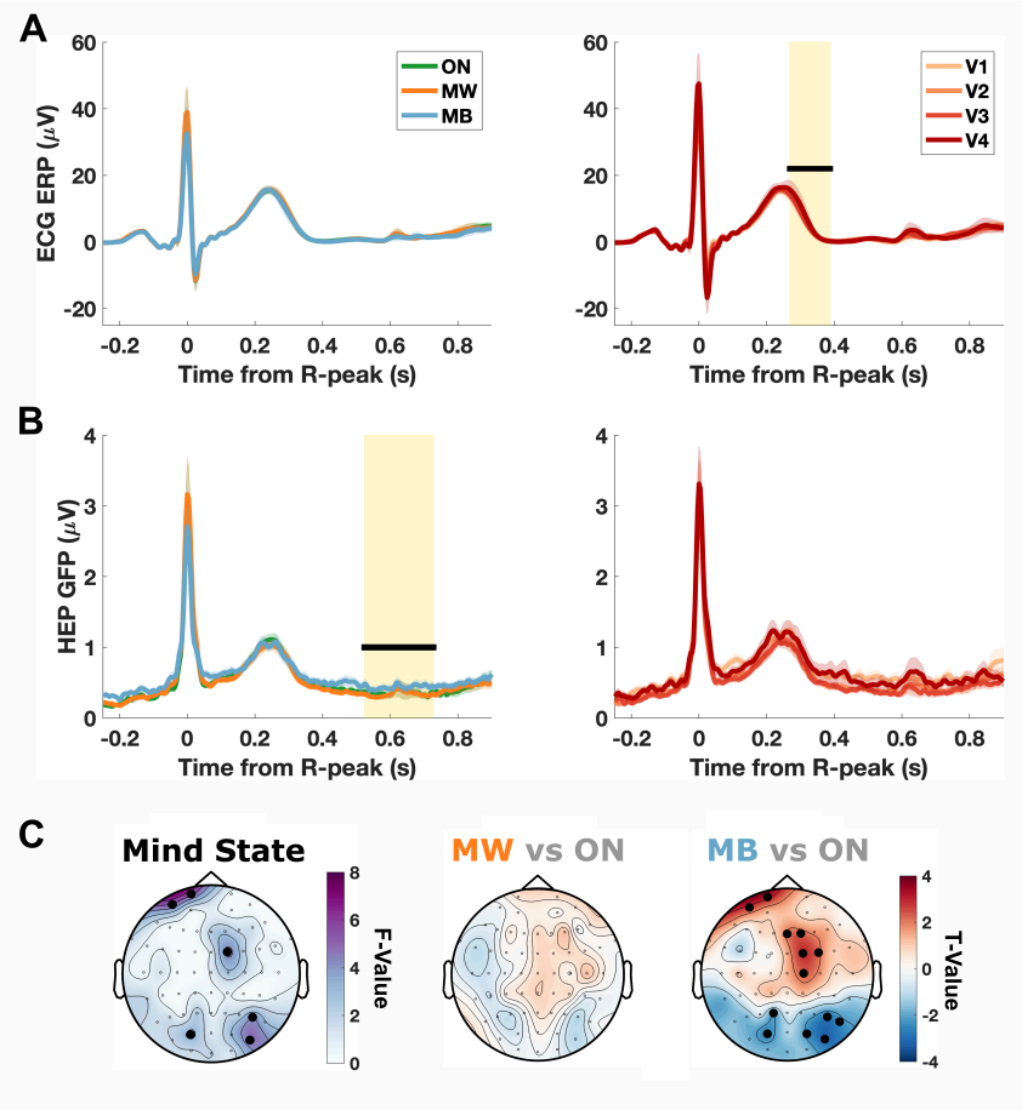

Figure 3: Heartbeat-evoked potentials are modulated by the attentional state

A: Event-related potential (ERP) of the ECG averaged across individuals for the different attentional states (left) and vigilance levels (right). B: Global Field Power (GFP) of the HEP (EEG) averaged across individuals for the different attentional states (left) and vigilance levels (right). For both A and B, shaded areas denote the standard error of the mean (SEM) across participants. Horizontal black bars and yellow shadings indicate the timing of significant clusters (mixed-effect models, $p_{cluster}$<0.05, correction with cluster permutations; see Methods). C: Topography of the attentional state effect (F-values; left) and MW vs. ON, MB vs. ON contrasts (t-values; middle and right) computed over the cluster in panel B with mixed-effect models fitted at the electrode level (see Methods). Black dots indicate significant electrodes (p < 0.05 uncorrected; post-hoc analysis).

Discussion

This study investigated how spontaneous fluctuations of attention are related to tonic and phasic modulations of arousal, with specific focus on the brain-heart axis. In summary, we found that task disengagement was characterised by decreases in tonic arousal (greater interbeat interval duration, smaller pupil diameter), which manifested subjectively as increased sleepiness and behaviourally as reduced sensitivity and increased response speed variability. Notably, mind-blanking states were accompanied by more pronounced heartbeat and response slowing than mind-wandering states, thus suggesting that mind-blanking is more likely to occur in the context of hypoarousal. Mind-wandering, by contrast, was characterised by subtler decreases in arousal that were associated with more stereotypic behaviour (increased response bias, unchanged response speed). Although phasic heartbeat fluctuations neither discriminated amongst attentional states nor covaried with vigilance level, increased heart-rate variability predicted greater pupil dilation and more biassed, faster responding. Short-term heart-rate fluctuations thus afford unique information pertaining to what appear to be impulsive patterns of behaviour.

Our results add to recent evidence that mind-blanking constitutes a low-arousal state distinct from other forms of task disengagement, such as mind-wandering (Andrillon et al., 2019, 2021; Boulakis and Demertzi, 2024; Boulakis et al., 2024; Musat et al., 2024). Our focus on cardiac parameters and measures of heart-brain coupling complement previous reports on the oscillatory, event-related, and information-theoretic EEG signatures of mind-blanking (Andrillon et al., 2021; Musat et al., 2024), demonstrating that these signatures are accompanied by detectable alterations in peripheral electrophysiology (i.e., interbeat interval dynamics). They also cohere with recent evidence that mind-blanking reports elicited during task-free resting-state conditions are more prevalent in the context of low-arousal conditions induced by sleep deprivation (Boulakis et al., 2024). While the latter study indicated that the addition of cardiac parameters to EEG measures helped improve the automated classification of mental state reports, we isolate here the information afforded by particular cardiac parameters with respect to subjective, neurophysiological, and behavioural measures of arousal and attentional state dynamics.

Mean interbeat interval duration (IBI_{μ}) and pupil diameter provide complementary psychophysiological indices of arousal state that reflect the balance between sympathetic and parasympathetic tone (Grossman and Taylor, 2007; Wang et al., 2018; Joshi and Gold, 2020; Liu et al., 2021). Our findings reveal that mind-blanking episodes are predicted by a

relative shift towards parasympathetic dominance, as indicated by increased IBI_{μ} and decreased pupil diameter. Notably, these effects were observed after controlling for time-on-task, indicating that markers of parasympathetic outflow afford specific information about the transition from on-task through to mind-blanking states over and above generic effects pertaining to prolonged task performance (e.g., motivational state, mental fatigue, drowsiness, etc.; Pattyn et al., 2008; Gergelyfi et al., 2015; Hopstaken et al., 2015; Stawarczyk and D'Argembeau, 2016; Stawarczyk et al., 2020).

Intriguingly, short-term heart-rate variability ($IBIc_v$) – which is commonly used to assess phasic fluctuations in parasympathetic activity – was positively associated with pupil diameter. While this finding might seem counterintuitive given the aforementioned negative association between IBI_{μ} and pupil diameter, two points need to be borne in mind: first, increases in HRV need not derive from tonic increases in parasympathetic outflow (or a relative shift towards parasympathetic dominance), but may simply reflect altered phasic patterning of parasympathetic discharge (Grossman and Taylor, 2007); second, by taking the coefficient of variation as our estimator of HRV (and by controlling for potential confounding from time-on-task effects), we ensured that our measures of tonic and phasic heartbeat activity were orthogonal to one another – thus enabling us to uncover different relations between unique components of autonomic control.

Increased pupil-linked arousal in the context of enhanced HRV may be mechanistically explained by phasic input from ascending parasympathetic pathways into the noradrenergic locus coeruleus (Hulsey et al., 2017; Collins et al., 2021), a major neuromodulatory system responsible for the regulation of arousal and task (dis)engagement (Aston-Jones and Cohen, 2005; Sara, 2009). Given that $IBIc_v$ was also associated with increased response bias, speed, and errors of commission, the positive correlation we observed between pupil dilation and HRV may be partially explained by error-related orienting (Danev and de Winter, 1971; Stelmack and Siddle, 1982; Hajcak et al., 2003; Notebaert et al., 2009; Wessel, 2018), whereby the unexpected occurrence of an erroneous behavioural action (i.e., responding to a NoGo stimulus) precipitated a transient increase in arousal and the reallocation of attentional resources toward the task at hand (Yu and Dayan, 2005; Sara and Bouret, 2012; Sales et al., 2019; Strauch et al., 2022; Jordan, 2024).

Our analysis of cortical evoked responses time-locked to the heartbeat revealed a late modulation of heartbeat-evoked potentials (HEPs) derived from epochs preceding mind-blanking reports. HEPs are commonly interpreted as an electrophysiological index of interoceptive processing and are known to be modulated by attentional focus, whereby

attending to sensations generated by one's heartbeat amplifies the HEP (Coll et al., 2021; Engelen et al., 2023). Increased heartbeat-evoked responses have also been reported in the context of self-related spontaneous cognition (Babo-Rebelo et al., 2016a, 2016b) and mental imagery (Babo-Rebelo et al., 2019), indicating that HEP amplitudes are sensitive to the content of thought independent of cardiac dynamics. The enhanced neural processing of heartbeat-related signals may contribute to the experience of mind-blanking by diverting attentional resources away from exteroceptive channels and metacognitive processing – transiently 'blocking' (or attenuating) the intake of new information and limiting conscious access to the content of one's mental states.

In contrast to our HEP analysis, the mutual information between the IBI and bandpass-filtered EEG time-series did not significantly differ as a function of subjective attentional state. It is possible that our data-driven approach – which necessarily corrected for statistical tests spanning multiple time-lags, frequency bands, and channel locations – may have been insensitive to localised differences in phase coupling during epochs preceding probe reports (although our deployment of threshold-free cluster enhancement attempted to mitigate this potential limitation). Hence, while our findings do not rule out the possibility that spontaneous fluctuations in attentional state are accompanied by subtle changes in the temporal patterning of brain-heart connectivity, such state transitions do not appear to be associated with pronounced alterations in coupling dynamics akin to those observed in the context of heightened states of arousal (Valenza et al., 2016; Candia-Rivera et al., 2022b, 2022a).

In conclusion, this study adds to the growing body of literature characterising mind-blanking as a distinctive attentional state. Our analysis of cardiac dynamics in conjunction with subjective, behavioural, and pupillometric measures provides complementary evidence that mind-blanking arises in low-arousal contexts, likely mediated by global increases in parasympathetic tone. Late modulation of heartbeat-evoked responses further indicates that mind-blanking is associated with amplified cortical processing of interoceptive signals. The allocation of attentional resources towards interoceptive processes that typically unfold outside of awareness may contribute to the subjective experience of losing track of one's thoughts and surroundings. Furthermore, the link between heartbeat fluctuations, pupil dilation, and impulsive-like behaviour suggests transient bursts of vagal outflow promote phasic increases of arousal, possibly on account of driving input to the noradrenergic locus coeruleus. Together, these findings highlight how the neural processing and regulation of cardiac dynamics impact conscious experience and behavioural states on timescales spanning milliseconds to tens of seconds.

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