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**Voluntary movement initiation is associated with cardiac input in
Libet's task.**

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Abstract

The relationship between motor intention and initiation of voluntary movement remains a fundamental topic in neuroscience, originating from the seminal framework of B. Libet, introduced in 1983. Libet's paradigm significantly influenced discussions on intentionality, motor control, and free will. However, methodological critiques continue to challenge its interpretations, specifically the accuracy and validity of the 'urge to move' phenomenon. One understudied factor in this debate is the potential influence of interoceptive signals—such as cardiac activity—in shaping the experience of motor intention and movement initiation. In our study, we addressed this gap by examining whether cardiac signals modulate participants' experience of the 'urge to move', using behavioural and electrophysiological measures in 39 healthy human participants (17 males and 22 females) performing Libet's task. Crucially, when participants were asked to follow the 'urge to move', their button press timings were predominantly aligned with the diastolic phase of the cardiac cycle, indicating cardiac modulation of movement initiation. However, analysing heart evoked potential (HEP) amplitudes as a measure of cardiac input perception, we observed no differences in HEP amplitudes associated with

changes in introspective demands during the task in both source and sensor spaces. Our results suggest that implicit perception of cardiac signals biases voluntary action initiation in Libet's task, independently of cortical interoceptive markers. These findings have implications for models of motor preparation, intentionality, and the bodily basis of voluntary action, challenging conventional interpretations of motor intention and informing debates on volition and interoception.

Significance Statement

Our study provides evidence that implicit perception of cardiac signals influences movement initiation in Libet's task. We demonstrate, for the first time, that when attending to the 'urge to move', participants tended to initiate voluntary movements during the diastolic phase of the cardiac cycle. These findings challenge traditional views on factors affecting motor initiation in Libet's task, suggesting the relevance of interoceptive processing. By highlighting the role of cardiac input in experiencing motor intention, our findings expand on existing debates on volition, agency, and free will, further underscoring the importance of integrating bodily signals into these theoretical frameworks.

Introduction

Understanding preparation and initiation of voluntary movements remains a fundamental challenge in cognitive neuroscience, closely tied to broader questions related to volition, intentionality, and the free will debate. To study these questions, B. Libet introduced the notion of an internally generated 'urge to move', which he believed

67 precedes voluntary movement. In his experiments, he asked participants to perform
68 button presses and to retrospectively report the moment they became aware of this
69 introspective trigger event (Libet et al., 1983). However, these retrospective reports have
70 been repeatedly criticised: their timing varies with clock design, task parameters, and
71 condition order, raising concerns about the validity and reliability of the 'urge to move'
72 judgement (Banks and Isham, 2009; Dominik et al., 2017; Sanford et al., 2020; Schurger
73 et al., 2021; Ivanof et al., 2022; Bredikhin et al., 2023).

74 A critical issue may lie in the assumption that participants can consciously access
75 and report the 'urge to move'. In everyday life, movement initiation is unfolding without
76 explicit introspective monitoring. Given that the 'urge to move' phenomenon lacks a
77 precise definition, participants' interpretation and perception of this phenomenon may
78 vary considerably and depend on a multitude of competing sensory inputs. Consequently,
79 in the absence of external cues in the given experimental settings, participants could be
80 implicitly relying on visceral input. Particularly, the cardiac input, being event-like
81 structured, represents a plausible candidate for serving as an implicit internal cue for
82 movement initiation. In this study, we investigate whether the behavioural markers
83 traditionally interpreted as reflecting the 'urge to move' in Libet's task could be partially
84 modulated by cardiac signals rather than purely reflecting introspective access to motor
85 intention.

86 Influence of the cardiac input can be investigated by considering the phase of the
87 cardiac cycle (i.e., systole or diastole), during which the behavioural events occur.
88 Previous studies report cardiac phase effects in multiple aspects of sensorimotor

processing, including perception of weak stimuli, response inhibition, sensorimotor interactions, and motor cortex excitability (Veillette et al., n.d.; Larra et al., 2020; Al et al., 2023; Marshall et al., 2024). In particular, the phase of the cardiac cycle was shown to modulate movement initiation with more studies reporting systolic voluntary movement facilitation (Helin et al., 1987; Konttinen et al., 2003; Ohl et al., 2016; Kunzendorf et al., 2019; Galvez-Pol et al., 2020, 2022; Palser et al., 2021). Surprisingly, the role of the cardiac input in the classical Libet's paradigm remains understudied, even though the task has both a motor and an introspective components. Together, the existing findings suggest that cardiac signals could bias when individuals initiate a voluntary action—particularly under a condition of higher introspective demands, for instance, when attending to the 'urge to move'.

Another commonly used measure for studying heart-brain interactions is the amplitude of the heartbeat-evoked potentials (HEPs). Many studies advocate HEPs as a central electrophysiological marker of cardiac interoception, which might reflect active cardiac sensing (Al et al., 2020; Coll et al., 2021; Kumral et al., 2022). Although heterogeneous across studies, HEP amplitude differences are often interpreted as reflecting altered processing of cardiac signals. If participants utilise cardiovascular cues during the Libet's task, HEP amplitude may depend on the level of attention that is allocated towards interoceptive input.

We hypothesised that (1) when participants were required to report the perceived time of the 'urge to move' (W-condition), both self-initiated button presses and retrospective 'urge to move' reports would show preferential alignment with the cardiac

cycle; (2) when participants were required to report the timing of their button presses (M-condition), neither button presses nor retrospective reports would show such alignment; and (3) HEP amplitudes would differ between Libet W- and M- task conditions. By assessing behavioural and electrophysiological signatures of cardiac input and its' central processing, we examine whether interoceptive influences contribute to what has traditionally been interpreted as conscious access to the 'urge to move'.

Methods

Participants. We reanalysed data from a previous study with an initial dataset containing 49 participants (Bredikhin et al., 2023). We removed 10 participants due to technical problems resulting in missing behavioural trigger information. 39 remaining healthy volunteers (22 females; age range 18-57; mean age 26.31 +- 8.53) were included in this analysis. Participants were recruited through a local mailing list, being either university students or regular participants of the experiments in the research centre. Participation in the experiment was compensated. All participants were naive to Libet's clock paradigm and used their native language. The experiment was conducted following the ethical standards stated in the 1964 Declaration of Helsinki. The experimental protocol was approved by the local Ethics Committee of the HSE University (No. 19-3 dated 09 December 2019).

Experimental Design. We used an experimental design following a modification introduced by Dominik and colleagues (Dominik et al., 2017) to the original Libet's paradigm (Libet et al., 1982, 1983) (Figure 1A).

The participants were presented with two types of tasks, constituting two conditions: the W-task in the W-condition and the M-task in the M-condition. Before each condition, participants received instructions, completed three training trials, and had an opportunity to ask questions about the experimental procedure. For each trial participants were presented with a clock face. Next, a red dot appeared at a random position on a clock. A beeping sound indicated the start of the dot's clockwise rotation. Participants were instructed to fixate their gaze at the centre of the clock to avoid following the moving dot. Participants pressed the space bar at a self-chosen moment. The dot continued rotating for 500–800 milliseconds after the keypress before disappearing. In both conditions participants were instructed not to preplan their movements and to act spontaneously. When the movement was completed and the dot disappeared, participants were instructed to provide a behavioural report. In the W-condition, participants were asked to report the timing of experiencing an urge to perform a movement. In the M-condition, they reported the time of movement initiation. To provide these reports, participants were shown the clock face again and indicated the relevant time via a mouse click. The order of conditions was counterbalanced across participants.

Importantly, participants were not aware of the experimental instructions for the second condition while completing the first one, which made them naive to the second condition during the first part of the experiment. All participants completed 40 trials of each condition, 80 experimental trials in total. Since all movements were self-paced, participants could control the duration of the pause after each trial. The participants rested for three minutes between conditions. For further details on the experimental procedure, see Bredikhin and colleagues (Bredikhin et al., 2023).

EEG, EMG, and ECG Recording. All signals were recorded using a 32-channel (10-20 system) EEG system (BrainAmp DC amplifier, BrainProducts). All electrode impedances were maintained below 10 k Ω . During the recording, the data were band-pass filtered between 0.1 and 100 Hz, filtered with the notch-filter for 50 Hz and sampled at 500 Hz. The recording and online pre-processing were performed using PyCorder software (BrainProducts). The eye movements (EOG) were monitored by electrodes below and from the outer canthi of the left eye. Reference electrodes were linked to mastoid processes (TP9, TP10), whereas the forehead electrode was used as the ground electrode (GND). EMG recording electrodes were placed on the first dorsal interosseous muscle of the right hand and its tendon, and the ground electrode was placed on the ulnar styloid process. The ECG was recorded using the two external channels with a bipolar ECG lead I configuration (on the forearms). All peripheral electrodes were placed after the skin was prepared with abrasive paste and alcohol wipes.

ECG Data Processing. The ECG data were processed using Python-based custom scripts, the MNE Python toolbox (Gramfort et al., 2013) and the NeuroKit2 toolbox (Makowski et al., 2021). We divided the cardiac cycle into the systolic and the diastolic phases, defining the systolic phase as the interval from R-peak to T-wave offset, and the diastolic phase as the remaining part of the cycle (Bury et al., 2019). For the individual assessment of the onsets of the cardiac cycle phases, we determined the timings of R-peaks and T-wave offsets within the PQRST complex using algorithms from MNE Python (`mne.preprocessing.find_ecg_events`) and NeuroKit2 (`ecg_process`), respectively. The ECG data were visually inspected to ensure the correctness of parameter detection.

Behavioural and Physiological Data Alignment. As the next step, we examined the relationship between the W- and M-time reports and button press timings with regard to the cardiac cycle. First, for both conditions we extracted timestamps of button presses and reports, aligning the latter to the movement onsets (Libet et al., 1983; Bredikhin et al., 2023). Next, we transformed all timestamps into radians in relation to R-R intervals for alignment with the cardiac cycle (Figure 1B). This transformation was achieved using the following formula:

$$\varphi(b) = 2\pi((b - t_1)/(t_2 - t_1)),$$

where t_1 and t_2 denote the timestamps of the R-peaks occurring before and after the behavioural timestamp b that we wanted to align. Consequently, $t_2 - t_1$ represented an R-R interval for the cardiac cycle (Helin et al., 1987; Park et al., 2020; Caparco et al., 2025). To identify the onset of the diastolic phase of the cardiac cycle, we first computed the T-wave offset for each trial and then averaged these offsets within each participant. The resulting participant means, and their group-level mean, were subsequently used for plotting and for the control analysis examining the contributions of systolic and diastolic phases to the observed non-uniform distribution of W-condition button presses.

EEG Data Processing. The EEG data were processed and analysed using custom Python scripts and the MNE-Python toolbox (version 1.8; Gramfort et al., 2013). We had to exclude 5 participants from the EEG analysis due to excessive noise in their recordings. The EEG data were high-pass filtered at 0.5 Hz and low-pass filtered at 40 Hz, then the

data were visually inspected for the removal of large artefacts (e.g., movements). To remove eye movement and cardiac-field artefacts (CFA), we used independent component analysis (ICA), carried out through an FastICA algorithm (a threshold for selecting a number of principal components was 0.99, as a contrast function the logcosh was used). To ensure the correctness of ICA components selection, we used the MNE-Python toolbox functions **find_bads_ecg** and **find_bads_eog** with the z-scoring method and selected the candidate components for rejection (Dammers et al., 2008). Next, for detected components, we analysed the power spectral density (PSD) and signal coherence with the ECG and the EOG signals to ensure that only components with maximum signal coherence and similar spectral profiles were excluded from the EEG data. We removed one CFA and two ocular components for each participant.

For analysis of HEPs, the filtered signals were segmented into epochs centred around the R-peaks of the ECG signal. HEP-epochs were extracted between 200 ms prior to R-peak and 600 ms post-R-peak (Petzschner et al., 2019; Coll et al., 2021). The HEP epochs were baseline-corrected using a 100 ms interval from -200 to -100 ms of the epoch. Then the EEG epochs were inspected visually, the ones still containing excessive noise were rejected from further analysis. For between-condition comparisons, we first selected all available R-peak-related epochs from the trial onset until the button presses, yielding an average of 335 epochs for the W-condition and 309 for the M-condition available for analysis. Because interoceptive processing may vary over the course of a trial, we complemented our original analysis (which averaged *all* R-peak-locked HEP epochs from trial onset to button press) with an analysis focused on the epochs immediately preceding the action. Specifically, we repeated the between-condition

comparison while constraining the number of epochs per trial: first using only the last epoch before the button press, then the last two epochs, and so on, up to seven epochs prior to the button press. This allows us to test whether effects differ when focusing on the time window closest to intention and button press.

Source Reconstruction. Source reconstruction was implemented using MNE-Python functions and pipelines (Gramfort et al., 2014). For source localisation, we used the difference between average HEPs for W- and M-condition and the standard 'fsaverage' brain from FreeSurfer (Fischl, 2012). The forward model was computed using the 3-layer Boundary Element Method (BEM) with 4098 voxels per hemisphere. Next, we applied eLORETA (Pascual-Marqui et al., 2011) for source reconstruction with the following parameters: normal orientation of sources to the cortical surface, regularisation parameter set to 0.05, and identity noise covariance matrix.

Statistical Analysis. To robustly analyse the distribution of latencies of behavioural responses along the cardiac cycle, we employed a Rayleigh test for uniformity at the individual-subject level, using the R **circular** toolbox (Lund and Agostinelli, 2004). For each participant, the test yielded the mean resultant length of the vector representing the distribution of latencies in each cycle, along with a *p-value* to determine whether this circular distribution deviated from uniformity. The single-subject analysis was followed by a second-level group statistical analysis. Each participant's distribution was represented by the mode angle on the unit circle (Galvez-Pol et al., 2022), and a group-level Rayleigh test was conducted (Al et al., 2020a; Park et al., 2020; Galvez-Pol et al., 2022). For each of our two behavioural hypotheses, one for the W-condition and one for the M-condition, we controlled the family-wise alpha-level using the false discovery rate (FDR) correction

for multiple comparisons. We complemented this analysis with Bayesian testing using the **BayesCircIsotropy** R toolbox. We adopted the conjugate prior for the von Mises distribution, using **computeIsotropyBFHaVMConj** function with the following parameter values: $R_0 = 0$ (prior resultant vector length), $c_0 = 10$ (prior concentration parameter, reflecting a weakly informative prior), μ_0 (prior mean direction) was set to the mean angle of the provided sample (Mulder and Klugkist, 2021). To interpret Bayes Factors (H_1/H_0 as BF_{10}) we referred to Wagenmakers and Wetzels (Wetzels and Wagenmakers, 2012).

As a control analysis, we assessed the likelihood that the Rayleigh test results could be explained by a random distribution of latencies along the unit circle in our participants. We created a null distribution for each participant. For this purpose, we randomly generated angles between 0 and 2π for each trial and participant, effectively simulating W-condition button presses that are uniformly distributed along the unit circle. We then computed the mean resultant vector for each participant based on these randomly generated angles. Following this, we combined these subject-specific mean resultant vectors to compute a group-level mean resultant vector, reflecting the collective orientation of the responses within a hypothetical uniform distribution. The Rayleigh test was then applied to this second-level data. This entire process was repeated 1000 times to construct a distribution of test statistics under the null hypothesis of uniformity. By comparing the original Rayleigh test result with this null distribution, we quantified the likelihood of observing our data assuming a uniform distribution of response latencies. We assessed whether our original Rayleigh test statistic result was larger than the values in the null distribution, at least in 95% of the cases (0.05 alpha level, one-sided test).

Crucially, this analysis aims at detecting deviations from uniformity in our circular data and is independent of the systole and diastole phase length.

Next, in a second control analysis, we developed a sliding-segment test to determine whether the observed preferential alignment of W-condition button presses to diastole could be explained by the longer relative duration of the diastolic phase (Figure 1C). Because diastole occupies a larger proportion of the cardiac cycle than systole, a greater number of events might fall within diastole even under a uniform distribution. To achieve this, we divided the unit circle into 36 overlapping bins, each representing a potential position of a sliding segment whose length was fixed to match the average duration of the systolic phase in our sample. This fixed-length segment was shifted along the unit circle in incremental steps of $2\pi/36$ radians, generating 36 overlapping positions. For each segment position, we calculated the number of data points that fell within it. To evaluate whether the observed number of data points within each overlapping segment significantly deviated from chance level, we compared the observed counts per segment to expected counts given a random distribution of data points around the cardiac cycle. We established expected counts for each position by treating the probability of a datapoint falling into the fixed-length segment as proportional to the relative length of the segment (segment length divided by total circle length, 2π). Using this probability, binomial distribution parameters were defined, and critical cutoff values for statistical significance ($\alpha = 0.05$) were calculated to identify segment positions with significantly higher observed counts when compared to expected counts. Additionally, we quantified the overlap between each shifted segment and the physiologically defined systolic interval (R-peak to T-wave offset). This overlap proportion (overlap length divided by total systolic length)

provided an estimate of the relative contribution of systolic versus diastolic phase for each segment position.

As recommended by a reviewer, we compared cardiac coupling effects across conditions and tasks by implementing a factorial analysis. Analyses were conducted using a 2 x 2 within-subject factorial design (Libet condition: W vs M; behavioural task: press vs report). For phase location, trial angles were converted to Cartesian coordinates and analysed with a repeated-measures MANOVA ($\text{cbind}(\cos \varphi, \sin \varphi) \sim \text{condition} \times \text{task} + \text{Error}(\text{subject}/(\text{condition} \times \text{task}))$), following Landler et al., 2025). In addition to the Rayleigh tests, we assessed departure from uniformity separately for each condition and event type using individual trial and subject mean and median values MANOVA intercept tests on $(\cos \varphi, \sin \varphi)$ (following Landler et al., 2022, 2026).

To perform a within-subject comparison of HEP amplitudes between conditions in the sensor space, the HEP epochs were separately averaged for W- and M-conditions. We then performed a dependent-sample two-sided spatio-temporal cluster-based permutation test (full-epoch length, $N = 1000$ permutations, $\alpha\text{-level} = 0.05$ for initial t-test thresholding, and 0.025 for cluster selection in a two-sided test) to identify clusters with significant amplitude differences between the W- and M-condition using the MNE-Python toolbox. The same statistical procedure was applied to the source-reconstructed HEP epochs difference.

Results

Behavioural data coupling with the cardiac cycle

First, we examined the relationship between participants' behavioural reports, button presses, and the cardiac cycle in two task conditions (M and W). In both conditions participants were instructed to press upon registering the 'urge to move' (W and M button presses) and later in the W-condition they retrospectively reported the moment they registered the 'urge to move' (W-time report) using a mouse click. In the M-condition, participants retrospectively reported the moment of movement initiation (M-time report) (Figure 1A). Analysing data from 39 participants at the first level of statistical analysis, we observed significant Rayleigh test results in six participants for W-condition button presses, three for W-time reports, three for M-time reports, and four for M-condition button presses. The group-level statistics on median values, in line with our first hypothesis, revealed that the distribution of button presses in the W-condition displayed a significant non-uniform distribution across the cardiac cycle (Rayleigh test $p\text{-value} = 0.007$, $\alpha_{\text{FDR}} = 0.014$). The direction of the group-level mean resultant vector for the button presses in the W-condition indicated an alignment to the diastolic phase of the cardiac cycle—its mean length being 0.353 (Figure 2A). The BF analysis revealed a $\text{BF}_{10} = 5.4$, which corresponds to substantial evidence in favour of the alternative hypothesis H_1 . For the W-time reports ('urge to move' reports) we did not observe non-uniform distribution across the cardiac cycle ($p\text{-value} = 0.623$). This indicates that the effect predicted by our first hypothesis was specific to the timing of self-initiated button presses under W instructions and did not extend to retrospective reports of the 'urge to move' (Figure 2B). Regarding the second hypothesis, that behavioural events in the M-condition would not align with the cardiac cycle, group-level analyses revealed no deviation from a uniform distribution. Neither M-condition button presses (Rayleigh test, $p\text{-value} = 0.341$) nor M-time reports

(p -value = 0.452) showed significant non-uniformity across the cardiac cycle (Figure 2C and 2D). BF analyses (BF_{10} in 0.68–0.86 range) provided anecdotal support for the null hypothesis, consistent with our a priori hypotheses of no cardiac modulation.

To assess the robustness of the observed non-uniform distribution of the W-condition button presses across the cardiac cycle we conducted two control analyses. First, comparison to the null distribution with proportional statistics (Monte Carlo p -value = 0.006) confirmed that the obtained results were not explained by a uniform distribution of events (Figure 2E). Second, we evaluated whether the preferential alignment of button presses to diastole could be explained by the longer relative duration of the diastolic phase of the cardiac cycle. Using a sliding segment test, we found significantly higher counts in 13 out of 36 segment positions (p -value < 0.05) (see Figure 2F). Those segment positions were located within the diastolic phase of the cardiac cycle. As a complementary analysis, we examined the distribution of W-condition button presses in linear time by binning these events in milliseconds after R-peak (Caparco et al., 2025), confirming that the results were consistent with the diastolic preference obtained with circular analysis (see Supplemental Materials, Figure S2).

As a complementary uniformity analysis, we also tested departure from a uniform distribution on the cardiac cycle using the intercept multivariate test on $(\cos \varphi, \sin \varphi)$ for each event type separately (Landler et al., 2022, 2026). Consistent with the Rayleigh results, only W-condition button presses showed significant non-uniformity. At the trial level $p=0.0012$, with similar patterns for subject-level mean ($p=0.015$) and median ($p=0.006$) values, with no significant departure from uniformity for W reports, M presses, or M reports.

Collectively, the results show that the W-condition button press alignment with diastolic phase is unlikely to arise under a uniform distribution nor a simple consequence of the diastole's longer duration but reflects phase-specific alignment with the diastole.

To compare event cardiac coupling across our 2×2 factorial design, we submitted trial-level phase values to a repeated-measures MANOVA, with condition (W vs M) and task (press vs report) as within-subject factors (Landler et al., 2022, 2026). We observed a significant main effect of Task ($p=0.048$), but neither Condition ($p=0.418$) nor the Condition $\times$ Task interaction ($p=0.389$) reached significance. Together these results indicate that the cardiac cycle coupling location of events differed between button presses and retrospective reports, but there was no evidence that the cardiac coupling differed between W and M conditions of Libet's task.

HEP comparison between experimental conditions

Within-subject statistical analysis of differences between the W- and M-conditions in HEP amplitude including all epochs did not show any significant clusters (minimum p -value = 0.3) (see Figure 3). The complementary source-space analysis of all epochs likewise revealed no significant effects (see Supplemental Materials, Figure S1). To address potential fluctuations in interoceptive processing between the trial onset and the button press, we repeated the analysis including a fixed number of epochs for each trial (ranging from maximum to minimum number of epochs available). This alternative approach yielded the same results, with no significant between-condition differences observed.

379

380 **Discussion**

381 In this study, we investigated the functional role of cardiac input for movement
382 initiation in Libet's paradigm utilising EEG and ECG recordings to elucidate the link
383 between visceral input and participants' reports and button presses in Libet's task.

384 We observed a non-uniform distribution of button press timings across the cardiac
385 cycle when participants were required to report the time of their decision to move (the
386 'urge to move'; W-condition). In particular, W-condition button presses were
387 predominantly aligned with the diastolic phase of the cardiac cycle. Importantly, button
388 press instructions were similar in the W- and M-conditions: in both, participants pressed
389 a button when they felt an 'urge to move'. The conditions differed in what was reported
390 afterwards - the urge onset in W, and the button press timings in M. We did not find
391 significant cardiac-cycle modulation for reported 'urge to move' timings (W-time reports),
392 nor for M-condition button presses or reports in separate uniformity tests. A factorial
393 analysis, requested by a reviewer, did not show a main effect of condition (W vs M) on
394 phase location; instead it revealed a main effect of task (press vs report). The distribution
395 of button presses significantly differed from the distribution of retrospective reports, with
396 presses tending to occur in the second half of the cardiac cycle (diastole). Thus, while
397 coupling was clear for W presses in a separate test, we did not observe a statistically
398 confirmed difference between conditions in phase location. Finally, we did not find
399 significant differences in HEP amplitudes between task conditions.

The cardiac cycle alignment of the button presses was significant (based on frequentist statistics and BF analysis) only in the W-condition. This pattern is consistent with a potential association between the cardiac input processing and introspective demands of the W-condition (Dominik et al., 2024). Since the observed W-condition button presses occurred more often in the diastolic phase of the cardiac cycle it cannot be explained by the higher motor cortex excitability, which might facilitate movement execution during systole (Kunzendorf et al., 2019; Galvez-Pol et al., 2020; Palser et al., 2021; Al et al., 2023). Therefore, alternative mechanisms should be considered.

Our findings might be explained by participants utilising their cardiac signals as an implicit movement initiation cue, possibly associating it with the 'urge to move'. Given that 'the urge to move' phenomenon lacks precise definition, they, being unfamiliar with Libet's task, might struggle when asked to be guided in pressing a button by an ambiguous event they have never consciously attended to. In such instances, they could default to a familiar, ever-present internal cue—their heartbeats.

Importantly, significant cardiac cycle modulation was observed for W-condition button presses. We suggest that the 'urge to move', which preceded voluntary movements, could be better reflected in the button presses of the W-condition rather than 'urge to move' reports, as these button presses occur upon the 'urge to move' registration by design of the task, and W-condition uniquely requires later report of that urge. One should expect a delay from registering the 'urge to move' and the consequent button presses, similar to the reaction time, so the button press phase locking cannot be directly equated to the 'urge to move' phase locking, nevertheless, we argue that presses are still more reliable estimate of the 'urge to move' compared to reports.

Button presses and retrospective 'urge to move' reports rely on distinct processes: presses are executed upon detecting the internal trigger, whereas reports require retrospective temporal reconstruction using the Libet clock, introducing substantial variability. This variability—previously shown to depend on clock parameters and condition order (Dominik et al., 2017; Ivanof et al., 2022; Bredikhin et al., 2023)—may account for the absence of cardiac-cycle alignment in 'urge to move' reports, and is consistent with the factorial main effect of task rather than condition.

Taken together, these findings suggest that participants might act upon cardiac input as a movement initiation cue, which manifests clearer in locking W-condition button presses to the cardiac cycle, and not the 'urge to move' reports. Whether the same coupling is weaker or absent in M-condition presses remains unresolved. A plausible account is that the W-condition's requirement to report the urge increases introspective monitoring at the time of button press.

One study examining movement initiation and cardiac cycle coupling, found no preferential alignment to the cardiac cycle for tasks involving voluntary movement initiation, including a modified Libet's task (Park et al., 2020). Importantly, in the study by Park et al. (Park et al., 2020), participants were presented with only one of the classical Libet task conditions - the W-condition, distinguishing their paradigm from the task implemented in our study. Previous publications (Dominik et al., 2017; Bredikhin et al., 2023) with critiques of the 'urge to move' construct showed that both W- and M-conditions of the classical Libet's task might be important so that participants can grasp a conceptual difference between the two conditions.

A growing body of work suggests that cardiac cycle modulates motor control and perceptual processing, with the direction of these effects depending on task demands and cardiac phase. Systolic facilitation was reported for movement execution (Ohl et al., 2016; Kunzendorf et al., 2019; Galvez-Pol et al., 2020; Larra et al., 2020), motor response inhibition (Marshall et al., 2024), proactive inhibition (Mussini et al., 2025). In contrast, the diastolic phase was beneficial for more introspective tasks, like motor imagery, where diastolic cue presentation elicited stronger beta- and alpha-band suppression in the contralateral hemisphere (Lai et al., 2024).

This functional dissociation aligns with our findings. If W-condition button presses reflect the mere movement execution, systolic facilitation would have been expected. Instead, the W-condition emphasises internal monitoring and acting upon introspective detection of an internal trigger, rather than movement execution per se. Preferential alignment of W-condition button presses to the early diastole might, therefore, reflect an internal sampling process rather than acting. Providing that early diastole immediately follows systole and that heartbeat constitutes a salient internal systolic event, it is a plausible candidate for such internal sampling and movement initiation cue. This interpretation aligns well with previous statements that the diastolic phase is preferential for exploratory behaviour and active sampling of the environment (Galvez-Pol et al., 2020, 2022).

We did not observe a significant difference in HEP amplitudes between the conditions of the task. The absence of HEP effects may reflect methodological constraints, particularly the limited number of epochs and the resulting low signal-to-noise

ratio for evoked responses. Given the small HEP amplitudes typically reported and fluctuations in interoceptive state during the task, detecting condition-related differences is inherently challenging (Steinfath et al., 2025). Increasing the number of HEP epochs would require extending the R-peak selection window, including periods further away from the critical event (button press), introducing a trade-off between improved SNR and reduced temporal specificity.

While the HEP is often treated as an objective measure of interoceptive processing (Buot et al., 2021; Kumral et al., 2022; Poppa et al., 2022; Verdonk et al., 2024), its relation to interoception remains unclear. Reported HEP effects are heterogeneous in their spatio-temporal localisation with multiple confounding factors, crucially inconsistent control for the pulsatility artifact (Coll et al., 2021). When it is properly controlled, some studies report that previously observed HEP differences vanish (Buot et al., 2021). Thus, caution is needed when interpreting HEP amplitude modulation as direct evidence of heightened interoceptive processing.

Moreover, recent evidence suggests that the neural correlates of cardiac signals extend beyond cortical processing indexed by HEP. Cardiac input is relayed through subcortical and peripheral structures, primarily through Piezo-dependent mechanoreceptors located in the heart, arteries, skeletal muscle, and chest wall (Hamill, 2023; Salameh et al., 2024). These signals, transmitted via the vagus, glossopharyngeal, and spinal nerves to brainstem and thalamic regions before ascending to cortical areas associated with autonomic and somatosensory processing (Park and Blanke, 2019; Hamill, 2023; Zhang et al., 2025). Cardiac input may influence cortical neuronal dynamics

through vascular-neural coupling (VNC), whereby intracranial vascular pulsations affect neuronal activity via slow autoregulatory and rapid pressure-activated mechanisms (Wang and Hamill, 2021; Hamill, 2023). Animal studies provide evidence for the neuronal origin of slow local field potential oscillations coupled to vascular pulsations (Salameh et al., 2024). Together, these findings suggest that cardiac-related effects may arise from distributed subcortical and vascular-neural mechanisms without necessarily being reflected in HEP amplitude.

A substantial limitation of our study is the absence of control for respiratory effects on behavioural events. Voluntary movement initiation has previously been reported to preferentially align with inspiration in a Libet-like task (Park et al., 2020).

In conclusion, our study contributes to the understanding of interoceptive processing in the context of voluntary movement initiation, particularly emphasising the role of the cardiac input. The observed non-uniform distribution of button presses aligning predominantly with the diastolic phase of the cardiac cycle, highlights a connection between cardiac input and motor initiation in Libet's task. Additionally, our results did not provide any evidence of the 'urge to move' reports locking to the cardiac cycle. Our findings also underscore the unresolved debate regarding the reliability of HEP as a direct measure of interoceptive engagement.

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Figure Legends

Figure 1. Methods. A. The trial structure. Each trial started with the presentation of an empty clock face, accompanied by a beep sound. After 400 [$\pm$ 100] ms, a dot appeared on the clock face and started its clockwise rotation. The dot stopped when the participant pressed a space button after a random delay of 650 [$\pm$ 150] ms. In both the W- and M- conditions, participants were instructed to spontaneously press the button focusing their gaze on the centre of the clock face. In both conditions, participants were asked to refrain from preplanning their movements. In the W-condition, after a button press (W button press), participants were asked to report the time when they first experienced the intention to move (W-time report), using a mouse click. For the M-condition, after pressing the button (M button press), they had to indicate, via mouse click, the time of movement initiation (M-time report). Before the next trial, participants were

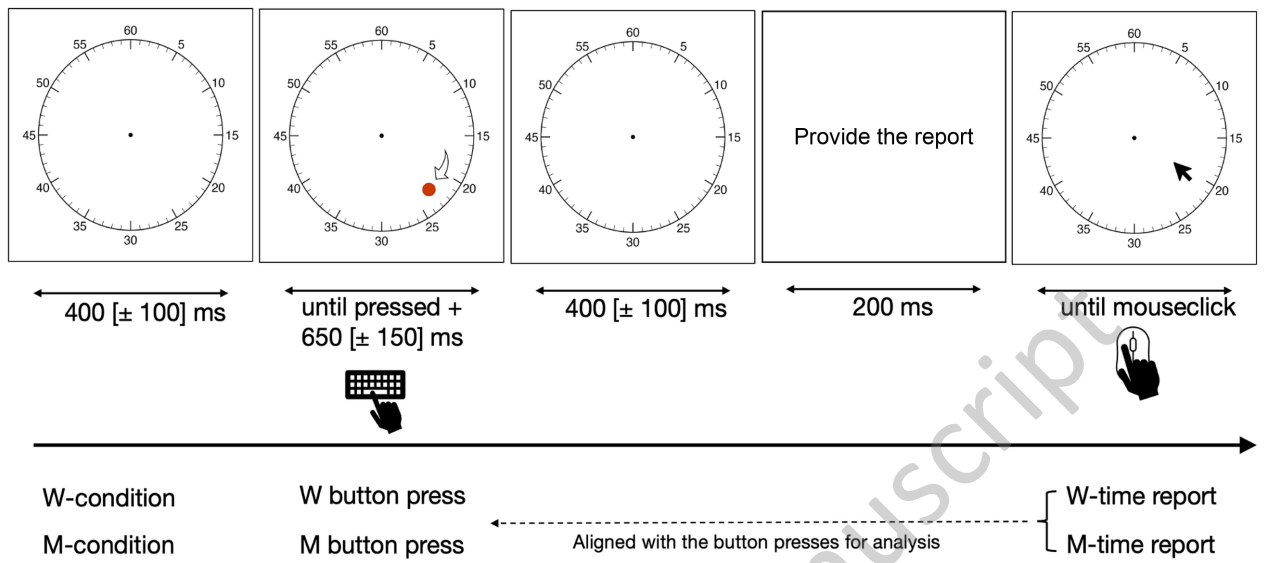
instructed to rest as long as they needed. **B.** Schematic diagram illustrating the alignment process of behavioural and cardiac cycle data. To align the behavioural report of W/M button presses and W-/M-time reports (example report shown as a blue dot) with the cardiac cycle, we first determined the corresponding R-R interval. We then converted the timestamp value into a radian value, following the formula provided in the methods (see the 'Behavioural and physiological data alignment' section). The orange colour indicates the systolic phase (R-T-offset), while the blue colour indicates the diastolic phase (T-offset-R) of the cardiac cycle. An example of how the behavioural report timestamp value is converted into radian value is shown by the dotted black arrow connecting subplots B and C. **C. Sliding segment control analysis.** Illustration of the control analysis used to test whether the observed preferential alignment of button presses to diastole in the W-condition could be explained by the longer relative duration of the diastolic phase rather than a phase-specific effect. A systolic-like segment of fixed length (orange) is systematically shifted along the unit circle in 36 overlapping steps. At each position, the number of observed button presses within the segment is compared to chance-level expectations under a binomial model accounting for segment length. This approach determines whether clustering is specific to the physiological diastolic phase or reflects general properties of segment duration.

Figure 2. Distribution of within-subject button press and report values (n=39) across phases of the cardiac cycle. The orange-coloured section of the outer circle denotes the systolic phase, while the blue-coloured line marks the diastolic phase of the cardiac cycle. The grey curve reflects the distribution of data points across the cardiac cycle; the grey dots represent within participant median values. **A.** Button presses in the W-condition. The analysis displayed a significant non-uniform distribution across the cardiac cycle (Rayleigh test $p\text{-value} = 0.007$, $\alpha_{\text{FDR}} = 0.014$) with the resultant vector length being 0.353. **B.** W-time reports. **C.** Button presses in the M-condition. **D.** M-time reports. **Control analysis for behavioural data and cardiac cycle coupling.** **E.** Distribution of surrogate data and original data (orange line) statistical values obtained with Rayleigh uniformity test for button presses in the W-condition aligned with the cardiac cycle. The dotted red line represents the 95% distribution cutoff. The proportional statistics $p\text{-value} = 0.006$. **F.** Distribution of observed data points per segment positions assessed by the sliding segment test with horizontal dashed line representing expected mean value from the binomial distribution and solid black

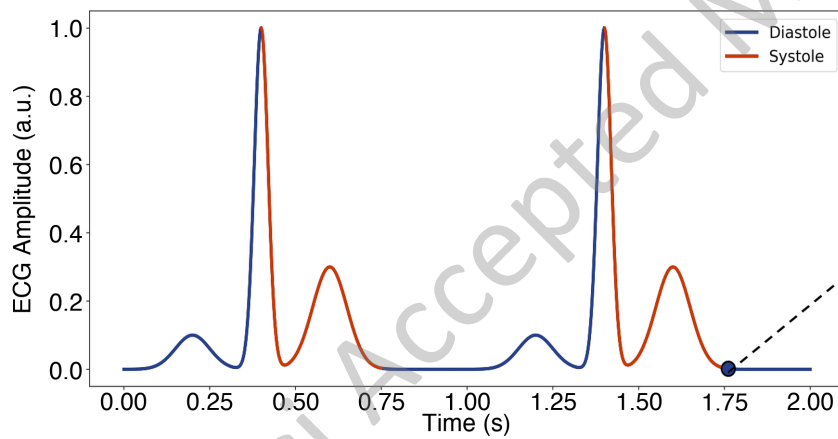
lines representing high and low cutoff values. The colour gradient represents the proportion of systolic (orange) and diastolic (blue) phases per each segment position. The cumulative distribution plot (CDF) of the binomial distribution contextualises the observed counts relative to the expected probabilities.

Figure 3. HEP amplitude in W-condition and M-condition. A. Descriptive ERP plot showing HEP averages for both conditions. The R-peak corresponds to 0.0 s, orange colour represents the W-condition HEP, grey colour–M-condition HEP, shaded area represents SEM. **B.** Descriptive topographical plots (n=34, average number of epochs in W-condition 335, in M-condition 309) for W-condition, M-condition and between-conditions difference (*W minus M*).

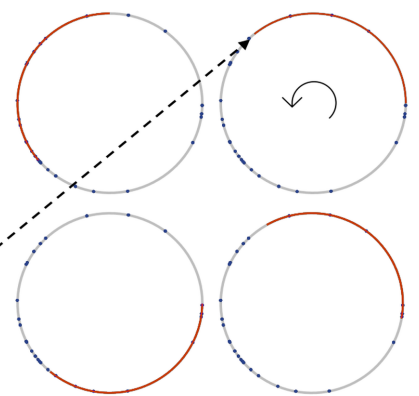
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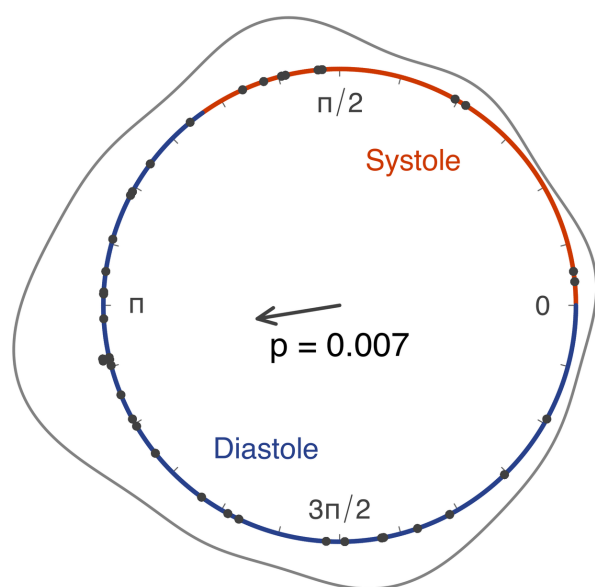
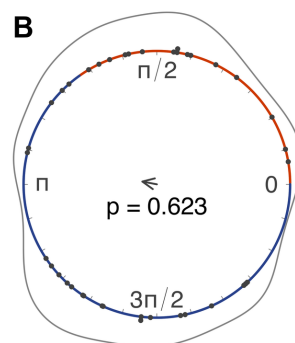
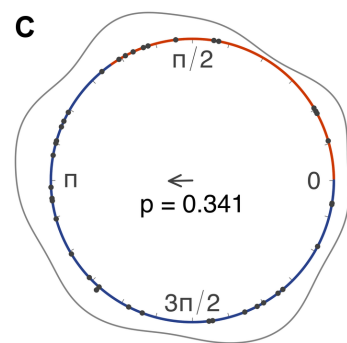
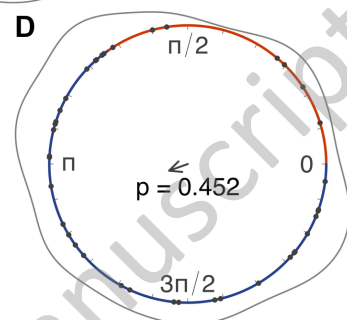
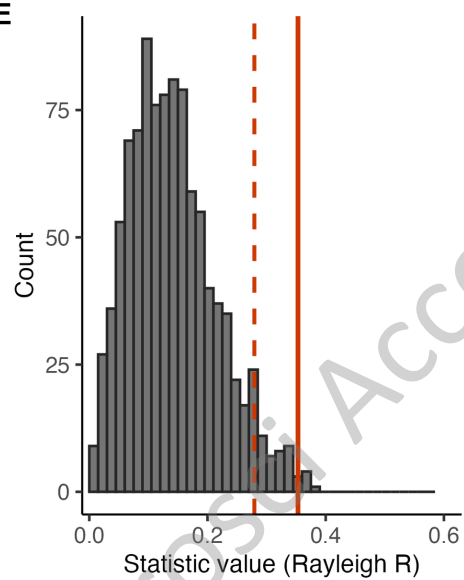
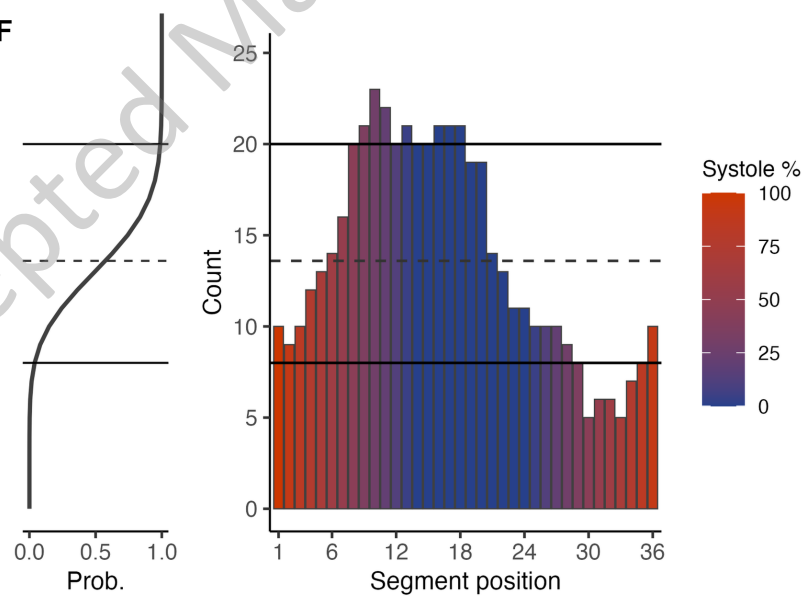


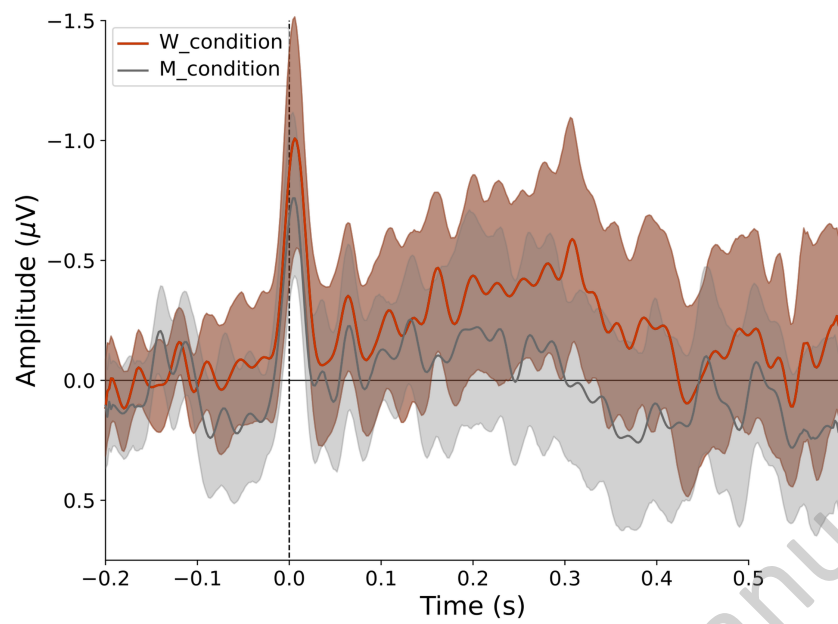
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C



A**B****C****D****E****F**

A**B**