The impact of cardiac afferent signaling and interoceptive abilities on passive information sampling

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ABSTRACT

A growing body of research suggests that perception and cognition are affected by fluctuating bodily states. For example, the rate of information sampling is coupled with cardiac phases. However, the benefits of such spontaneous coupling between bodily oscillations and decision-making remains unclear. Here, we studied the role of the cardiac cycle in information sampling by testing whether sequential information sampling phase-locked to systolic or diastolic parts of the cardiac cycle impacts the rate of information gathering and processing. To this aim, we employed a modified Information Sampling Task, a standard measure of the rate of information gathering before reaching a decision, in which the onset of new information delivery in each trial was coupled either to cardiac systole or diastole. Information presented within cardiac systole did not significantly modulate the information processing in a manner that would produce clear behavioral changes. However, we found evidence suggesting that higher interoceptive awareness increased accuracy, especially in the costly version of the task, when new information was sequentially presented at systole. Overall, our results add to a growing body of research on body-brain interactions and suggest that our internal bodily rhythms (i.e., heartbeats) and our awareness of them can interact with the way we process the noisy world around us.

Keywords: interoception; decision-making; cardiac cycle; Information Sampling Task; baroreceptor; heartbeat.

1 INTRODUCTION

'Interoception' refers collectively to the processing of internal bodily stimuli by the nervous system (Khalsa et al., 2018). Even though interoceptive processing occurs across all major biological systems involved in maintaining bodily homeostasis, including the cardiovascular, pulmonary, gastrointestinal, or osmotic systems (Khalsa et al., 2018), cardioception has received particular attention. A single cardiac cycle consists of two main phases. In the systolic phase the heart contracts and ejects the blood to the great vessels that leave the heart, increasing the activity of arterial baroreceptors (pressure sensors) and providing information about the strength and timing of each heartbeat to the brain. In the diastole phase the heart expands while being filled and baroreceptors are quiescent.

Cardiac afferent signaling plays an important role in the interaction between body and the brain, affecting cognitive, affective, and sensory processing (Critchley and Garfinkel, 2018; Critchley and Harrison, 2013; Khalsa et al., 2018). Historically, baroreceptor activity (occurring at systole) was generally considered to be inhibitory (Lacey and Lacey, 1978, 1970). Indeed, in some domains, systolic cardiac signals show inhibitory effects on perceptual and cognitive processing. Systolic afferent signals suppress startle responses, attenuate memory encoding for words, and dampen subjective pain and somatosensory perception (Al et al., 2020; Garfinkel et al., 2013; Motyka et al., 2019; Schulz et al., 2016; Wilkinson et al., 2013). However, in some other domains, baroreceptor signals show facilitatory effects instead. Specifically, the detection of rapidly presented visual stimuli, particularly conveying fear, is enhanced during cardiac systole compared to cardiac diastole (Azevedo et al., 2017; Garfinkel et al., 2014; Park et al., 2014; Pramme et al., 2016).

Those past studies that have documented modulations of perception and cognition as a function of the cardiac cycle (e.g. Garfinkel et al., 2013; Wilkinson et al., 2013; Schulz et al., 2016; Motyka et al., 2019; Al et al., 2020) have deliberately time-locked the presentation of stimuli to diastole or systole phases. However, there is a growing interest in determining whether spontaneous actions or decisions in daily life also occur in synchrony with natural fluctuations of bodily states. Recent evidence suggests that cardiac phase is not coupled to either voluntary actions (Park et al., 2020) or self-paced responses (Herman and Tsakiris, 2020). However, several studies suggest that active sampling of the external world occurs preferentially in certain phases of the cardiac cycle (Galvez-Pol et al., 2020; Kunzendorf et al., 2019; Ohl et al., 2016). Kunzendorf et al. (2019) reported a higher rate of keypress generation, which led to the onset of images to-be-sampled (i.e. reflected readiness to gather information), during the systolic than diastolic phase. Ohl et al. (2016) demonstrated that the generation of involuntary microsaccades occurred preferentially during the systolic phase of the cardiac cycle. Similarly, Galvez-Pol et al. (2020) showed that task-related oculomotor events are linked to the cardiac cycle. Eye movements were predominantly generated during the systolic phase of the cardiac cycle, which has been reported as the period of maximal effect of the baroreceptors' activity upon cognition, while fixations and blinks were predominantly generated in the diastole phase (early and late diastole, respectively).

These findings suggest that such preferential information gathering in synchrony with naturally occurring bodily oscillations is in some way adaptive or optimal. Possibly, we act in a way, consciously or subconsciously, to maximize the likelihood of relevant signals being processed during optimal phases of the cardiac cycle (Kunzendorf et al., 2019). However, what exactly the advantages for information processing are remains unclear. For example, in the study by Kunzendorf et al. (2019), although a higher rate of key-presses, leading to the onset of images to-be-sampled, was observed during cardiac systole than diastole, the information sampled at systole was later not recalled better than that encoded at diastole. However, if agents truly try to maximize the likelihood of relevant signals being processed during optimal phases of the cardiac cycle, by presenting information in the 'sub-optimal' phases of bodily oscillations, we should be able to influence this information processing, potentially disturbing it. Thus, whether information sampling in specific phases of the cardiac cycle has benefits for information gathering and the effectiveness of the processing of this information, in a measurable way, remains unclear. The current study aimed to investigate in greater detail the relationship between cardiac timing of information gathering and information processing accuracy and efficiency. Specifically, our aim was to experimentally test the hypothesis that information sampling during cardiac diastole (when cardioceptive information is quiescent) is more optimal than during cardiac systole (when cardioceptive information is increased), thus, resulting in more efficient information processing (e.g., resulting in fewer errors). Additionally, as accurate perception of afferent cardiac signals can influence perception and behavior (Dunn et al., 2010; Garfinkel et al., 2013; Pfeifer et al., 2017), we also investigated the relationship between cardiac modulation of performance in the IST and individual differences in interoception, measured with a heartbeat tracking task. Based on past research on interoceptive influences on memory (Garfinkel et al., 2013; Pfeifer et al., 2017), we hypothesized that better interoceptive abilities may be related to more efficient information accumulation and/or increased decision accuracy when information is sampled during cardiac systole. To this aim, we employed the Information Sampling Task (IST) (Clark et al., 2006), a standard measure of 'reflection impulsivity' defined as a degree of information gathering before reaching a decision (Caswell et al., 2015; Herman et al., 2018). Based on past findings, we expected that information sampling during cardiac diastole, that is when participants tend to fixate (Galvez-Pol et al. 2020) and interoceptive signaling is quiescent, would lead to more efficient information processing. Conversely, we expected that sampling information during systole, when baroreceptors signaling is increased and people tend to produce saccades (Ohl et al. 2016; Galvez-Pol et al. 2020), i.e. visual information is diminished, would lead to less efficient information processing.

2 METHODS

2.1 PARTICIPANTS

139 (28 males; age 18-37, 20.54±2.77) participants recruited from the university community participated in the study. Inclusion criteria were: 18-40 years old; normal or corrected-to-normal vision; and no current diagnosis of any mental or neurological disorders. The sample size was based on previous cardiac cycle studies (e.g. Rae et al., 2018; Kunzendorf et al., 2019). We aimed for a net sample size minimum of 50 (per task version), expecting 10% participant exclusions. All participants were compensated for their time (£10 per hour).

The study procedures were approved by Royal Holloway Ethics Committee.

2.2 CARDIAC INFORMATION SAMPLING TASK (cIST)

Our task (cIST) was a modified version of the Information Sampling Task (Clark et al., 2006), which is a measure of information gathering before reaching a decision. This task does not depend on motor response accuracy, instead it assesses how much information one needs to reach a decision. On each trial, participants saw a 5x5 (=25) grid of greyed-out boxes

(Figure 1). The boxes uncovered themselves, one-by-one, to reveal one of two colors (red or blue). In our modified cIST, on half of the trials, the uncovering of the boxes was synchronized with cardiac systole (R-wave + 200ms, systole condition), on another half with cardiac diastole (R-wave + 500ms, diastole condition). Participants could wait as long as they wished before making a decision about which color prevailed. In other words, they could wait until all the boxes were revealed or could make a decision at any point before that (as long as at least one box was uncovered). The relation between the two colors (i.e. red and blue) in each condition varied between 12:13 and 8:17 in a trial. Thus, the proportion of the dominant color was between 52% and 68%. The proportion of colors was the same for all participants and cardiac conditions. Boxes remained open throughout the trial; hence, the task did not test working memory. At the point when the participant reached their decision, they chose the color presented by pressing a corresponding key at the bottom of the screen. Following the decision, the full matrix was revealed and a feedback message was presented on the screen: “Correct/Wrong! You win/loose XX points”. The participant’s running score was presented on the screen throughout the task.

Participants completed one practice trial followed by the experimental trials. Participants were randomly assigned to one of the two versions of the task:

- Fixed win (FW): Participants won 100 points if they made the right decision (regardless of how many boxes they had opened), otherwise they lost 100 points.
- Reward conflict (RC): For every box opened, participants lost 10 points from a bank of 250. If a participant chose correctly, they won the remaining points from the bank, otherwise they lost 100 points (e.g., responding correctly after opening 12 boxes would yield 130 points). The Reward Conflict condition introduced a conflict between

reinforcement and certainty (Clark et al. 2006), i.e. to maximize points the participant must tolerate high uncertainty, because sampling information until they have high certainty would win very few points.

The only difference between the Fixed Win and Reward Conflict versions was that the amount listed next to “Win”: The amount stayed fixed at 100 points in the Fixed Win version but decreased by 10 with each box opened in the Reward Conflict version. In each version, participants completed 10 trials for each cardiac condition (systole and diastole) in a shuffled order (20 experimental trials in total).

The length of the inter-trial interval was adjusted, based on the response time for each trial, to establish a minimum duration of 30s per trial. For example, if participant made a choice only after opening of five boxes (duration of approximately 5 seconds), he/she had to wait for an additional 25s for the next trial to begin. This feature is inserted to discourage prompt responses, which otherwise would lead to shorter trial duration and shorter duration of the task. During this inter-trial delay, the fixation cross was presented centrally.

The FW and RC versions are standard forms of the Information Sampling Task (Clark et al., 2006) and we used both of them in our adaptation of this classic reflection impulsivity measure. The Fixed Win version, in which the potential gain depends solely on accuracy, is simpler and contains no trade-offs. The optimal strategy is to sample all information necessary to be sure which color prevails. The Reward Conflict version, was originally designed to introduce a conflict between reinforcement and certainty: to maximize reinforcement the subject must tolerate high uncertainty, whereas sampling information until a point of high certainty would win very few points (Clark et al., 2006). Thus, in this version participants must trade off the small immediate costs incurred by information sampling against the larger potential loss resulting from an incorrect decision. It was originally stipulated (Clark et al., 2006) that inclusion of such reward conflict might further enhance impulsive responses in highly impulsive individuals. Therefore, inclusion of both versions, enables us to examine more fully the effects of cardiac timing and interoceptive abilities on information sampling both with and without trade-offs.

The dependent variables for the Fixed Win and Reward Conflict versions and cardiac conditions were: the average number of boxes opened (NoOpened); accuracy (the average number of correct answers given); and the score (number of points earned). The number of boxes opened before a decision is a good indicator of the amount of information that a subject opts to collect before making a decision. General task performance was indexed by accuracy in each condition and the total number of points scored.

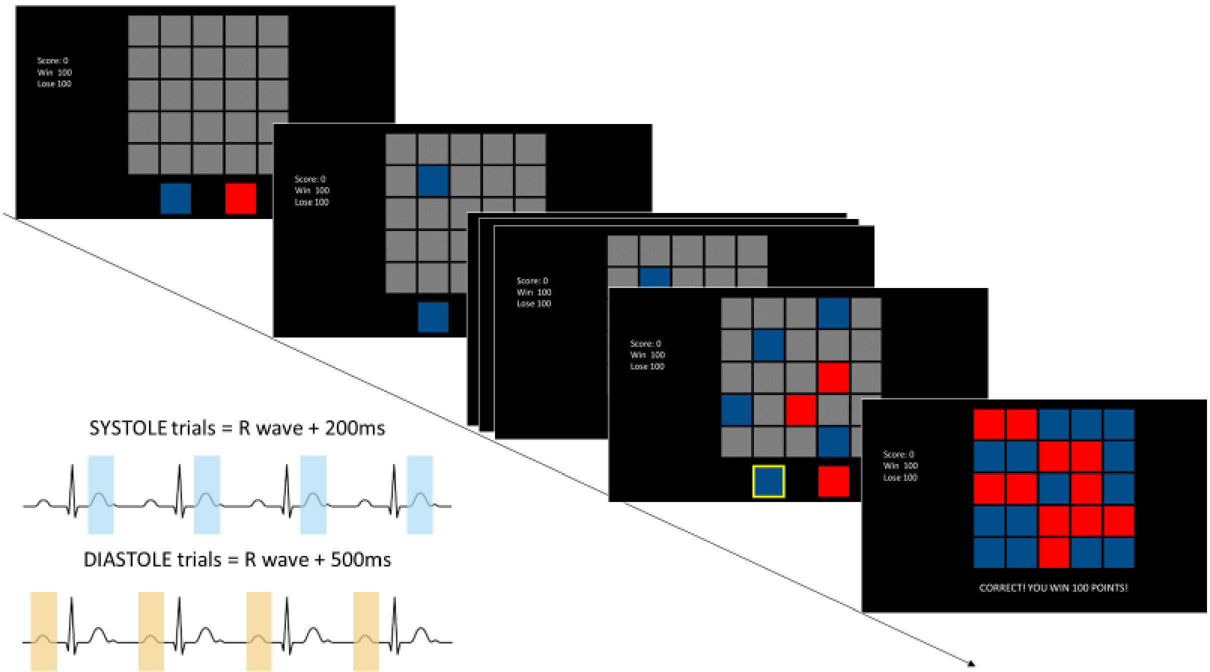

Figure 1 Cardiac Information Sampling Task. The figure shows an example of a single trial of the Fixed Win version. The uncovering of the boxes (of both colors) on each trial was either synchronized with cardiac systole or cardiac diastole.

2.3 HEARTBEAT TRACKING TASK

We assessed interoceptive accuracy with the heartbeat (HB) tracking task (Garfinkel et al., 2015; Schandry, 1981). Participants were instructed to silently count, without manually checking or guessing, heartbeats they feel in the body during variable periods. These ratings were compared against the actual number of HBs, as recorded objectively and noninvasively by ECG. There were six trials with variable time windows of 25, 30, 35, 40, 45, and 50 s, presented in a randomized order. At the end of each trial, participants immediately rated their confidence in their answer, using a continuous visual analogue scale ranging from total guess (0) to complete confidence (100). During the task, participants sat upright in a dimly lit room to avoid distractions and were not allowed to take their pulse throughout the experiment. Participants were explicitly instructed not to guess, to only report heartbeats that they could feel with confidence, and that reporting zero heartbeats, if none were detected, was acceptable. This was introduced to minimize the effects of some known confounds associated with the HB tracking task (Desmedt et al., 2020). The task lasted approximately 10 minutes.

For each trial, an interoceptive accuracy (IAcc) score was calculated as [1 − (|nbeats real − nbeats reported|)/nbeats real]. Resulting values were averaged over the six trials, yielding an overall accuracy score for each participant.

Interoceptive awareness (or insight) refers to the metacognitive measure of one's performance, that is, the extent to which confidence tracks accuracy on the task (Garfinkel et al., 2015; Khalsa et al., 2018). Awareness score was assessed by calculating the within-participant Pearson correlation between confidence and accuracy scores.

2.4 ECG RECORDING

To record participants' ECG, two electrodes were attached under the left and right clavicle and one on the left lower back, within the ribcage frame. The ECG signal was recorded using a Powerlab 8/35 box (Bio Amp 132) and LabChart 8 software (https://www.adinstruments.com). The sampling rate was 1 kHz and a hardware band-pass filter between 0.3 and 1,000 Hz was applied, as well as a 50 Hz notch filter to reduce electrical noise. During the cIST, heartbeats were detected online with the LabChart's fast response output function. This is a hardware-based function that identifies the R-wave, with minimal delays (~1ms), each time the ECG amplitude exceeds an individually tailored threshold.

The ECG recording for cIST task and HB tracking task was visually inspected for artefacts. For the cIST, we cross-checked whether the markers of boxes-opening indeed occurred in the intended phases of the cardiac cycle (systole/diastole, respectively) using T-wave end as a marker of interest. We adopted a conservative approach, with trials, in which this procedure did not occur as intended, removed from the analysis. In cases when more that 10% of trials had to be removed, the participants data were removed from the analysis entirely.

2.5 DATA ANALYSIS

The performance in the cIST was analyzed in JASP v0.13.1.0 (JASP Team, 2020) (https://jasp-stats.org/). The .jasp file, containing the data, analysis options, and output, is available at (https://osf.io/purkj/?view_only=5e04aaba35f24a5287a98ae1ea86ddbc).

Firstly, to compare behavior between systole and diastole trials on both versions of the cIST (Fixed Win and Reward Conflict), we used two-tailed repeated measures *t*-tests (in case of violation of normality, we employed Wilcoxon signed-rank test instead), for: (1) NoOpened boxes; (2) accuracy; and (3) score (number of points earned). Secondly, to investigate the role of interoception, we used the Linear Mixed Models (LMM) approach. We modelled a linear relationship between dependent variables (performance in the task: accuracy, NoOpened, score) and cardiac phase conditions, cIST version (Fixed Win and Reward Conflict), as well as interoceptive abilities (accuracy and awareness), including their interaction terms. Participants were treated as a random factor. The random-effects structure was determined automatically in JASP as the maximal random effects structure justified by the design (Barr et al., 2013).

3 RESULTS

3.1 EXCLUSIONS AND MISSING DATA

139 volunteers participated in the study. Inspection of the ECG signal revealed that for 8 of them, the presentation of stimuli was not always time-locked to the intended cardiac phase (due to excessive motion-induced noise or unusually low or high inter-beats-intervals). Therefore, these individuals were excluded from the analysis entirely and the final sample consisted of 131 participants (27 men). 78 individuals remained in the Fixed Win version, while 53 the Reward Conflict version of the cIST. Data from the HB tracking task was missing for six individuals.

3.2 PERFORMANCE IN THE cIST

Table 1 and Figure 2 present the descriptive statistics and comparison of performance between cardiac conditions in the cIST. Comparisons between the cardiac conditions (systole and diastole) showed no significant differences for any of the three task variables in either version of the task. This suggests that the timing of passive information sampling (cardiac systole or diastole) does not module how much information individuals gather before reaching a decision, nor how effectively they use this information for deciding. Also see Supplementary Materials for additional Bayesian analysis.

Cronbach‘s α (Cronbach, 1951) for interoceptive accuracy (α = 0.95, 95% CI [0.93, 0.97]) and confidence ratings (α = 0.93, 95% CI [0.91, 0.95]) showed that interoceptive measures reached satisfactory internal consistency. The performance in the HB tracking task is summarized in Table 2.

Regarding LMM analyses that link individual differences in interoception to performance in the task, interoceptive awareness was related to higher decision accuracy, overall (main effect of interoceptive awareness). This suggests that greater metacognitive awareness of one’s own cardiac activity might be related to more efficient integration of information generally. Moreover, interoceptive awareness interacted with the cardiac condition and task version, such that increased cardiac awareness was related to higher accuracy of decision when the information was sampled at cardiac systole rather than diastole of the Reward Conflict, but not in the Fixed Win, version of the cIST (3-way interaction; see Table 3 and Figure 3A). Regarding the measure of information gathering, participants opened more boxes in the Fixed Win compared to Rewards conflict version (Table 3), proving that participants understood the instructions well. The 3-way interaction (cardiac condition x task version x interoceptive awareness) did not reach statistical significance but was at trend level (see Table 3 and Figure 3B). There were no significant results for the score in the task nor for interoceptive accuracy (see Table 3 for details of the Fixed effects estimates and Table 4 for random effects).

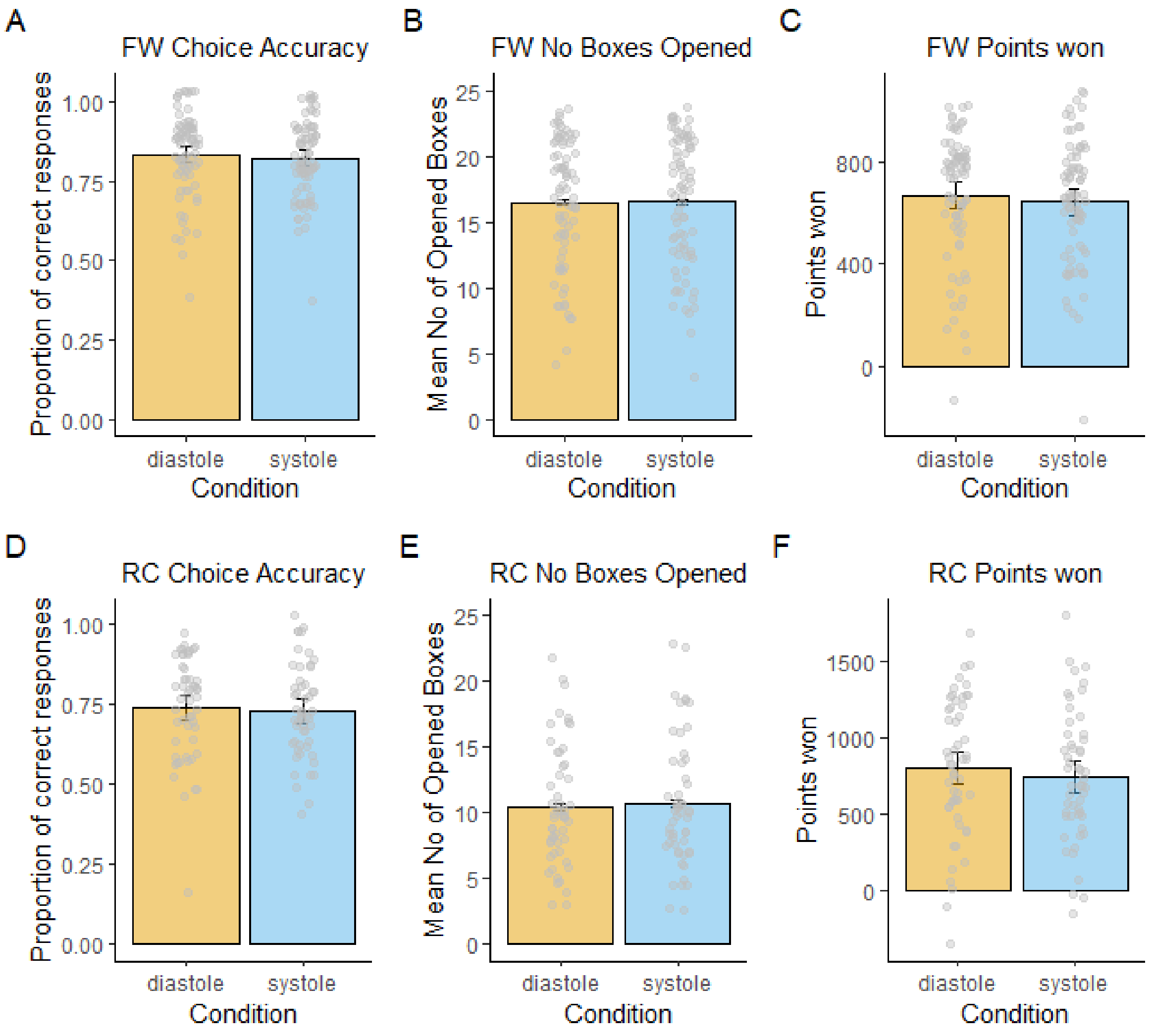

Figure 2 Performance in the cIST. The top row shows the data from the Fixed Win (FW) version and the bottom row from the Reward Conflict (RC) version. Error bars represent 95% confidence intervals.

Table 1 Descriptive statistics and comparison of task variables between cardiac conditions. NoOpened – number of boxed opened

Task Version	**Variable**	**Mean**	**SD**	**Mean**	**SD**	**Test**	**Statistic**	**df**	***p***	**Effect Size**
		Systole		**Diastole**						
Fixed Win	NoOpened	16.54	4.93	16.49	4.89	T-Test	0.26	77	0.796	0.029
	Accuracy	0.82	0.12	0.83	0.13	Wilcoxon	900		0.457	-0.107
	Score	643.59	242.6	666.67	257.19	Wilcoxon	913		0.508	-0.094
Reward Conflict	NoOpened	10.69	4.83	10.47	4.55	T-Test	1.21	52	0.233	0.166
	Accuracy	0.73	0.15	0.74	0.15	T-Test	-0.4	52	0.688	-0.055
	Score	740.38	418	801.13	448.02	T-Test	-0.83	52	0.409	-0.114

Note. For the Student t-test, effect size is given by Cohen's d. For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

Table 2 Performance in the HB tracking task.

	Iacc	**Meta**	**Confidence**
Mean	0.65	0.06	49.37
Std. Deviation	0.20	0.52	17.98
Minimum	0.02	-0.92	10.33
Maximum	0.99	0.97	94.17

Table 3 Estimated models fixed effects to explain performance on the cIST (accuracy, number of boxes opened, total score) using predictors of cardiac cycle condition, task version (FW and RC), interoceptive abilities (interoceptive accuracy and awareness) and their interaction. Iacc – interoceptive accuracy; NoOpened – number of boxes opened

Fixed Effects Estimates

Term	**Estimate**	**SE**	**df**	**t**	**p**
Accuracy					
Intercept	0.76	0.04	119	21.63	**< .001**
Iacc	0.04	0.05	119	0.81	.417
cardiac condition	0.03	0.03	119	0.91	.367
version	0.07	0.04	119	1.94	.055
Awareness	0.05	0.02	119	2.45	**.016**
Iacc * cardiac condition	-0.04	0.04	119	-0.83	.406
Iacc * version	-0.05	0.05	119	-1.02	.309
cardiac condition * version	-0.01	0.03	119	-0.20	.840
cardiac condition * Awareness	0.02	0.02	119	1.39	.168
version * Awareness	-0.02	0.02	119	-0.97	.336
Iacc * cardiac condition * version	0.00	0.04	119	0.01	.996
cardiac condition * version * Awareness	-0.04	0.02	119	-2.52	**.013**
NoOpened					
Intercept	11.77	1.68	119	6.99	**< .001**
Iacc	2.92	2.42	119	1.21	.229
cardiac condition	0.20	0.26	119	0.79	.434
version	3.41	1.68	119	2.03	**.045**
Awareness	1.52	0.94	119	1.62	.108
Iacc * cardiac condition	-0.16	0.37	119	-0.42	.676
Iacc * version	-1.09	2.42	119	-0.45	.653
cardiac condition * version	0.11	0.26	119	0.41	.682
cardiac condition * Awareness	0.21	0.14	119	1.46	.147

version * Awareness	-0.68	0.94	119	-0.73	.470
Iacc * cardiac condition * version	-0.29	0.37	119	-0.79	.433
cardiac condition * version * Awareness	-0.27	0.14	119	-1.85	.067
Score					
Intercept	738.72	94.09	119	7.85	**< .001**
cardiac condition	89.61	72.15	119	1.24	.217
version	-86.42	94.09	119	-0.92	.360
Iacc	-43.70	134.99	119	-0.32	.747
Awareness	27.86	52.41	119	0.53	.596
cardiac condition * version	-46.18	72.15	119	-0.64	.523
cardiac condition * Iacc	-143.63	103.51	119	-1.39	.168
version * Iacc	22.80	134.99	119	0.17	.866
cardiac condition * Awareness	18.26	40.19	119	0.45	.650
version * Awareness	30.16	52.41	119	0.58	.566
cardiac condition * version * Iacc	70.26	103.51	119	0.68	.499
cardiac condition * version * Awareness	-57.08	40.19	119	-1.42	.158

Note. The intercept corresponds to the (unweighted) grand mean; for each factor with k levels, k - 1 parameters are estimated. Consequently, the estimates cannot be directly mapped to factor levels.

Table 4 Random effects

PID: Variance Estimates

Term		**Std. Deviation**	**Variance**
Accuracy			
	Intercept	0.05	0.00
	Residual	0.12	0.02
NoOpened			
	Intercept	4.74	22.45
	Residual	1.04	1.08
Score			
	Intercept	172.05	29599.62
	Residual	290.68	84497.14

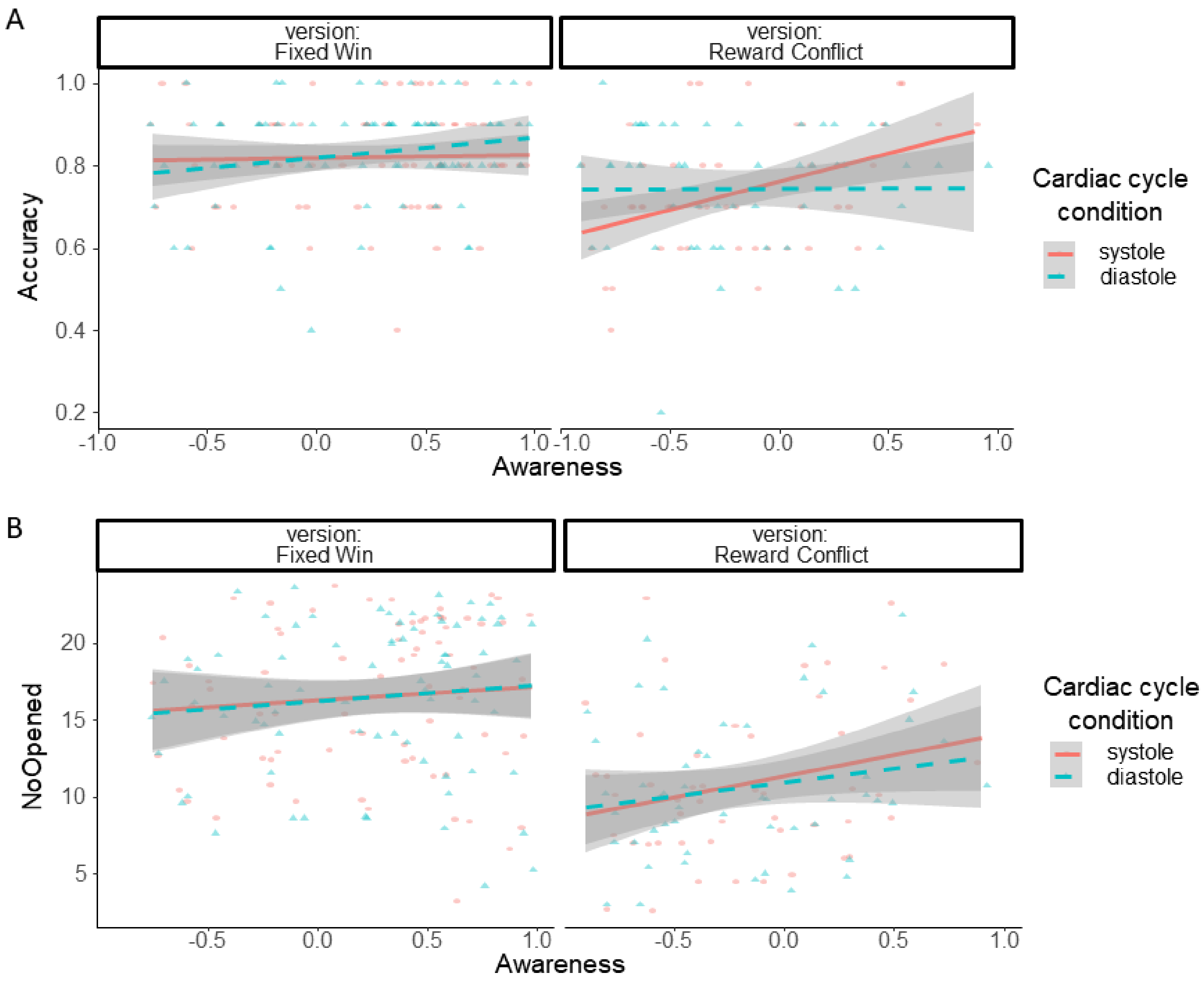

Figure 3 The relationship between interoceptive awareness and the accuracy (A) as well as the number of boxes opened (B) by the cIST version.

4 DISCUSSION

Given the recent evidence for the role of cardiac afferent signaling in spontaneous information gathering, we aimed to examine the effects of information delivery in synchrony with cardiac systole and diastole on measures of information gathering and effective processing of the data in forming decisions. To this aim, we constructed a modified IST (which we call the cIST), as a measure of reflection impulsivity. Our results indicate that new information presentation at cardiac systole or diastole does not modulate information processing in a manner that would produce clear behavioral differences. However, individual differences in interoceptive awareness might interact with the cardiac cycle, in information gathering.

Previous studies on active information sampling reported that both oculomotor responses and voluntary key-presses (to sample images in a memory encoding task) are coupled to the cardiac cycle (Galvez-Pol et al., 2020; Kunzendorf et al., 2019; Ohl et al., 2016). However, the significance of this type of synchronicity for information processing is unclear. For example, even though voluntary keypresses were more likely to occur during a systolic than a diastolic phase, information encoded at systole was not better recalled than that encoded at diastole (Kunzendorf et al., 2019). Our findings also indicate that neither the level of information gathering (number of boxes opened) nor the effectiveness of its processing (as reflected in accuracy or points earned) was affected by the presentation of information either during cardiac systole (when baroreceptor firing is maximal) or during diastole (when baroreceptors firing is minimal). Thus, there was no effect of the cardiac cycle on performance in either our Fixed Win version of cIST, in which winnings were only dependent on accuracy, nor the Reward Conflict version, in which the information gathering was costly. Nevertheless, LMM analysis that considered the relationship between cardiac afferent signaling, interoceptive abilities and cardiac impact on the cIST performance, revealed that higher interoceptive awareness was related to increased decision accuracy in the Reward Conflict (but not the Fixed Win) version, when the information was presented at cardiac systole compared to diastole. Thus, the inferential processes involved in information gathering and decision-making under conditions of uncertainty are indeed influenced by the bottom-up visceral state (presence and absence of baroreceptor activation) and interoceptive awareness of these states. Specifically, systole increases the search for information, and thus accuracy, in those with greater conscious awareness of their cardiac interoceptive signals. This suggests that, in the context of informational uncertainty, individuals with greater metacognitive awareness of their own cardiac activity might show behavioral benefits (increased decision accuracy due to searching for more information) in uncertain situations, when they sample new information during cardiac systole. Importantly, we observed such a relationship only in the Reward Conflict version, which introduces a conflict between reinforcement and certainty: To maximize reinforcement the participant must tolerate high uncertainty, whereas sampling information until a point of high certainty results in small gains (Clark et al., 2006). Thus, the benefit of more reflective decisions in individuals who are more cardiac-aware is present only in circumstances when a trade-off occurs between information gathering and potential reward.

As IST is typically used as a measure of reflection impulsivity (Caswell et al., 2015; Clark et al., 2006; Herman et al., 2018), our results are also important for informing our understanding of the relationship between interoception and impulsivity. Specifically, information gathering in the state of increased (systole) or decreased (diastole) interoceptive signaling does not affect reflection impulsivity in all individuals equally. Increased cardiac awareness is linked to decreased reflection impulsivity (as shown by a higher accuracy and slightly greater degree of information sampling), particularly when information was sequentially sampled at cardiac systole. This is in line with previous reports linking better interoceptive abilities with lower levels of non-planning impulsivity (measured with self-report Barratt Impulsiveness Scale) (Herman et al., 2019). Together, these results suggest that greater awareness of bodily sensations may be linked to less impulsive decisions.

These results support the notion that the accurate perception and awareness of afferent cardiac signals can influence perception and cognition (Dunn et al., 2010; Garfinkel et al., 2013; Pfeifer et al., 2017). Historically, baroreceptor activity was generally considered to be inhibitory (Lacey and Lacey, 1978, 1970). While this has been shown not always to be the case (Garfinkel et al., 2014; Park et al., 2014; Pramme et al., 2016), this view generally implies that the inhibitory effect of cardiac timing ought to be magnified in individuals with higher interoceptive awareness. Our results instead suggest a protective, rather than attenuating, effect on the processing of information delivered at systole in individuals with higher interoceptive awareness. We found that interoceptive awareness was associated with increased accuracy at systole than at diastole in the RC version cIST, i.e. when information gathering was costly. This is in line with past findings demonstrating that better interoceptive ability enhances the retrieval of confidently encoded words during cardiac systole (Garfinkel et al., 2013) as well as associative learning for fearful images reinforced at systole (Pfeifer et al., 2017). Conceivably, (healthy) individuals with enhanced interoceptive abilities can generate a more accurate predictive model of their internal state (Ainley et al., 2016; Seth et al., 2012), whereby the central effects of afferent baroreceptor signaling are attenuated early on by accurate prediction and therefore interact less with stimulus processing (Garfinkel et al., 2013).

Some methodological considerations deserve comment. Previous studies on information sampling and afferent cardiac signaling (Galvez-Pol et al., 2020; Kunzendorf et al., 2019; Ohl et al., 2016) assessed ‘active’ information sampling, by studying participants’ freely-generated oculomotor responses or their reactions indicating readiness to sample more information. In those paradigms, the timing of the self-paced responses was mapped onto the cardiac cycle. In the present study, to assess what the effects of cardiac afferent signaling on information processing might be, we synchronized the delivery of sequential information with the cardiac cycle. Thus, our paradigm can be referred to as ‘passive’ information sampling. Perhaps the element of volition could affect the relationship between information sampling onset and the cognitive/behavioral effects. Additionally, although these past investigations suggested that self-paced responses and microsaccades were more likely to occur within the cardiac systole than diastole at the group level, there were also marked individual differences in tendencies to generate these responses. There may be certain individual differences in the ‘optimal’ window of processing within the cardiac cycle. In the present study, we delivered stimuli at fixed delays (R-wave + 200ms for systole and 500ms for diastole trials) and did not investigate a wider range of delays.

5 CONCLUSIONS

We examined the effects of information delivery in synchrony with the cardiac cycle on measures of information gathering and effective processing of data in forming decisions. Using a modified IST, we observed that information presentation either on cardiac systole or diastole did not modulate the information processing in a manner that would produce clear behavioral changes. Instead, we found some evidence suggesting that higher interoceptive awareness increased information gathering and accuracy in the costly version (Reward Conflict) of the cIST, particularly when new information was sequentially presented at systole (i.e. on every consecutive systole). Overall, our results add to a growing body of research on body-brain interactions and imply that our internal bodily rhythms (i.e., heartbeats) and our awareness of them can interact with the way we process the noisy world around us.

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Supplementary results

The impact of cardiac afferent signaling and interoceptive abilities on passive information sampling

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We compared the performance between systole and diastole conditions in JASP v0.13.1.0 (JASP Team, 2020) using both frequentist tests and Bayesian equivalents. This has the effect of extending insights to guide interpretation of significance (*p* values) according to how likely the alternative hypothesis is versus the null (BF10). For the Bayesian analyses, in the absence of pilot data on relationships amongst performance variables in the IST and cardiac cycle effects, we used the default JASP priors, which assume a medium effect size on a Cauchy distribution of 0.707. The .jasp file, containing the data, analysis options, and output, is available at (https://osf.io/purkj/?view_only=5e04aaba35f24a5287a98ae1ea86ddbc). This also contains graphical robustness checks that examine the evidence for H1 and H0 under different prior widths, for *t*-tests. We interpret Bayes Factors (BF10) according to the heuristic of: 1–3 indicating anecdotal evidence in favor of H1; 3–10 moderate evidence; and >10 strong evidence in favor of H1; BF10 of 0.33–1 indicating anecdotal evidence for H0; 0.1–0.33 moderate evidence; and < 0.1 strong evidence in favor of H0 (Lee and Wagenmakers, 2013).

STable 1 presents the descriptive statistics and comparison of performance between cardiac conditions in the cIST. Comparisons between the cardiac conditions (systole and diastole) showed no significant differences for any of the three task variables in either version of the task, with anecdotal to moderate (for Fixed Win) and moderate (for Reward Conflict) evidence for H0 according to BF10. Thus, both analyses suggest that the timing of passive information sampling (cardiac systole or diastole) does not module how much information individuals gather before reaching a decision, nor how effectively they use this information for deciding.

STable 1 Descriptive statistics and comparison of task variables between cardiac conditions. NoOpened – number of boxed opened

Task Version	**Variable**	**Mean**	**SD**	**Mean**	**SD**	**Test**	**Statistic**	**df**	***p***	**Effect Size**	**BF_{10}**
		Systole		**Diastole**							
Fixed Win	NoOpened	16.54	4.93	16.49	4.89	T-Test	0.26	77	0.796	0.029	0.129
	Accuracy	0.82	0.12	0.83	0.13	Wilcoxon	900		0.457	-0.107	0.555
	Score	643.59	242.6	666.67	257.19	Wilcoxon	913		0.508	-0.094	0.567
Reward Conflict	NoOpened	10.69	4.83	10.47	4.55	T-Test	1.21	52	0.233	0.166	0.297
	Accuracy	0.73	0.15	0.74	0.15	T-Test	-0.4	52	0.688	-0.055	0.162
	Score	740.38	418	801.13	448.02	T-Test	-0.83	52	0.409	-0.114	0.208

Note. For the Student t-test, effect size is given by Cohen's d. For the Wilcoxon test, effect size is given by the matched rank biserial correlation.

For completeness, we additionally completed a Linear Mixed Models analysis also including confidence judgements, alongside interoceptive accuracy and awareness scores, as a fixed effect. The model for the task accuracy did not converge. For the number of boxes opened, the main effect of task version was approaching significance (*p* = .071, see STable 2 for details). For the score analysis, the three-way interaction between cardiac condition, task version and interoceptive confidence was significant. The interaction, plotted in SFigure 1, suggests that individuals reporting higher confidence in the HB tracking task, tended to have lower scores in the Reward Conflict version of the task, regardless of the cardiac condition. For the Fixed Win version, those with higher confidence ratings tended to show lower scores in the cardiac systole condition, but tended to present higher scores in the cardiac diastole condition. Since we did not have any hypothesis regarding the effect of interoceptive confidence in the cIST, we refrain from interpreting these results.

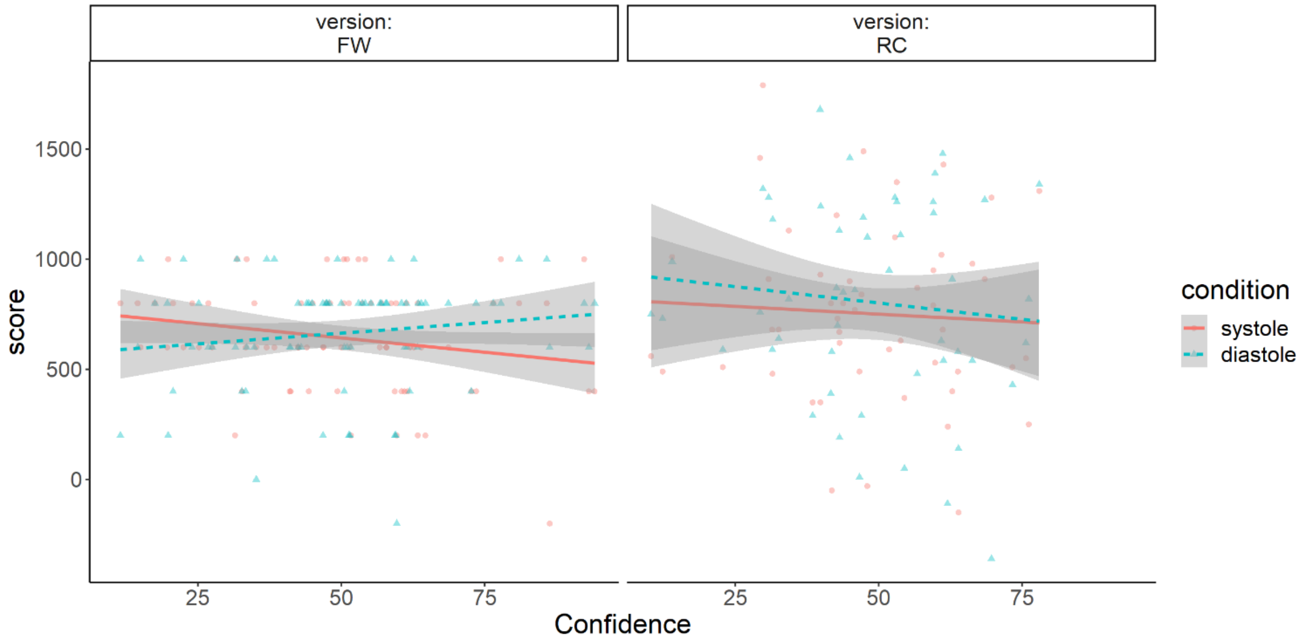
STable 2 Estimated models fixed effects to explain performance on the cIST (number of boxes opened and total score, the model for accuracy did not converge and is not presented) using predictors of cardiac cycle condition, task version (FW and RC), interoceptive dimensions (interoceptive accuracy, confidence and awareness) and their interaction. Iacc – interoceptive accuracy; NoOpened – number of boxes opened

Fixed Effects Estimates

Term	**Estimate**	**SE**	**df**	**t**	**p**
NoOpened					
Intercept	11.40	1.91	117	5.96	**< .001**
cardiac condition	0.21	0.29	117	0.71	.480
version	3.48	1.91	117	1.82	.071
Iacc	2.62	2.53	117	1.03	.304
Confidence	0.01	0.03	117	0.44	.664
Awareness	1.60	0.97	117	1.65	.101
cardiac condition * version	-0.03	0.29	117	-0.12	.908
cardiac condition * Iacc	-0.11	0.39	117	-0.27	.786
version * Iacc	-0.91	2.53	117	-0.36	.719
cardiac condition * Confidence	0.00	0.00	117	-0.25	.802
version * Confidence	0.00	0.03	117	-0.17	.869
cardiac condition * Awareness	0.22	0.15	117	1.47	.145
version * Awareness	-0.68	0.97	117	-0.70	.486
cardiac condition * version * Iacc	-0.40	0.39	117	-1.03	.306
cardiac condition * version * Confidence	0.00	0.00	117	1.04	.303
cardiac condition * version * Awareness	-0.24	0.15	117	-1.60	.114
Score					
Intercept	767.13	106.56	117	7.20	**< .001**
Iacc	-11.65	141.28	117	-0.08	.934
version	-118.59	106.56	117	-1.11	.268
cardiac condition	119.96	80.18	117	1.50	.137
Awareness	23.28	53.87	117	0.43	.666
Confidence	-1.07	1.50	117	-0.71	.478
Iacc * version	-10.83	141.28	117	-0.08	.939
Iacc * cardiac condition	-148.08	106.30	117	-1.39	.166
version * cardiac condition	35.64	80.18	117	0.45	.657
version * Awareness	35.77	53.87	117	0.66	.508
cardiac condition * Awareness	7.26	40.54	117	0.18	.858
version * Confidence	1.16	1.50	117	0.77	.442
cardiac condition * Confidence	-0.39	1.13	117	-0.34	.732
Iacc * version * cardiac condition	121.62	106.30	117	1.14	.255
version * cardiac condition * Awareness	-76.74	40.54	117	-1.89	.061

version * cardiac condition * Confidence	-2.28	1.13	117	-2.02	**.046**

Note. The intercept corresponds to the (unweighted) grand mean; for each factor with k levels, k - 1 parameters are estimated. Consequently, the estimates cannot be directly mapped to factor levels.



SFigure 1The relationship between interoceptive confidence and the score achieved in the task by the cIST version