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Heartfelt choices: The influence of cardiac phase on free-choice actions

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Abstract

The influence of cardiac phases on cognitive and sensorimotor functions is noteworthy. Specifically, during systole, as opposed to diastole, there is an observed enhancement in tasks demanding the suppression of instructed responses. This suggests that systole contributes to inhibitory control in motor functions. However, the extent to which systolic inhibition is significant in volitional free-choice actions, such as choosing to execute or refrain from a cue-initiated response, remains to be clarified. To fill this gap in the current literature, the purpose of this study was to test whether during the systole phase, compared with the diastole phase, the tendency to enact volitional actions decreased due to the systolic inhibitory effect. We used a modified version of the Go/No-Go task with an added condition for volitional free-choice actions, where participants could decide whether to respond or not, to test whether systolic inhibition could affect the volitional decision to act. The results showed that participants' responses were less frequent in systole than in diastole in the volitional action condition. Then, to test the robustness of the cardiac effect on volitional actions, we used two established manipulations: the Straw Breathing Manipulation and the Cold Pressor Test, which were able to induce anxiety and increase the heart rate, respectively. Results showed that the systole/diastole difference in the number of volitional action trials in which participants decided to respond tended to remain the same despite all manipulations. Overall, our results provide convergent evidence for the effect of the heart on the decision to act, an effect that appears independent of manipulations of both the physiological and psychological state of the individual.

KEYWORDS

cardiac phase, cold pressor test, diastole, free-choice action, interoception, straw breathing manipulation, systole, volitional actions, voluntary action

1 | INTRODUCTION

Our brain continuously integrates information that comes from within and outside the body, to guide optimal response strategies and allow flexible adjustments to the demands of the environment. Brain–body interactions influence several perceptual and cognitive processes (for a review, see Berntson & Khalsa, 2021), including decision-making, especially under risk and uncertainty (Ambrosini et al., 2019; Edwards et al., 2009; Herman et al., 2021; Kimura et al., 2023; Pramme et al., 2014, 2016). Here, we focus on the impact of cardiovascular arousal on cue-initiated free-choice actions (volitional actions that involve a deliberate choice to perform in response to a specific stimulus, as opposed to spontaneous exploratory actions).

Cardiovascular arousal is signaled by the phasic discharge of arterial baroreceptors during cardiac systole (the ventricular ejection period in a cardiac cycle). At each pulse, the baroreceptors send a volley of afferent signals to the brainstem conveying information on the strength and timing of individual heartbeats. These signals, which are used for the baroreflex regulation of blood pressure, are then forwarded to higher-order cortical structures, such as the amygdala, insula, and cingulate cortex (Critchley & Harrison, 2013). In particular, according to the "*baroreceptor hypothesis*" (Lacey & Lacey, 1958), afferent neural signals originating from arterial baroreceptors during systole induce changes in cortical inhibition (Duschek et al., 2013), resulting in a globally reduced cortical excitability (Bonvallet et al., 1954; Rau et al., 1993; Skora et al., 2022).

Multiple studies have investigated the impact of cardiac arousal on information processing through the timing of stimulus presentation to the maximal (systole) and the minimal (diastole) baroreceptor activity (Al et al., 2021; Ambrosini et al., 2019; Edwards et al., 2009; Grund et al., 2022; Motyka et al., 2019; Park et al., 2020; Saari & Pappas, 1976; Salomon et al., 2016; Salomon et al., 2016; Sandman et al., 1977; Sandman, 1984; Sandman, 1984). In the domain of action, according to the "*baroreceptor hypothesis*" (Lacey & Lacey, 1958), research has demonstrated that reaction times (RTs) are slower when stimuli are presented during the systolic phase compared to the diastolic phase (Birren et al., 1963; Jennings & Wood, 1977). Additionally, cardiac arousal affects response inhibition triggered by external stop cues (Rae et al., 2018), indicating that participants' efficiency in inhibiting motor responses increases when stop cues are presented during systole (higher cardiac arousal) compared to diastole (lower cardiac arousal).

In everyday life, however, beyond inhibiting actions in response to an external decision cue (for example, when we encounter a red traffic light that indicates to stop), we often find ourselves having to choose between inhibiting an action or performing it (e.g., when we are about to cross a yellow traffic light, which presupposes a free choice). The volitional withholding of cognitive processes, including motor action, is called intentional inhibition (Brass & Haggard, 2010). Interestingly, neuroimaging studies have shown that intentional decisions to withhold actions, beyond activations within prefrontal and motor preparation areas (Dall'Acqua et al., 2018; Filevich et al., 2012; Schel et al., 2014), also elicit responses in the anterior insular cortex (Brass & Haggard, 2010; Zapparoli et al., 2017) an interoceptive hub integrating information about the internal state of the body and cueing homeostatic adjustments of behavior (Craig, 2002; Critchley & Harrison, 2013; Jackson et al., 2011). Moreover, behavioral studies have shown that sensory cues which do not enter awareness, including cardiac cues, may nevertheless shape volitional motor behavior (i.e., intentional inhibition; Haggard, 2008; Parkinson & Haggard, 2014). These studies have used a modified version of a Go/No-Go task that incorporates volitional action trials, that is, trials requiring participants to decide whether to act or to withhold a button press (e.g., Parkinson & Haggard, 2014). Despite this evidence, to the best of our knowledge, only one study has tested the hypothesis that cardiac cues may impact motor intentional inhibition, that is, an individual's free decision to make or withhold an action (Rae et al., 2020).

Specifically, Rae et al. (2020) hypothesized that cardiovascular arousal can facilitate inhibition to mitigate impulsive actions. They expected participants to choose to respond less frequently when the stimulus was presented during systole compared to diastole. To test this, they used a Go/No-Go task that included "*choose*" trials. Participants were presented with traffic lights showing a green (Go), red (No-Go), or yellow (Choose) light, either during systole or diastole. Unexpectedly, the authors found no significant difference in the frequency of choosing to go on Choose trials between systole and diastole.

Existing evidence suggests that cardiac arousal facilitates risky decision-making (Kimura et al., 2023). Despite the different contexts and functions involved, the motor decision to pass at a yellow traffic light exemplifies a risky decision-making process. It is possible that, without information such as the varying duration of the yellow light or the potential for receiving a traffic violation, the decision to pass was not perceived as risky and uncertain in Rae et al. (2020). To emphasize this aspect, we modified the "cardiac" Go/No-Go/Choose task (Rae et al., 2020) in our present work by introducing feedback after the yellow light and varying the duration of the choose trials (Experiment 1). Specifically, during Choose trials, after a variable time interval of which the participants were

unaware, the yellow light turned red in 50% of the trials. If participants responded when the yellow signal turned red, they received auditory feedback signaling traffic violation, whereas no feedback was provided if the yellow light did not change color. We expected that, under these more risky and uncertain conditions, the impact of cardiac cues on free decisions to make or withhold actions would emerge.

To further test the robustness and consistency of this effect, we also examined whether it persisted following psychological (e.g., increased anxiety state) and physiological (e.g., increased heart rate) induced changes. These forms of stress are common in daily life and frequently influence our decisions to act or refrain from acting—for instance, when we encounter traffic lights driving home and we are in a state of anxiety, or when the temperature outside and inside the car is close to freezing. At the psychological level, anxiety in response to stressors may become maladaptive reducing the individual's ability to effectively interact in a given environment. For instance, anxiety can promote withdrawal behaviors (Davidson, 1998; Shankman & Klein, 2003), leading to less efficient movements within one's surroundings (Pijpers et al., 2005) and negatively influencing judgments of one's action capabilities (Pijpers et al., 2006). Moreover, elevated anxiety levels degrade cognitive control in a Go/No-Go task (Mussini & Di Russo, 2023). At the physiological level, it is known that stress response can directly modulate baroafferent signaling (e.g., Schulz et al., 2011, 2013, 2020; von Haugwitz et al., 2024) activating pathways that can influence baroreceptor sensitivity and the transmission of baroafferent signals to the brain.

To assess the robustness and consistency of the impact of cardiac cues on cue-initiated free decisions to make or withhold actions, we employed two different manipulation protocols that induced changes in psychological and physiological arousal. Specifically, we used the Straw Breathing Test (SBT) in Experiment 2 and the Cold Pressor Test (CPT) in Experiment 3. Participants performed the same task as in Experiment 1, referred to as the "Cardiac Free-Choice Inhibition Task" (CFCI), before and after stress induction. During the SBT (Experiment 2), participants were required to breathe through a straw for 2 min, a method known to induce anxiety (Graydon et al., 2012; Ruginski et al., 2019; Spaccasassi & Maravita, 2020). This task imposes a resistive load on the respiratory system, affecting various cardiovascular parameters, although not necessarily the heart rate. During the CPT (Experiment 3), participants submerged their non-dominant hands in a bowl of cold water for 2 min (Lamotte et al., 2021; Levtova et al., 2022). Cold exposure disrupts homeostasis, triggering regulatory mechanisms to restore it, typically resulting in an increased heart rate (Duncko et al., 2009; Graydon et al., 2012; Huang et al., 2010; Lentini et al., 2021; von Haugwitz et al., 2024). Notably, the heart rate can influence decision-making processes (Forte et al., 2021, 2022), with recent studies uncovering possible mechanisms supporting this phenomenon (Fujimoto et al., 2021). CPT can be aversive and painful. Therefore, participants were instructed to notify the experimenter if they experienced any discomfort, at which point the experiment would be stopped.

We anticipated that both increased state anxiety (especially in Experiment 2) and increased heart rate (especially in Experiment 3) would lead participants to make faster and more frequent choices. Additionally, we explored the potential interplay between stress and cardiac cycle. Specifically, we aimed to determine whether these alterations in psychological or physiological arousal states would modulate the momentary effect of cardiac cues on the decisions to make or withhold actions. If confirmed, our results would provide the first evidence that, under conditions of risk and uncertainty, phasic changes in cardiac activity affect cue-initiated free decisions to act. Moreover, they would demonstrate whether psychological and physiological changes influence the momentary impact of cardiac cycle phases on intentional inhibition.

2 | METHODS

2.1 | Participants

The entire study consists of three experiments (Figure 1). The G*Power 3.1 software was used to determine the sample size. To detect a medium effect Cohen-*d* effect size (0.5), with power set at 85% and $\alpha = .05$, the recommended minimum sample size was 38 for analyses of variance (ANOVAs). Hence, 40 healthy volunteers (20 females, mean age 23.16 years, SD 2.79, range 20–31) participated in Experiment 1 (CFCI). Forty healthy volunteers (26 females, mean age 24.68 years, SD 2.99, range 21–31), of which 20 were from Experiment 1, participated in Experiment 2 (Straw Breathing Manipulation). Finally, 40 healthy volunteers (30 females, mean age 23.49 years, SD 2.74, range 20–31), of which 20 also participated in Experiment 1, but not in Experiment 2, participated in Experiment 3 (Cold Pressor Manipulation). Only participants who did not report a history of psychiatric, neurological, or cardiac disorders were recruited for each experiment. Also, participants who reported color-blindness were excluded. All the participants were right-handed. Participants were recruited from students enrolled at the University "G. d'Annunzio" of Chieti-Pescara. Six participants were excluded from the analysis of Experiment 1 due to excessive

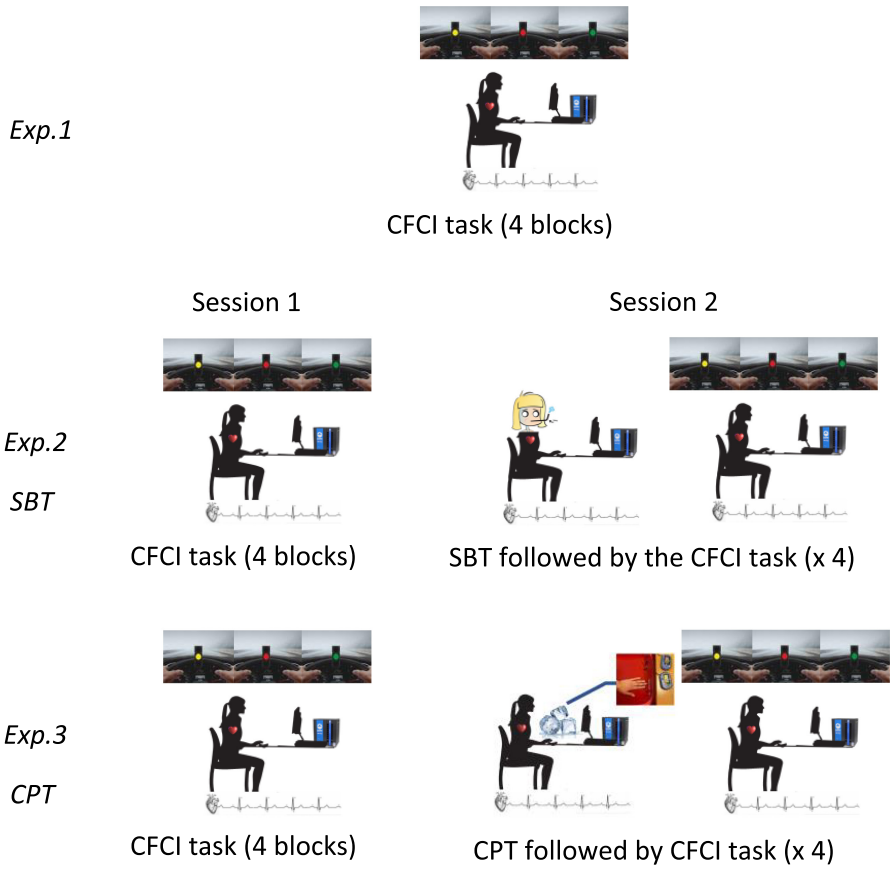

FIGURE 1 The design of the experiment procedure. The Cardiac Free-Choice Inhibition (CFCI) task consisted of four blocks (Exp. 1). In the first session of Exp. 2 and Exp. 3, all four blocks were performed consecutively. In the second session of Exp. 2 and Exp. 3, each of the four blocks was preceded by the manipulation of interest, which were the Straw Breathing Test (SBT) and the Cold Pressor Test (CPT), respectively.

or scarce choose-trial responses (>90% or <10% of trials), and four participants were excluded because did not report increased subjective anxiety after the Straw Breathing manipulation (Experiment 2), and three participants were not able to complete the Cold Pressure Manipulation (Experiment 3).

2.2 | Ethics statement

The study was approved by the Institutional Review Board of Psychology, Department of Psychological, Health and Territorial Sciences, "G. d'Annunzio" University of Chieti-Pescara (Protocol Number 4187), in compliance with the Declaration of Helsinki guidelines and its later amendments. All subjects signed a written informed consent.

2.3 | Experiment 1

2.3.1 | Cardiac free-choice inhibition task

Participants performed a modified Go/No-Go task which included "Choose" trials involving volitional actions, along with "Go trials" and "No-Go trials." Task stimuli were traffic lights showing a yellow, a green, or a red circle, in Choose, Go and No-Go trials, respectively. Each trial started with a turned-off traffic light presented in the center of a computer screen, on a virtual driving scene (see Figure 2). Stimuli were presented using E-studio 3.0 software (Psychology Software Tools, Pittsburgh, PA). Stimulus presentation was synchronized to the participant's cardiac cycle (see Section 2.3.2; Figure 2). Participants were asked to (i) respond to the presentation of the green light by pressing a button with the right index finger, (ii) withhold the button press when the red light was presented, and (iii) freely decide whether to provide a motor response or not to the yellow light. Participants were warned that if they responded to a red stimulus (No-Go trials), they would receive a horn signal alerting them of the error. Moreover, to avoid expectation effects, make the context more realistic, and increase uncertainty about the behavioral performance, after 250 ms, the yellow light turned into red in 50% of trials. Only in these trials that changed color, if participants decided to respond when the signal had already turned red, they would receive feedback alerting them that they had responded to the red light. In this case (Choose trials), would not be counted as errors, although still followed by alerting auditory feedback (horn signal). The choice to use this experimental variable is based on existing evidence that cardiac signals are more likely to influence decision-making (Herman et al., 2021; Kimura et al., 2023), as well as information processing (e.g., Ambrosini et al., 2019; Edwards et al., 2009; Pramme et al., 2014, 2016), under uncertainty and ambiguity. There

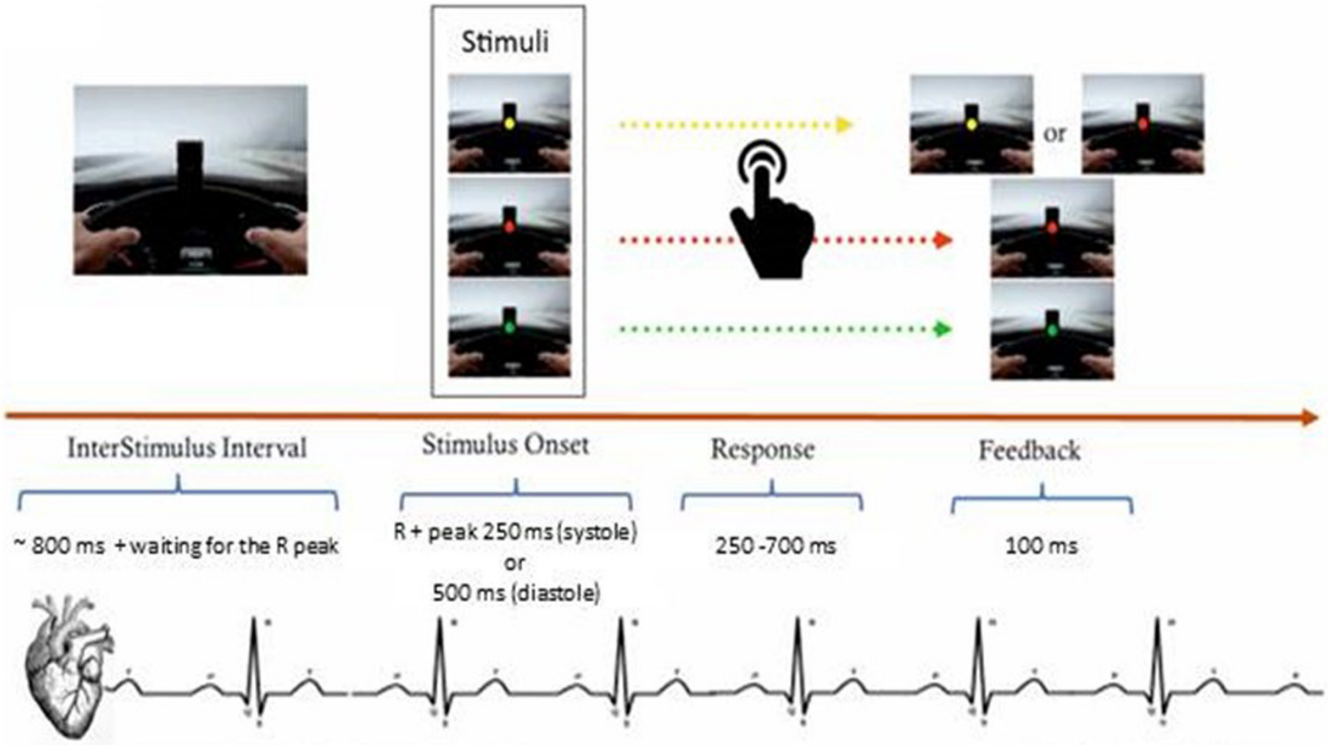

FIGURE 2 Representation of the stimuli used and trial time-course synchronized with the cardiac cycle (systole or diastole).

were 400 trials in total: 160 Go trials (40%), 80 No-Go (20%), and 160 Choose (40%). All stimuli were randomly presented in four blocks, each consisting of 100 trials. A lower frequency of No-Go trials was expected to induce a prepotent tendency to go, as in traditional Go/No-Go tasks, emphasizing a proactive control strategy. Participants were instructed to provide responses as quickly as possible.

2.3.2 | Synchronization of stimulus presentation to the cardiac cycle

To synchronize the onset of task stimuli to specific phases of the cardiac cycle (i.e., systole and diastole), participants' cardiac activity was continuously monitored during the three experiments. To this purpose, three pre-gelled electrocardiogram (ECG) electrodes (Ag/AgCI) were positioned in an III-Lead configuration, with two electrodes positioned on the left side and right side of the participant's lower abdomen, and one electrode located underneath the right collarbone. ECG was recorded using the AcqKnowledge software and a BioPac ECG100C Electrocardiogram Amplifier (band-pass filter: 0.5–35 Hz; sampling rate: 2000 Hz). The occurrence of the R-peaks in the ECG signal was identified online through a Digital Trigger Unit (DTU100, BIOPAC System, Inc.). For each trial, the last R-wave peak that occurred after 800 ms from the onset of the inter-trial interval was taken as the reference for stimulus presentation. Stimuli were presented 250 ms after the R-peak in the systole condition, and 500 ms after the R-peak in the diastole condition. Such delays were chosen according to several previous studies, which estimated the maximum peak of arterial baroceptor activity at R + 250 ms, and the absence of baroreceptor-mediated information at R + 500 ms (Ambrosini et al., 2019; Edwards et al., 2009; Garfinkel et al., 2014; Kroeker & Wood, 1955; Saltafossi et al., 2023). Stimuli were presented for a maximum duration of 700 ms, with the trial ending sooner if the participant pressed the response button. The duration of the feedback (horn signal) following a response to the red light (No-Go trials or half of Choose trials) was 100 ms. Due to the individual differences in heart rate, additional offline analyses were conducted to ensure that task stimuli were accurately delivered during the diastole phase (from the end of the T wave to the next R peak in the ECG signal) and the systole phase (from the onset of the R peak to the end of the T peak in the ECG signal) for each participant. A maximum delay of 7.2 ms was observed in the delivery of stimuli during the systole condition (R + 250 ms) and a maximum delay of 8.7 ms during the diastole condition (R + 250 ms). Consequently, all stimuli were delivered within the valid range for the systole and diastole windows.

2.4 | Experiment 2

Participants performed two sessions (see Figure 1, Exp.2). The first session mirrored Experiment 1, consisting of four consecutive blocks of the CFCI, with stimuli synchronized

to cardiac cycle phases. In the second session, each of the four blocks of the CFCI was preceded by 2 min of the SBT. The SBT was repeated to maintain its effect. This task imposed a resistive load on the respiratory system, which was expected to increase participants' anxiety levels (Graydon et al., 2012; Ruginski et al., 2019; Spaccasassi & Maravita, 2020; see Supplementary Material for a pilot study assessing the procedure's efficacy). The total duration of Experiment 2, including pre- and post-sessions, ranged from 50 to 60 min, depending on the individual cardiac frequency and break durations.

2.4.1 | Straw breathing task

The SBT consisted of participants placing a straw between their lips, holding the straw with one hand and plugging their nose with a swimming nose clip. Participants were instructed to breathe in and out solely through the straw for 2 min. This manipulation has been shown to induce mild to moderate states of anxiety associated with physiological sensations lasting about 3/4 min (Schmidt & Trakowski, 2004; Teachman et al., 2007), which corresponds to the average duration of a block of the CFCI. The SBT procedure does not involve any serious harm or risk to participants, despite the changes in subjective anxiety measures (Steinman & Teachman, 2010). Participants were welcomed to stop at any point during the procedure if it became excessively uncomfortable. In this case, their data were not considered for data analyses.

2.5 | Experiment 3

Participants performed two sessions (see Figure 1, Exp 3). The first session mirrored Experiment 1, consisting of four consecutive blocks of the CFCI, with stimuli synchronized to cardiac cycle phases. In the second session, each of the four blocks of the CFCI was preceded by 2 min of the CPT. The CPT was repeated to maintain its effect (Lamotte et al., 2021). This manipulation was expected to primarily induce an increase in participants' heart rates (Duncko et al., 2009; Huang et al., 2010; Levtova et al., 2022; see S1 in the Supplementary Material section for a pilot study assessing the procedure's efficacy). The total duration of Experiment 2, including pre- and post-sessions, ranged from 50 to 60 min, depending on the individual cardiac frequency and break durations.

2.5.1 | Cold pressor task

The CPT apparatus was not present when the participant entered the testing room to prevent an alerting response (e.g., Huang et al., 2010; Lentini et al., 2021; Levtova et al., 2022; McRae et al., 2006; Mohan & Marshall, 1994; Saab et al., 1993; Velasco et al., 1997). The cold apparatus was a modified washbowl with freezer packs and two precision thermometers affixed to the interior walls of the washbowl. Crushed ice and cold water were added until the bath reached the stable temperature of 4°C (Levtova et al., 2022; for a review, see Lamotte et al., 2021). The temperature of the testing room was about 22°C. Participants were asked to submerge their non-dominant hand to wrist level for 2 min. They were also instructed to not move their hand or make a fist. This manipulation has been shown to induce a heart rate change lasting about 4 min, with cardiac acceleration during the hand-dipping phase and deceleration afterward (Lentini et al., 2021; Levtova et al., 2022; Pramanik et al., 2009; see S1 in the Supplementary Material section for a pilot study assessing the procedure's efficacy). This duration corresponds to the average length of a block of the CFCI. The CPT procedure does not involve any serious harm or risk to participants, despite the physiological changes, such as increased heart rate (e.g., Lentini et al., 2021; Levtova et al., 2022; for a review, see Lamotte et al., 2021). Participants were welcomed to stop at any point during the procedure if it became excessively uncomfortable. In this case, their data were not considered for data analyses.

2.5.2 | Statistical analyses

Data were analyzed in JASP (version 2.16.3) for all the experiments.

Experiment 1

To compare behavior on the CFCI between systole and diastole trials, we performed 2-tailed paired-sample t-tests. Participants' free-choice response rates (% responses on Choose trials) were the primary measures of interest. However, we analyzed also RTs for the same trials to provide complementary information on different facets of motor behavior. Moreover, accuracy and RTs on Go trials were analyzed using two-tailed paired-sample *t*-tests between systole and diastole. This analysis aimed to extend the investigation of cardiac effects on motor behavior to externally triggered actions—specifically, actions elicited by stimuli in the external environment (e.g., Go stimuli, which require a response, and No-Go stimuli, which require the response to be withheld; e.g., Mussini & Di Russo, 2023; Mussini et al., 2020, 2021, 2022; Tortosa-Molina & Davis, 2018). Finally, also the accuracy of No-Go trials was analyzed through a two-tailed paired-samples

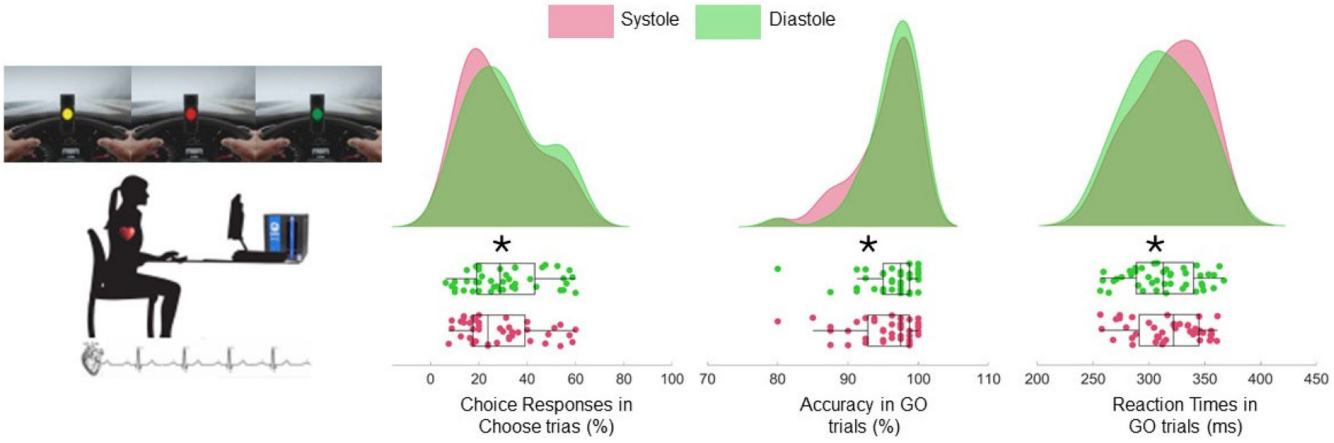

FIGURE 3 Raincloud plots illustrate the percentage of responses in Choose trials (left panel), the percentage of correct responses in Go trials (middle panel), and reaction times for Go trials (right panel). These results are compared between two conditions: when the stimulus was delivered during systole (pink) or diastole (green). Asterisks indicate significant differences between the conditions.

t-test between systole and diastole trials for the sake of completeness. All the data were normally distributed. To guide the interpretation of significance (*p* values) the Bayesian Factors (BF) was also calculated (Rae et al., 2020; Tsakiris & Critchley, 2016).

Experiment 2

To investigate the modulation of cardiac cycle effects on Choose trials by the SBT, we performed 2×2 ANOVAs with Cardiac Phase (*systole* vs. *dias*tole) and Session (*pre-* vs. *post*-SBT) as within-subject factors. Free-choice response rates and RTs were separately analyzed. To investigate the modulation of cardiac cycle effects on externally-triggered responses, we performed similar ANOVAs on accuracy and RTs on Go trials. Finally, the modulation of cardiac cycle effects on inhibition (No-Go trials) by the SBT was analyzed in a separate ANOVA. All the data were normally distributed. To guide the interpretation of significance (*p* values) the BF was also calculated.

Experiment 3

To investigate the modulation of cardiac cycle effects on Choose trials by the Cold Pressor Task, we performed 2×2 ANOVAs with Cardiac Phase (*systole* vs. *dias*tole) and Session (*pre-* vs. *post- Cold Pressor Task*) as within-subject factors. Free-choice response rates and RTs were separately analyzed. To investigate the modulation of cardiac cycle effects on externally triggered responses, we performed similar ANOVAs on accuracy and RTs on Go trials. Finally, the modulation of cardiac cycle effects on inhibition (No-Go trials) by the Cold Pressor Task was analyzed in a separate ANOVA. All the data were normally distributed. To guide the interpretation of significance (*p* values) the BF was also calculated.

3 | RESULTS

3.1 | Experiment 1

3.1.1 | Effects of the cardiac cycle on Choose trials

Paired t-test on response frequency revealed a significant effect of the cardiac phase on volitional actions. The frequency of participants choice to respond (% Choose trials) was significantly higher when the stimulus was delivered at diastole than systole (31.39 ± 15.52% vs. 29.23 ± 15.77%; $t_{(43)} = 2.31$, $p = .026$, $d = 0.348$, BF10 = 302.959; see Figure 3). This result supports our main hypothesis that the inhibitory effect of systole impacts the free-decision to act or withhold a response. On the other hand, cardiac phases do not affect the speed of free-choice actions. RTs did not differ significantly between systole and diastole (292.32 ± 30.88 ms vs. 287.32 ± 28.66 ms; $t_{(43)} = 1.50$, $p = .14$; BF10 = 0.459).

3.1.2 | Effects of the cardiac cycle on Go and NoGo trials

Paired t-tests revealed a significant effect of cardiac phases on motor behavior when participants were externally triggered to respond (Go trials). Participants were more accurate (no omission error) when the Go stimulus was delivered at diastole than systole (96.8 ± 5.68% vs. 95.71 ± 5.13%; $t_{(43)} = 2.43$, $p = .020$, $d = 0.366$; BF10 = 2.233; see Figure 3). Moreover, participants were faster when the stimulus was delivered at diastole than at systole (311.57 ± 30.87 ms vs. 317.08 ± 30.33 ms; $t_{(43)} = 3.46$, $p = .001$, $d = 0.521$; BF10 = 24.468; see

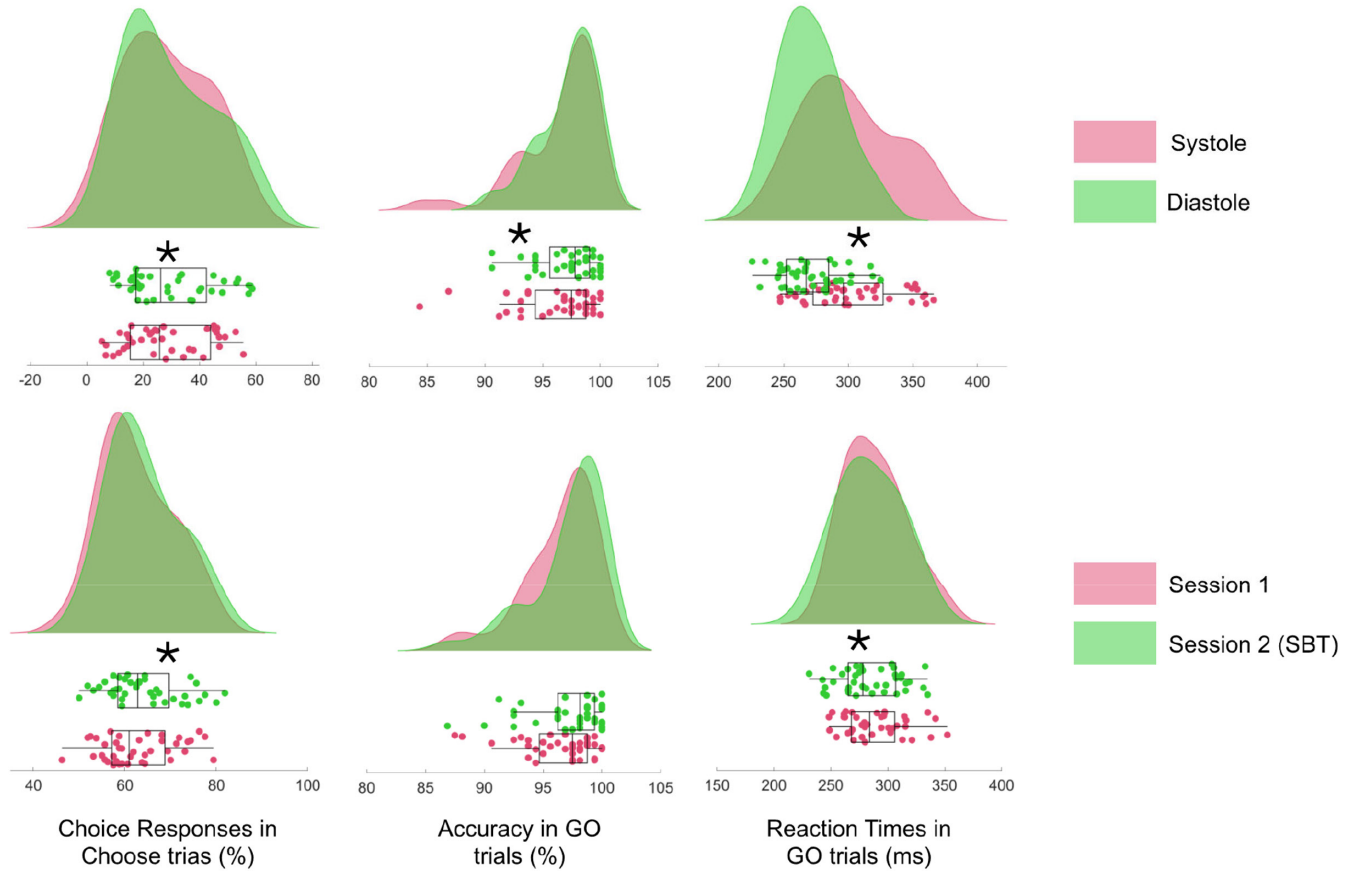

FIGURE 4 Raincloud plots depict the results of the percentages for choice responses (left panels), accuracy responses of Go trials (middle panels), and reaction times for Go stimuli (right panel). The two main conditions: cardiac phase (systole and diastole, represented respectively in pink and green) and session (before the Strow Breathing Task, represented in pink, and after the stimulation, represented in green) are depicted in the top and lower panels, respectively. Asterisks indicate that the conditions are significantly different.

Figure 3). Overall, these results are consistent with the idea that the inhibitory effect of baroreceptor activation at systole results in slower RTs for both Choose and Go trials and lower accuracy on Go trials (Lacey & Lacey, 1958, 1978).

Finally, when participants had to inhibit the motor response (No-Go trials), their performance was similarly accurate (no commission error) regardless of whether the cue was presented at diastole (96.9 ± 15.66%) or systole (98.8 ± 5.01%; $t_{(43)} = 0.91$, $p = .37$; BF10 = 1.364).

3.2 | Experiment 2

3.2.1 | Modulation of cardiac cycle effects on Choose trials by the SBT

The 2 × 2 ANOVA on the frequency of choice responses revealed a significant main effect of the Cardiac Phase on volitional actions. Participants responded more frequently when the stimulus was presented at diastole than systole ($F_{(1,39)} = 5.54$, $p = .024$, $\eta_p^2 = .124$, 33.88 ± 17.10% vs. 32 ± 16.54%; BF10 = 1.782; see Figure 4). The main effect of the Session was also significant, in that participants responded more frequently in the post-treatment session than in the pre-treatment session ($F_{(1,39)} = 4.47$, $p = .041$, $\eta_p^2 = .103$; 36 ± 21.72% vs. 29.88 ± 15.81%; BF10 = 1.000). No significant interaction between the Cardiac Phase and Session was found ($F_{(1,39)} < 1$, $p = 1$; BF10 = 0.284). Results suggest that stress-induced anxiety (see Supplementary Material for the psychological effects of SBT) does not disrupt the cardiac cycle effect on free-choice actions while inducing a general increase in the frequency of participants' choice responses. The 2 × 2 ANOVA on RTs did not reveal a significant main effect of the Cardiac Phase ($F_{(1,39)} = 2.28$, $p = .14$; BF10 = 0.500). The main effect of the Session was significant with faster responses after the SBT ($F_{(1,39)} = 29.08$, $p < .001$, $\eta^2 = .427$; 270.95 ± 23.90 ms vs. 290.32 ± 25.18 ms; BF10 = 1.000). The interaction between Cardiac Phase and Session was not significant ($F_{(1,39)} = 0.44$, $p = .51$; BF10 = 0.276).

3.2.2 | Modulation of cardiac cycle effects on Go and NoGo trials by the SBT

The 2×2 ANOVA on accuracy to Go signals revealed a significant main effect of the Cardiac Phase. Participants were more accurate (no omission error) when the stimulus was delivered at diastole than systole ($F_{(1,39)}=6.71$, $p=.013$, $\eta^2=.147$; 97.45±2.99% vs. 96.66±3.98%; BF10=0.718). However, neither the main effect of Session ($F_{(1,39)}=0.07$, $p=.79$; BF10=.177) nor the interaction Cardiac Phase by Session ($F_{(1,39)}=1.53$, $p=.22$; BF10=.130) were significant. The 2×2 ANOVA on RTs revealed a significant effect of the Cardiac Phase when participants were externally triggered to respond (Go trials). Participants were faster when the stimulus was delivered during diastole than systole ($F_{(1,39)}=46.41$, $p<.001$, $\eta^2=.543$; 303.98±29.79 ms vs. 310.89±32.83 ms; BF10=2.294). Also, the main effect of the Session was significant, as participants were faster when the stimulus was delivered after the SBT ($F_{(1,39)}=11.60$, $p=.002$, $\eta^2=.229$; 301.77±35.38 SD vs. 313.11±27.56; BF10=0.045). The interaction Cardiac Phase by Session was not significant ($F_{(1,39)}=3.03$, $p=.08$; BF10=1.000).

Finally, the 2×2 ANOVA on accuracy (no commission errors) in the NoGo condition did not reveal any significant effect: Cardiac Phase ($F_{(1,39)}<1$, $p=.95$; BF10=.029), Session ($F_{(1,39)}<1$, $p=.40$; BF10=0.071), and Cardiac Phase by Session interaction ($F_{(1,39)}<1$, $p=.42$; BF10=0.245).

3.3 | Experiment 3

3.3.1 | Modulation of cardiac cycle effects on free-choice actions by the CPT

The 2×2 ANOVA on the frequency of choice responses revealed a significant main effect of the Cardiac Phase, as participants chose to respond more frequently when the stimulus was delivered at diastole than systole ($F_{(1,39)}=9.80$, $p=.003$, $\eta_p^2=.201$; 33.16±17.66% vs. 30.56±16.85%; BF10=3.609; see Figure 5). The main

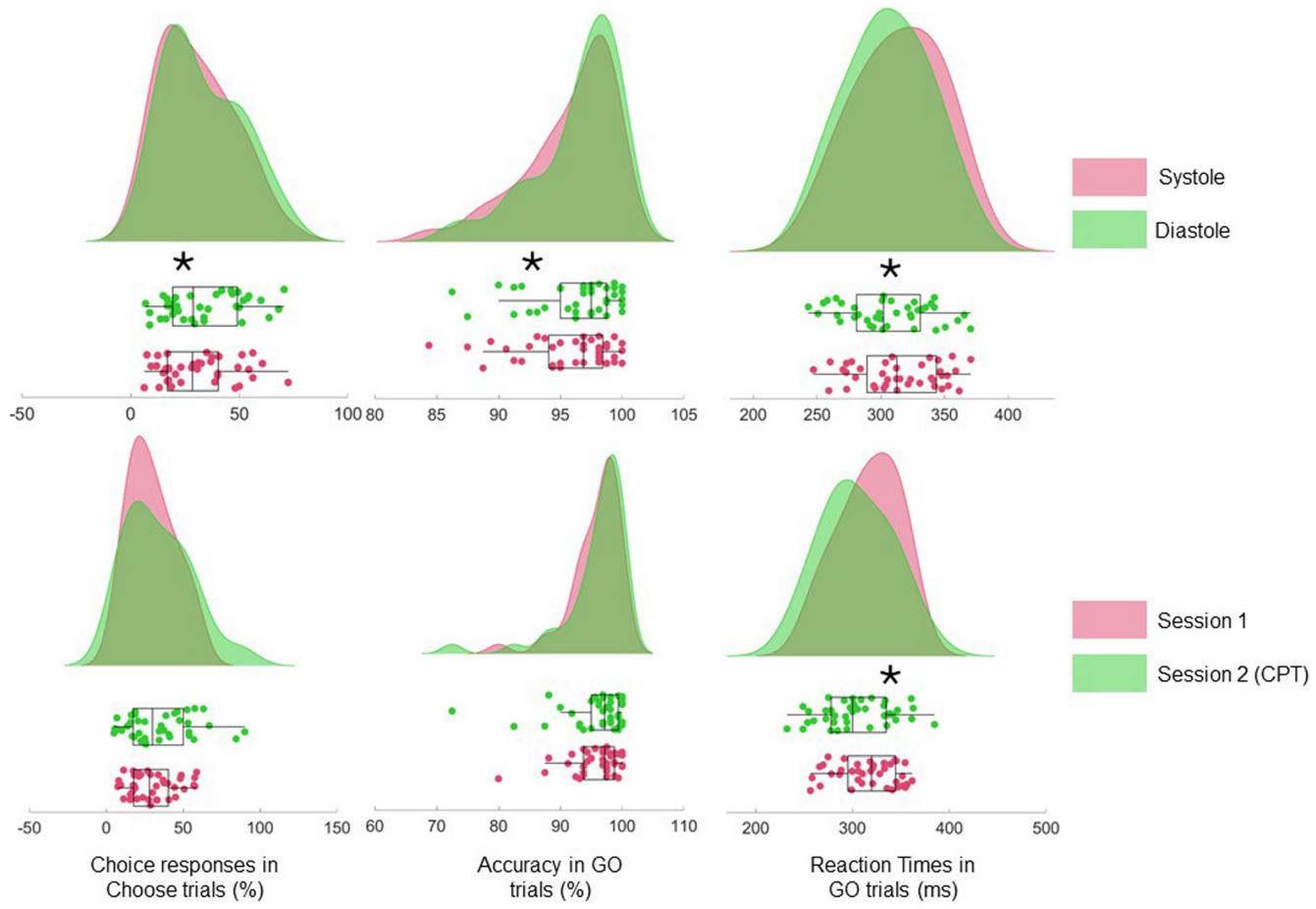

FIGURE 5 Raincloud plots depict the results of the percentages for choice responses (left panels), accuracy responses of Go trials (middle panels), and reaction times for Go stimuli (right panel). The two main conditions: cardiac phase (systole and diastole, represented respectively in pink and green) and the session (before the Cold Pressure Task, represented in pink, and after the stimulation, represented in green) are depicted in the top and lower panels, respectively. Asterisks indicate that the conditions are significantly different.

effect of Session ($F_{(1,39)}=3.40$, $p=.07$; BF10 = 0.107) and its interaction with the Cardiac Phase were not significant ($F_{(1,39)}<1$, $p=1$; BF10 = 0.668). Results suggest that physiological stress inducing an increase in the heart rate does not disrupt the cardiac cycle effect on free-choice actions.

The 2×2 ANOVA on RTs did not reveal a significant main effect of the Cardiac Phase ($F_{(1,39)}=2.34$, $p=.13$; BF10 = 1.000). The main effect of Session was, instead, significant with faster choice responses after than before the CPT ($F_{(1,39)}=8.35$, $p=.006$, $\eta^2=.176$; 280.56 ± 29.73 ms vs. 292.02 ± 27.17 ms; BF10 = 0.020). The interaction Cardiac Phase by Session was not significant ($F_{(1,39)}<1$, $p=.94$; BF10 = 0.445).

3.3.2 | Modulation of cardiac cycle effects on Go and NoGo trials by the CPT

The 2×2 ANOVA on accurate responses to GO signals revealed a significant main effect of the Cardiac Phase. Participants were more accurate (no omission error) when the stimulus was delivered at diastole than systole ($F_{(1,39)}=4.50$, $p=.040$, $\eta^2=.103$; 96.40 ± 3.51%; 95.72 ± 3.77; BF10 = 0.222). Neither the main effect of Session ($F_{(1,39)}=0.17$, $p=.68$; BF10 = 0.253) nor the interaction Cardiac Phase by Session ($F_{(1,39)}=0.98$, $p=.32$; BF10 = 0.050) was significant.

The 2×2 ANOVA on RTs revealed a significant effect of the Cardiac Phase when participants were required to respond (Go trials). Participants were faster when the stimulus was delivered at diastole than systole ($F_{(1,39)}=16.45$, $p<.001$, $\eta^2=.297$; 306.18 ± 32.97 ms vs. 314.26 ± 32.83 ms; BF10 = 0.023). Also, the main effect of the Session was significant, with faster responses when the stimulus was delivered after than before the CPT ($F_{(1,39)}=19.67$, $p<.001$, $\eta^2=.335$; 293.26 ± 33.18 ms vs. 316.33 ± 30.76 ms; BF10 = 3.492). The interaction Cardiac Phase by Session was not significant ($F_{(1,39)}<1$, $p=.35$; BF10 = 1.000).

Finally, the 2×2 ANOVA on accuracy (no commission errors) in the NoGo condition did not reveal a significant effect of Cardiac Phase ($F_{(1,39)}<1$, $p=.46$; BF10 = 0.180) and Session ($F_{(1,39)}<1$, $p=.77$; BF10 = 0.200). The interaction Cardiac Phase by Session was not significant ($F_{(1,39)}<1$, $p=.33$; BF10 = 0.035).

All results are summarized in Table 1.

TABLE 1 The table shows a summary of the results from the three experiments.

Experiment 1				
				Cardiac phase
FreeChoice		%Response		Diastole>systole*
		RT		ns
Go		Accuracy		Diastole>systole*
		RT		Diastole<systole*
NoGo		Accuracy		ns
Experiment 2				
		Cardiac phase	**Session**	**Interaction**
FreeChoice	%Response	Diastole>systole*	Post>pre*	ns
	RT	ns	Post<pre*	ns
Go	Accuracy	Diastole>systole*	ns	ns
	RT	Diastole<systole*	Post<pre*	ns
NoGo	Accuracy	ns	ns	ns
Experiment 3				
		Cardiac phase	**Session**	**Interaction**
FreeChoice	%Response	Diastole>systole*	Post<pre*	ns
	RT	ns	Post<pre*	ns
Go	Accuracy	Diastole>systole*	ns	ns
	RT	Diastole<systole*	Post<pre*	ns
NoGo	Accuracy	ns	ns	ns

Note: Asterisks indicate that the conditions are significantly different ($p<.05$), while "ns" indicates that the conditions do not differ statistically.

4 | DISCUSSION

The primary observation in the current study highlights a systematic coupling between the participants' cardiac phase and their cue-initiated volitional actions. Specifically, in a condition where participants were completely free to choose whether or not to engage in movement, they chose to act less frequently during the systolic phase, a phase of contraction of the heart muscle, than the diastolic phase, a period of relaxation of the heart muscle after contraction (Experiment 1). This finding is in line with the inhibitory effect of systole (Birren et al., 1963; Jennings & Wood, 1977; Lacey & Lacey, 1958) and extends it to volitional action. These results were obtained using a well-established paradigm frequently used to study both the motor processes associated with voluntary versus forced action (i.e., externally triggered action) and decision-making processes (e.g., Parkinson & Haggard, 2014; Rae et al., 2018; Schel & Crone, 2013). Specifically, the study employed a Go/No-Go task with "choose" stimuli, enabling participants to decide whether to respond or not. Additionally, this task was conducted following psychophysiological stress-induction procedures. These included the SBT (Experiment 2), which successfully increased anxiety levels, and the CPT (Experiment 3), which effectively elevated heart rate (see Supplementary Material). The aim was to examine whether the coupling between participants' cardiac phase and volitional actions persisted despite manipulations or was disrupted by its psychophysiological effects. We found that none of the manipulation procedures disrupted the momentary effect of the cardiac phase on free decisions to either initiate or withhold actions. Based on previous literature (Graydon et al., 2012; Huang et al., 2010; Lentini et al., 2021; Ruginski et al., 2019; Spaccasassi & Maravita, 2020; von Haugwitz et al., 2024) and our supplementary results, showing that the SBT increases anxiety while the CPT increases the heart rate, we can reasonably conclude the following: although both stress-inducing manipulations are unlikely to act purely at psychological or physiological levels, neither psychological stress nor physiological stress disrupt the coupling between participants' cardiac phase and volitional actions. These findings are consistent with a recent study by von Haugwitz et al. (2024), which reported no effect of the CPT on systole and diastole.

4.1 | Influences of cardiac phase on volitional actions in uncertain and engaging task environments

As expected, our results indicate that cardiac arousal promotes intentional inhibition: participants tended to withhold actions more frequently during the systole phase compared to the diastole phase. These findings align with previous research suggesting an inhibitory effect of systole on motor behavior, demonstrating that systole facilitates response inhibition (Rae et al., 2018; see also Makowski et al., 2020). Previous studies on self-paced movements, where initiation relied entirely on the participant and was not triggered by a cue (unlike in the current study), have shown an increase in spontaneous active movements during systole. These include a higher frequency of saccades (Galvez-Pol et al., 2020; Ohl et al., 2016) and self-paced exploratory actions (Kunzendorf et al., 2019; Palser et al., 2021). This appears to contrast with our findings and suggests an alternative explanation: the subsequent action might be influenced by the presence of the visual cue. The cardiac cycle could affect the processing of the visual cue, likely enhancing it during diastole (see Skora et al., 2022 for a review), rather than the free action itself. Future studies employing electroencephalography will help further clarify these contributions.

Our study echoes the work of Rae et al. (2020), which started with the same hypothesis—that participants would choose to withhold a button press more frequently during systole than diastole—and employed a similar task but did not report significant results. We attribute the discrepancy between our findings and those of Rae et al. (2020) to the differences in the characteristics of our paradigm, which we designed to induce and enhance uncertainty and task engagement during execution.

The first difference lies in the fixed duration allocated for the execution of volitional actions in Rae et al. (2018) study, as opposed to our paradigm where we introduced a shorter and variable time (1000 ms in Rae et al., 2018 vs. 250–500 ms in our study). The prolonged timing in stimulus presentation in Rae et al. (2018) work probably resulted in reduced engagement during the task, leading to the subsequent absence of the cardiac phase effect in Choose trials. Previous studies have indicated that contextual variables, especially those promoting heightened arousal and keeping participants in a more task-oriented state, facilitate the manifestation of the systole/diastole effect on performance (Carroll & Anastasiades, 1978; Yang et al., 2023). The reduction in stimulus presentation time and the introduction of variability in stimulus duration for choice actions, promoting increased engagement in the task, likely facilitated the occurrence of the systole/diastole effect observed in our study. The lack of task engagement could also account for the negative results in Park et al.'s (2020) study. The research revealed a connection between the spontaneous breathing phase and the onset of voluntary action but not with the cardiac phase. This was tested using two classic voluntary tasks, the Libet and Kornhuber tasks (Baek et al., 2017; Kornhuber &

Deecke, 1965; Libet et al., 1993; Pfurtscheller et al., 2010; Schurger et al., 2012, 2021). These tasks, which do not induce heightened arousal, fail to keep participants in a more task-oriented state.

A second distinction from Rae et al.'s (2018) study lies in our introduction of feedback to increase risk and uncertainty about performance (Ullsperger & Von Cramon, 2003). Crucially, after a variable time interval, the "Choose" signal was followed by a stop signal in half of the cases. Upon response, this stop signal triggered an audible alert feedback. We made this modification based on evidence suggesting that cardiac signals are more likely to influence decision-making (Herman et al., 2021; Kimura et al., 2023) and information processing (e.g., Ambrosini et al., 2019; Edwards et al., 2009; Pramme et al., 2014, 2016), under conditions of risk, uncertainty and ambiguity. For instance, Kimura et al. (2023) demonstrated that fluctuations in cardiac signals impact risky decision-making processes. Their study revealed a higher percentage of uncertain options chosen in a risky condition for stimuli delivered during systole compared to diastole. Additionally, the level of risk aversion was lower in systole trials than in diastole trials, indicating an increased propensity for risk-taking during systole. Although at first glance these results may seem at odds with our results, the authors explain how the effect of systole on risk disposition depends on the type of feedback given. Specifically, with positive feedback, the decision to take a risk during systole may occur more frequently; with negative feedback, the decision to take a risk during systole may occur less frequently, as observed in the present study where an alerting signal was delivered as feedback. In the same vein, other research (Buckert et al., 2014; FeldmanHall et al., 2016) suggests that the inclination toward risk during systole may be influenced by the nature of the feedback in the reward-learning process under uncertainty.

At a neural level, in line with our findings, neuroimaging studies have shown that the anterior insular cortex (AIC) is involved not only in cardiac signal processing (e.g., Babo-Rebelo et al., 2016) but also in the decision-making process (Delgado et al., 2011; Dunn et al., 2010, 2012; Werner et al., 2009) and self-management behaviors (Ryan & Sawin, 2009) crucial during voluntary decision-making. In line with our data and the findings of Kimura et al. (2023), a larger activation of the AIC has been observed when uncertainty about performance is high (Mussini et al., 2022; Ullsperger & Von Cramon, 2003) and when more demanding performance monitoring is required (Hester et al., 2004, 2005; Ullsperger & Von Cramon, 2003).

While beyond the scope of this article, the results from the Go and No-Go conditions provided interesting insights. In the Go condition, where actions are externally triggered, participants showed greater accuracy and shorter RTs during diastole compared to systole, supporting the inhibitory role of systole on motor initiation. In the No-Go condition, we found no significant difference in accuracy between systole and diastole, consistent with Rae et al. (2020). This lack of effect may be due to the simplicity of the task, as participants demonstrated a ceiling effect, with accuracy close to 100% on No-Go trials, making it difficult to detect differences based on the cardiac cycle. Additionally, the lower number of No-Go trials compared to Choose and Go trials further limits the statistical power to observe subtle effects. Moreover, the No-Go and Choose trials differ in cognitive processes and levels of uncertainty, suggesting that the effect of the cardiac cycle on motor inhibition might only emerge under specific conditions and tasks (e.g., the stop-signal task; Rae et al., 2018). Systolic inhibition may also affect concurrent processing, potentially influencing motor decision-making in free-choice scenarios more than in inhibitory control scenarios like No-Go trials. If there is a systolic effect on cue processing, we would expect it to impact both Choose and No-Go trials similarly.

4.2 | The persistent influence of cardiac phase on volitional actions: Insights from physiological and psychological manipulations

When we tested the robustness of the cardiac effect on volitional action by manipulating participants' psychological states—inducing heightened anxiety (Experiment 2)—and physiological states—increasing the heart rate (Experiment 3), we found that the inhibitory effect of systole on the decision to act remained unchanged. These results are in line with a recent study that found no effect of the CPT task in relation to the cardiac phase (von Haugwitz et al., 2024). However, it is also possible that the task we used to change psychophysiological states was insufficient to disrupt systolic amplification, or that a different type of psychophysiological stressor might be more effective in producing such a disruption.

Supporting this persistent inhibitory role of systole despite the experimental manipulations, early theories suggested that oscillating cardiovascular activity originating from baroreceptor activation influenced central cortical excitability independently of changes in blood flow or pressure (Elbert & Rau, 1995; Lacey & Lacey, 1978). Interestingly, a temporary increase in blood pressure is a homeostatic mechanism, that is, a mechanism designed to keep specific internal parameters stable and constant, even in the face of external environmental changes (Duschek et al., 2013; Skora et al., 2022), including in response to acute stress. Taken together, this suggests that

the inhibitory role of systole, including its promotion of action withholding, may not be significantly influenced by the homeostatic adjustments elicited by external stressors. However, it is crucial to note that our study specifically investigated the inherent oscillatory nature of the cardiac cycle without exploring adaptive changes to it. Consequently, our findings do not directly address the adaptive control of cardiac activity in response to stress. Future investigations will shed light on the relationships between the inhibitory systolic effect and the cardiac homeostatic responses to physiological and psychological manipulations.

Regarding the effects of manipulations on response accuracy and RTs, participants exhibited increased frequency and quicker responses in Choose trials, along with a reduction in omitted responses in Go trials, following a session inducing heightened state anxiety (Experiment 2). State anxiety, characterized by apprehension in stressful situations and perceived tension (e.g., Spielberger, 1966), has been shown in previous research to influence motor performance, enhancing reaction and movement times in simple stimulus–response tasks among healthy participants (Bolmont et al., 2000; Hainaut & Bolmont, 2005; Langlet et al., 2017; Mussini & Di Russo, 2023). In alignment with the "Fight or Flight" concept (Cannon, 1925), heightened muscular tension due to increased state anxiety may have contributed to the observed session effect in our task. This suggests that physiological signals, such as the cardiac phase, not only influence emotion, cognition, and externally triggered action (Cyders et al., 2007; Damasio, 1996; Garfinkel & Critchley, 2016; Rae et al., 2018) but also impact free voluntary actions, regardless of physiological or psychological arousal changes, at least within experimental settings. Similarly, following a session inducing heightened heart rate (Experiment 3) participants responded faster in Choose trials and Go trials after manipulation. These results fit with previous findings where participants exhibited faster responses to stimuli after exposure to the cold, although accuracy tended to decrease under such conditions (e.g., Enander, 1987; Mäkinen et al., 2006; Pease et al., 1980; Thomas et al., 1989). However, a limitation of our study is that, although we thoroughly assessed the effectiveness of manipulations in the pilot studies (see Supplementary Material), we did not systematically monitor it during the experimental sessions. Specifically, participants' anxiety levels were only monitored in Experiment 2, where we expected it to change, but not in Experiment 3.

Overall, our results suggest that the cardiac phase plays a significant role in cue-initiated volitional actions, influencing individuals' choices during specific cardiac phases. These findings carry important implications for understanding the neural basis of motor decision-making and could potentially be applied in developing interventions for individuals with decision-making impairments (e.g., Morgado et al., 2015; Sobhani & Bechara, 2011). Future research should seek to extend these findings in more diverse samples and examine the underlying brain mechanisms by which the cardiac phase influences motor decision-making.

AUTHOR CONTRIBUTIONS

Elena Mussini: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review and editing. **Mauro Gianni Perrucci:** Data curation; methodology; resources; software; supervision; validation; visualization; writing – review and editing. **Marcello Costantini:** Funding acquisition; methodology; resources; supervision; writing – review and editing. **Francesca Ferri:** Conceptualization; data curation; funding acquisition; methodology; project administration; resources; supervision; validation; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

All data analyzed in this study are included in the manuscript and in the Supplementary Materials section.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1:

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