Does the cardiac cycle affect decision-making under uncertainty?

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Abstract

This study investigates whether decision-making under uncertainty is influenced by one's cardiac cycle. To test this, we examine the influence of the cardiac cycle on an individual's decision-making process in a gambling experiment. Participants are asked to choose one option with a sure payout or uncertain options with varying degrees of winning probability, ambiguity, and monetary amounts. To manipulate the cardiac cycle, the presentation of the options is timed to coincide with either the individual's cardiac systole or diastole. The results show that for most participants, the risk aversion score is lower in the systole trial than that in the diastole trial. The model-based exploratory analysis reveals that the higher propensity to take risks in the systole trial compared with that in the diastole trial could be captured better by the change in the gambling bias for/against the utility of the risky options, rather than by a change in risk attitude. The results provide evidence that the natural fluctuation of cardiac afferent signals can affect one's decision-making under uncertainty.

Introduction

In many situations, people are required to choose between options with uncertain outcomes. Imagine situations where you have to decide whether to buy insurance, invest in a new stock, or to eat the cake. These are examples of decision-making under uncertainty, which has been an active topic of interdisciplinary research. Over the past 20 years, research in psychology, economics, and neuroscience has provided evidence that affective processes are involved in one's decision-making under uncertainty (e.g., George & Dane, 2016; Loewenstein, O'Donoghue, & Bhatia, 2015; Roberts & Hutcherson, 2019). For instance, studies have shown that affective responses are associated with risk-taking behaviors in a decision context (e.g., Bechara et al., 1997; FeldmanHall et al., 2016; Herman et al., 2021), and the experimental modulation of the affective state can change decision-making under uncertainty (e.g., Lerner & Keltner, 2001; Shukla et al., 2019). Based on extant empirical findings, it is generally accepted that the affective processes play a key role in decision-making under uncertainty.

In addition, recent theoretical and practical research has proposed that affective processes are influenced by one's internal physiological state. Not only the brain regulates the internal physiological state of the one's body, but the information concerning the internal physiological state of the one's body is transmitted to the brain, which plays an essential role in the emergence of the affect (e.g., Tsakiris & Critchley, 2016) and one's behavioral and physiological adaptation to environmental challenges (for a review, see Critchley & Harrison, 2013). Although many suggest that the processing of one's internal physiological state in the brain (i.e., interoception) occurs across all major biological systems, including the cardiovascular, gastrointestinal, immune, and autonomic systems (for a comprehensive review, see Khalsa et al., 2018), the most demonstrative example is cardiac afferent signaling that occurs between one's body and brain, influencing mental, emotional, and physical processing. The strength and timing of arterial pressure at each heartbeat are encoded by the phasic discharge of arterial baroreceptors during cardiac systole, the contracting of the heart, which is transmitted to the brainstem and used for the baroreflex control of blood pressure. Importantly, the cardiac afferent signal from the arterial

baroreceptors travels to the brain areas involved in affective processes (for a review, see Garfinkel & Critchley, 2016). The pioneering work by Garfinkel et al. (2014) demonstrated that the detection of threat-related stimuli (i.e., a fearful face) was magnified when the stimuli were presented during cardiac systole (i.e., when cardiac afferent signals were active), rather than cardiac diastole, the relaxation of the contraction (i.e., when cardiac afferent signals were quiescent). Their results indicate that the cardiac cycle has an impact on the processing of affective stimuli, possibly via the modulation of neural activity involved in affective processes. Additionally, previous studies have reported that the cardiac cycle influences a variety of affective processes, including the perception of pain (e.g., Edwards et al., 2001, 2008), attention to threat-related stimuli (e.g., Azevedo et al., 2017, 2018), memory (e.g., Garfinkel et al., 2013), and reward feedback processing (Kimura, 2019). Extant results suggest that the natural fluctuation of the cardiac afferent signals during cardiac systole causes moment-to-moment fluctuations in affective processing.

While the effect of the cardiac cycle on the processing of affective stimuli has been investigated, no previous study has examined this in the context of decision-making under uncertainty. Considering that the affective processes play a prominent role in decision-making under uncertainty and are influenced by the natural fluctuation of cardiac afferent signals, the cardiac cycle may influence the affective processing of decision options and, hence, subsequent decisions. This possibility is supported by previous findings that cardiac afferent signals modulate neural activity in the brain areas involved in affective processing, which overlap with those involved in decision-making under uncertainty (e.g., Levy et al., 2010; Weller et al., 2009).

To test this, our study investigated whether the cardiac cycle influenced decision-making under uncertainty. Accordingly, we examined the effects of the cardiac cycle on the decision-making in a widely used gambling task (e.g., Herman et al., 2021; Tymula et al., 2012). In our gambling task, participants could choose the safe option with a sure payout of 200 Japanese yen (about US$2), or the gamble (i.e., uncertain options) where each option had varying degrees of risk, ambiguity, and monetary value. The task distinguished between two forms of uncertainty, namely, risk and ambiguity, depending on whether the probability of the outcomes were known or unknown. Since these two forms of uncertainty are believed to be distinct phenomena (Becker & Brownson, 1964; Camerer & Weber, 1992; Ellsberg, 1961), it is possible that the cardiac cycle would affect the decisions surrounding them differently. Based on previous studies examining the effect of the cardiac cycle on affective processes (e.g., Azevedo et al., 2017, 2018; Garfinkel et al., 2013), in our experiment, we timed the onset of the presentation of the decision options to coincide with either cardiac systole or diastole and recorded the participant's decisions. No feedback was provided to investigate decision-making independent of the learning processes. We assessed each participant's choice of uncertain options and estimated their risk and ambiguity aversion scores (e.g., Fujino et al, 2017; Pushkarskaya et al., 2015). In addition, we used model-based analysis to examine the effects of the cardiac cycle on the computational processes underlying participant decision-making under uncertainty. If the cardiac cycle affected decision-making under uncertainty, then participant behavior (i.e., the choice of the uncertain options and risk and ambiguity

aversion) would differ in the systole and diastole trials. In contrast, if the cardiac cycle had no influence on decision-making under uncertainty, then the behavior would not differ in the trials.

Methods

Participants. Thirty-five adults participated in our experiment (11 females, 24 males, age range = 20-42 years, mean = 24.3 years). All participants were right-handed, had normal or corrected-to-normal vision, and no history of neurological, cardiovascular, or mental disorders. Written informed consent was obtained according to the protocols approved by the Safety and Ethics Committee of the National Institute of Advanced Industrial Science and Technology (AIST) in Japan. The research was conducted in accordance with ethics regulations. The final sample size was selected based on previous cardiac cycle studies (e.g., Azevedo et al., 2017). Two female participants were excluded due to poor performance in their decision quality scores, indicating that they did not understand the structure of the experimental task (see Supplementary materials). Thus, the final data set comprised 33 participants.

ECG Recording. The electrocardiogram (ECG) was recorded using an MP150 Biopac System (ECG100C). The ECG was recorded with Ag/AgCl electrodes placed on the right collarbone and left rib. The sampling rate was 2,000 Hz, and a hardware band-pass filter between .3 and 1,000 Hz was applied. The signal was recorded using AcqKnowledge software (Biopac Systems).

To synchronize the onset of the presentation of the decision options, heartbeats were detected online using a threshold-based R-peak detection method in the AcqKnowledge software. Using the timing of each heartbeat, the software set the onset of the presentation of the decision options to coincide with the systolic (~300 ms after the R-peak) or diastolic (~550 ms after the R-peak) phases of the cardiac cycle (Azevedo et al., 2017, 2018; Gray et al., 2009; Garfinkel et al., 2014).

Setup and experimental task. Individuals were asked to participate in a gambling task where they could choose the safe option with a sure payout of 200 Japanese yen (about US$2), or a gamble where each gambling option had varying degrees of risk, ambiguity, and monetary value. The software (Neurobehavioral Systems installed on a Lenovo, ThinkPad W540 computer laptop) presented the stimuli and recorded the participant's responses. All visual stimuli were presented on a 22-inch LCD monitor (Dell E2210).

Figure 1A shows examples of the stimuli under the different risk and ambiguity conditions. In each trial, participants were required to choose between two monetary options. One was always a certain payoff of 200 Japanese yen, and the other was a lottery that varied systematically from trial to trial in terms of the monetary amount, and either the winning probability or ambiguity level. The lottery was shown in the form of a bag containing 24 red and blue chips. In the risk condition, the entire bag was visible, and five winning probabilities (12.5%, 25%, 37.5%, 50%, and 75%) were used. In the ambiguity condition, the center of the bag was hidden by a black square, and three sizes of the black square (25%, 50%, or 75% of the bag) were used. Note that increasing the size of the black square reduced the information about the content in the bag, raising the level of ambiguity. Five monetary amounts (200, 350, 850, 2,200, and 5,200

Japanese yen) were used for each risk and ambiguity level. Each unique lottery was presented four times, counterbalancing the winning color and the positions of the lottery on the monitor, yielding a total of 360 trials [five monetary amounts × (five winning probabilities + three ambiguity levels) × four repeated times × two cardiac cycles]. The trials were presented in a pseudo-randomized order.

Figure 1B illustrates the flow of the gambling trial. Each trial began with a fixation display, with a white cross presented in the center of a gray background. The duration of the fixation display was adjusted to synchronize with the onset of the presentation of the decision options. The fixation display lasted 1,000 ms on average and remained the same in all the cardiac cycle trials. The fixation display was followed by the display of the choices of a fixed monetary amount and an image of a lottery presented on either side of the fixation cross. The positions of the fixed monetary amount and the image of the lottery (left or right) were counterbalanced. Participants were required to choose between the fixed monetary amount and the lottery image by pressing the left button (i.e., “Z” button on a keyboard) with the right index finger or the right button (“X” button on a keyboard) with the right middle finger. The choices were displayed until the participant pressed a button. If the participant did not press a button within 5,000 ms, the word “ERROR” appeared in the center of the monitor, and that trial was skipped. After the participant’s response, an asterisk was displayed above the chosen option for 1,000 ms. The inter-trial interval was 2,000-3,000 msec.

The onset of the display of the monetary options was synchronized to coincide with either the participant's cardiac systole or diastole. To confirm the validity of the manipulation, we calculated the onset time of the presentation of the monetary options relative to the R-wave peak in each trial. Figure 1 illustrates the histogram detailing the presentation of the decision options in relation to the cardiac cycle. The precision of the onset timing in the cardiac cycle, relative to the R-wave peak, meant that >99% of the trials were within 200 ms of the manipulated timing in both the systole (red) and diastole (blue) trials. Specifically, the mean time from the R-wave peak for the systole trials was 271 ms (SD = 13 ms), whereas the mean time from the R-wave peak for the diastole trials was 541 ms (SD = 4 ms). The precision timing within the cardiac cycle was comparable to that reported in previous studies (e.g., Rae et al., 2018).

Procedure. The participants were tested individually in the laboratory. Upon arrival, the participants were informed about the experiment, and were then asked to provide informed consent. After their height and weight were measured, the participants were seated comfortably in front of the display, and the electrodes for the ECG were attached. The participants were then asked to relax for five minutes to become used to the laboratory environment and the electrodes. After the participants received instructions regarding the experiment, they were asked to complete two tests to assess their understanding of the probabilities and the experimental task (see Supplementary materials). Only if the participants answered all test questions correctly did they proceed to the experimental task. The participants were given a practice block of 10 trials to familiarize themselves with the task. They then performed the task, which consisted of 9 blocks of 40 trials (360 total trials), with a rest between blocks. The participants were instructed that at the end of the experiment, three trials would be randomly

selected, and their decisions in those trials would result in real monetary awards. In reality, the participants received a maximum pre-defined participation fee of 5,000 Japanese yen.

Behavioral data analysis. Reaction time was measured as the latency in milliseconds between the onset of the presentation of the decision options and when the button was pressed in each trial. The reaction time and the percentage of the uncertain options chosen in the systole and diastole trials were analyzed separately using a *t*-test for the risk and ambiguity conditions. Effect sizes were calculated as Cohen's *d*. To assess the effect of the cardiac cycle on behavior, we calculated the percentage of the trials where the participants chose the uncertain options under each condition and for each trial type. The percentages of the uncertain options chosen were subjected to an analysis of variance (ANOVA) with two-way repeated-measures in the risk condition; two trial types (systole and diastole) × five winning probabilities (12.5%, 25%, 37.5%, 50%, and 75%); and a two-way repeated-measures ANOVA in the ambiguity condition; two trial types (systole and diastole) × three ambiguity levels (25%, 50%, and 75%).

To assess the effect of the cardiac cycle on risk aversion and ambiguity aversion in accordance with previous studies (Fujino et al, 2017; Pushkarskaya et al., 2015), we estimated participant risk and ambiguity aversion scores. It is assumed that under risk, a risk-neutral decision maker will choose the higher expected monetary option, defined as the product of probability and monetary amount. In our experiment, a risk-neutral decision maker would be expected to choose the riskier option over the sure thing, equating to 60% of all trials under the risk condition. Based on this assumption, the risk aversion score can be calculated as follows:

$$\text{risk aversion score} = 0.6 - \frac{\text{number of risky options chosen}}{\text{total number of risky options}}$$

The risk aversion score would be positive for a risk-averse decision maker and negative for a risk-seeking decision maker.

We assumed that, under ambiguity, the ambiguity-neutral decision maker would choose the same options irrespective of level of ambiguity. In our experiment, the range of potential winning probabilities was centered at 0.5 in all of the ambiguous trials. Therefore, an ambiguity-neutral decision maker would be expected to make the same choice under the ambiguous condition and under the risk condition when the winning probability was 0.5. Based on this assumption, the ambiguity aversion score could be calculated by comparing the individual's choice of ambiguous options to his/her choice of risky options with a winning probability of 0.5, as follows:

$$\text{ambiguity aversion score} = \frac{\text{number of 50\% risky options chosen}}{\text{total number of 50\% risky options}} - \frac{\text{number of ambiguous options chosen}}{\text{total number of ambiguous options}}$$

The ambiguity attitude score would be positive for decision makers who were ambiguity-averse and negative for decision-makers who were ambiguity-seeking.

The risk and ambiguity aversion scores for the systole and diastole trials were analyzed using a *t*-test. The effect sizes were calculated using Cohen's *d*. An alpha level of .05 was used for all statistical analyses.

Exploratory model-based analysis. As an exploratory analysis, we examined the effect of the cardiac cycle on the computational processes during decision-making involving risk. To accomplish this, we used theoretical decision-making models based on the expected utility and compared their goodness-of-fit.

The first model was a decision-making expected utility (EU) model widely used in previous studies (e.g., FeldmanHall et al., 2016; Levy et al., 2010; Tymula et al., 2012). In this model, the expected utility of each option is estimated using the power utility function:

$$EU_{\text{uncertain}} = P(V_{\text{uncertain}})^{\alpha}$$

$$EU_{\text{certain}} = (V_{\text{certain}})^{\alpha}$$

where $V_{\text{uncertain}}$ is the potential monetary amount from the uncertain option, V_{certain} is the monetary amount from the certain option (i.e., 200 Japanese yen), P is the winning probability, and α is the degree of risk attitude. Here, α is less or more than one if the participant is risk-averse or risk-seeking, respectively. The probability of choosing an uncertain option was determined by the following softmax rule:

$$P_{\text{uncertain}} = \frac{1}{1 + \mathrm{e}^{-\gamma(EU_{\text{uncertain}} - EU_{\text{certain}})}}$$

where γ is the degree of stochasticity in the choice behavior; a lower γ means participants are more likely to choose randomly between certain and uncertain options, whereas a higher γ means participants increasingly prefer the option leading to the higher expected utility.

Following the study of Chew et al. (2019), the second model (EU+Bias) introduced an additional parameter into the softmax rule in the first model, representing the bias for/against the utility of the

uncertain options:

$$P_{\text{uncertain}} = \frac{1}{1 + e^{-\gamma(EU_{\text{uncertain}} - EU_{\text{certain}} + \kappa)}}$$

where κ is a gambling bias parameter that is additive to the expected utilities; a higher κ means participants are more likely to choose uncertain options, whereas a lower κ means participants will prefer a certain option, irrespective of the winning probability and monetary amount. We adopted the maximum-likelihood approach to estimate α, γ, and κ by fitting the models to the participant choices.

To determine which parameters in the models would be affected by the cardiac cycle (i.e., systole or diastole), the following procedure was adopted based on the study by Mizoguchi et al. (2015). First, we constructed a model set for all combinations for each parameter. The parameters (i.e., α, γ, and κ) were either allowed to have different values in the systole and diastole trials or the same values in both trials. Next, a fixed-effect analysis was conducted to obtain stable estimates. For each model, a single parameter set was estimated for all participants considered as a whole. The model parameters were optimized by minimizing the negative log-likelihood using the R function "optim." The Akaike information criterion (AIC) was used to compare the models, with the model with the smallest AIC regarded as the best. Finally, using the best model, we conducted the likelihood ratio test to assess whether the differences in parameters between the systole and diastole trials were significant, with the null hypothesis that the improvement in the likelihood of differentiation in the model parameters between the systole and diastole trials occurred solely by chance.

Results

Behavioral results. The mean reaction time under the risk condition was 1,171 ms (SD = 290 ms) in the systole trials and 1,163 ms (SD = 276 ms) in the diastole trials; and the mean reaction time under the ambiguity condition was 1,166 ms (SD = 346 ms) in the systole trials and 1,171 ms (SD = 342 ms) for the diastole trials. Thus, there was no difference in the mean reaction times between the systole and diastole trials under the risk and ambiguity conditions ($t(32) = 1.04$, $p = .31$, $d = 0.18$, $t(32) = 1.04$, $p = .78$, $d = 0.05$, respectively).

Figure 2A illustrates the percentages of the uncertain options chosen in the systole and diastole trials across the winning probabilities under the risk condition and across ambiguity level under the ambiguity condition. As shown in Figure 2A, as the level of risk increased (i.e., the winning probability decreased), the percentage of the uncertain options chosen decreased. In addition, even though the objective winning probability in all the ambiguous trials was 50%, the percentage of the uncertain options chosen under the ambiguous condition was lower than the 50% winning probability under the risk condition. This pattern of the uncertain options chosen under the risk and ambiguous conditions is consistent with that in previous studies using similar experimental tasks (Herman et al., 2021; Tymula et al., 2012).

The percentages of the uncertain options chosen under the risk condition were subjected to two-way repeated-measures ANOVA, with the two trial types (systole and diastole) × five winning probabilities (12.5%, 25%, 37.5%, 50%, and 75%). The results revealed the significant main effect of the trial types ($F(1,32) = 5.55$, $p < 0.05$, partial $\eta^2 = 0.15$). The percentage of the uncertain options chosen was higher in the systole trials than that in the diastole trials. In addition, the main effect of the winning probabilities was significant ($F(4,128) = 109.46$, $p < 0.01$, partial $\eta^2 = 0.77$), confirming that the differences in the percentages of the uncertain options chosen between the winning probabilities were significant across all winning probabilities ($ps < .01$). The interaction between trial type and winning probability was not significant under the risk condition. The percentages of the uncertain options chosen under the ambiguity condition were subjected to two-way repeated-measures ANOVA, with two trial types (systole and diastole) × three ambiguity levels (25%, 50%, and 75%). The results revealed a significant main effect for the ambiguity levels ($F(2,64) = 13.51$, $p < 0.01$, partial $\eta^2 = 0.30$), but no main effect of trial type or interaction between them.

Figure 2B shows the risk and ambiguity aversion scores in the systole and diastole trials. The *t*-test revealed that the risk aversion scores in the systole trials were lower than those in the diastole trials ($t(32) = 2.36$, $p < .05$, $d = 0.41$). A lower risk aversion score in the systole trial was present in 22 of the 33 participants (see Figure 2C). We found no significant differences in the ambiguity aversion scores in the systole and diastole trials.

Exploratory model-based analysis. We conducted an exploratory analysis to determine whether the difference in the percentages of the uncertain options chosen and the risk aversion scores between the systole and diastole trials under the risk condition could be captured better by a change in the participant's risk attitude or by a change in the bias for/against the utility of the uncertain options. To accomplish this, we constructed theoretical decision-making models based on the expected utility and applied them to the data under the risk condition for the 22 participants showing a difference in risk aversion between the systole and diastole trials (see Methods section for particulars).

Table 1 shows parameter estimates and model fit for the choice data. Overall, the AIC scores were lower in the EU+Bias models, which included the gambling bias parameter, than those in the EU models. In the EU+Bias models, based on the AIC score, the model using different values between the systole and diastole trials in the gambling bias parameter was the best fit. The log-likelihood ratio test revealed that the difference in the gambling bias parameter between the systole and diastole trials was significant ($\chi 2(1) = 6.39$, $p < .05$). We found no significant differences in risk attitude and inverse temperature parameters between the systole and diastole trials. The results indicate that the higher propensity to take risks in the systole trials compared with that in the diastole trials can be captured better by the change in the gambling bias for/against the utility of uncertain options, rather than by a change in risk attitude.

Discussion

This study examined whether the cardiac cycle affected one's decision-making under uncertainty. To that end, the presentation of decision options was experimentally timed to coincide with either cardiac systole or diastole. The onset of the presentation of the decision options relative to the R-wave peak indicated that the options were successfully presented at either the individual's cardiac systole or diastole (see Figure 1B). The results showed that under the risk condition, as the winning probability declined, the participants were less likely to choose the uncertain option (see Figure 2A). Although the objective winning probability under the ambiguous condition was always 50%, the participants chose even fewer uncertain options under this condition than they did under 50% uncertainty under the risk condition (see Figure 2A). This pattern is consistent with that in previous studies (e.g., FeldmanHall et al., 2016; Levy et al., 2010; Tymula et al., 2012), indicating that the participants performed the gambling task with the aim of maximizing their monetary gain. These results confirm the validity of our manipulation of the cardiac cycle and of our experiment overall.

Importantly, the percentage of the uncertain options chosen under the risk condition was higher in the systole trials compared with that in the diastole trials. Similarly, the risk aversion score was lower in the systole trials than that in the diastole trials. The implication is that there is a propensity to take greater risk during cardiac systole compared with that during cardiac diastole. In the study, we synchronized the onset of the presentation of the decision options with the systolic (~300 ms after the R-peak) or diastolic (~550 ms after the R-peak) phases of the cardiac cycle. The cardiac afferent signals caused by the activation of the arterial baroreceptor are centrally processed around the T-wave (e.g., Edwards et al., 2007; Gray et al., 2009), which is typically ~300 ms after the R-peak. Therefore, it would be reasonable to assume that the results imply that the natural fluctuations of cardiac afferent signals can affect decision-making under uncertainty; specifically, the propensity to take risks may increase when the decisions are presented when one's cardiac afferent signals are active.

We also conducted an exploratory model-based analysis of the choice data under the risk condition, which showed that the best model was the one using different values in the systole and diastole trials with the gambling bias parameter. The implication is that the higher propensity to take risks in the systole trials compared with that in the diastole trials can be captured better by the change in the gambling bias for/against the utility of uncertain options, rather than by a change in risk attitude. This means that the cardiac cycle may be influencing decision-making under uncertainty through the modulation of the general decision process rather than through a value computation process. This pattern has been observed in previous studies using similar experimental tasks (e.g., Chew et al., 2019).

Chew et al. (2019) demonstrated that endogenous fluctuations in dopamine levels can influence the propensity to take risks, which could be captured by the modulation of the gambling bias parameter in the same computational model used in our study. They concluded that the endogenous fluctuations of dopamine levels changed the gambling propensity through a modulation of the phasic responses to the decision options (i.e., potential rewards). Therefore, the increased propensity to take risks at cardiac systole shown here may be due to cardiac afferent signals affecting the phasic responses to the decision options. Theoretical and practical research has shown that making decisions under uncertainty elicits

affective responses, such as subjective and/or physiological arousal, which could guide subsequent decision-making (e.g., Bechara et al., 1997; FeldmanHall et al., 2016; Herman et al., 2021). Taken together, the present results suggest a possibility that the natural fluctuation of cardiac afferent signal modulates the affective processing of the decision options, which changes the subsequent decision-making. Future studies might examine this possibility with the recordings of the affective responses to decision options such as skin conductance response in the present experimental paradigm.

Notably, the effects of the cardiac cycle on decision-making were observed in the risk condition, but not in the ambiguity condition. Under the risk condition, the probability of the outcomes was known, while under the ambiguity condition, the probability of the outcomes was partially concealed. Given the fact that ambiguity is perceived as more aversive than risk (Becker & Brownson, 1964; Camerer & Weber, 1992; Ellsberg, 1961), a simple interpretation of the results might be that the effects of the cardiac afferent signals on decision-making are not strong enough to affect decision-making under ambiguity. Another interpretation could be that the effect of the cardiac afferent signals is specific to decision-making under risk. Previous studies have reported that risk aversion and ambiguity aversion showed only a weak correlation across individuals, suggesting that they are distinct phenomena (e.g., Fujino et al., 2017; Levy et al., 2010). From this viewpoint, the cardiac cycle may not necessarily influence decision-making under both risk and ambiguity conditions. This interpretation is supported by previous findings that have shown that one's internal physiological state of the body differentially affects one's decision-making, depending on the type of uncertainty (Buckert et al., 2014; FeldmanHall et al., 2016). Specifically, Buckert et al. (2014) reported that the elevation of endogenous cortisol elicited by acute psychosocial stress modulated decision-making under risk but not under ambiguity. These possibilities should be examined in more detail in future studies using larger samples.

Although our study cannot draw definitive conclusions regarding the underlying neural mechanisms of the influence of the cardiac cycle on decision-making under uncertainty, we can offer some thoughts. Previous studies have shown that the strength and timing of arterial pressure at each heartbeat are encoded by the phasic discharge of arterial baroreceptors during cardiac systole, which is transmitted to brain areas, such as the basal ganglia, amygdala, anterior cingulate cortex, and insular cortex (for a review, see Critchley & Harrison, 2013). These brain areas are known to overlap with the brain areas involved in decision-making under uncertainty (e.g., Levy et al., 2010; Weller et al., 2009). Therefore, our results suggest that the cardiac afferent signal modulates the neural activity related to the affective processing of decision options, which influences subsequent decision-making. Specifically, the dopaminergic system may be involved. Chew et al. (2019) reported that endogenous fluctuations in dopaminergic activity increased one's propensity to take risks by enhancing phasic neural responses to decision options. Previous studies have indicated as well that arterial baroreceptor information can affect the dopaminergic system (Yang & Lin, 1993). From this point of view, our results imply that cardiac afferent signals can lead to an increased propensity to take risks via the modulation of phasic responses to the decision options in the dopaminergic system. To understand the neural mechanisms underlying the influence of the cardiac cycle on decision-making under uncertainty, future studies should test this

possibility by combining experimental paradigms assessing decision-making and neuroimaging techniques.

Conclusion

The results of our study revealed that decision-making under risk, measured by the percentage of the uncertain options chosen and the risk aversion scores, can be influenced by the natural fluctuation of cardiac afferent signals. The results of the model-based analysis indicated that the cardiac afferent signals influenced decision-making through a change in the bias for/against the utility of the uncertain options. Our results suggest the possibility that the natural fluctuation of the cardiac afferent signal modulates the affective processing of decision options, which changes subsequent decision-making.

Declarations

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Author contributions

K. Kimura designed the behavioral paradigms. K. Kimura and N.K. conducted the experiments and collected the data. K. Kimura and K. Katahira analyzed the data. K. Kimura wrote the paper. All authors read and approved the final manuscript.

Declaration of Interests

The authors have no competing interests to declare.

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Table 1

Table 1 is available in the Supplementary Files section.

Figures

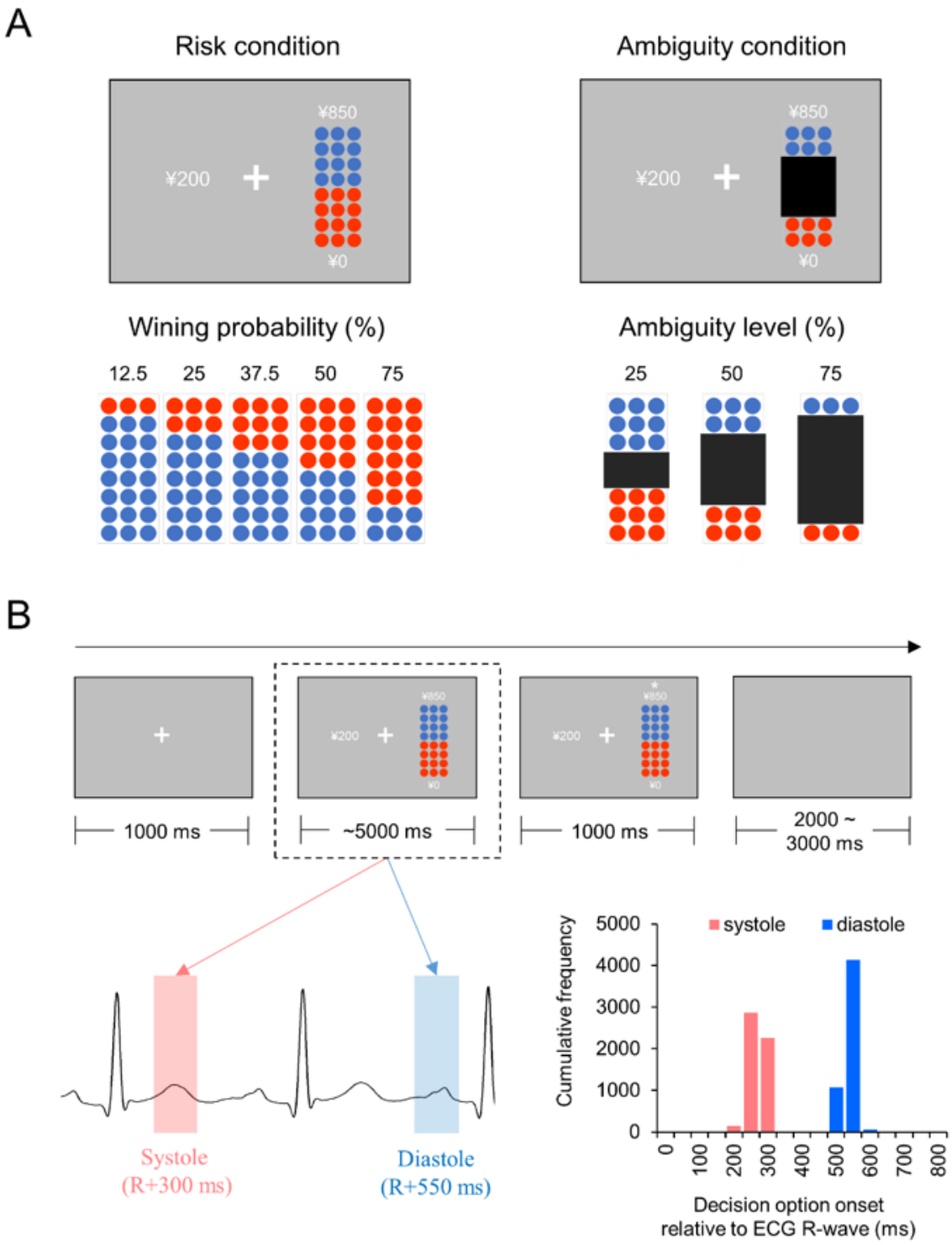

Figure 1

(A) Examples of the stimuli used in the gambling experiment. In the risk condition, the participants had a choice between the safe option with a sure payout of 200 Japanese yen (about US$2) and uncertain options with varying degrees of winning probability. In the ambiguity condition, they had a choice between the safe option and uncertain options with varying degrees of ambiguity. **(B)** Schematic illustration of the flow of one trial of the gambling task. The decision options (indicated by the dashed

line) were experimentally manipulated to coincide with either the participant's cardiac systole or diastole. The precision of the timing within the cardiac cycle, relative to the R-wave peak, is shown in the histogram.

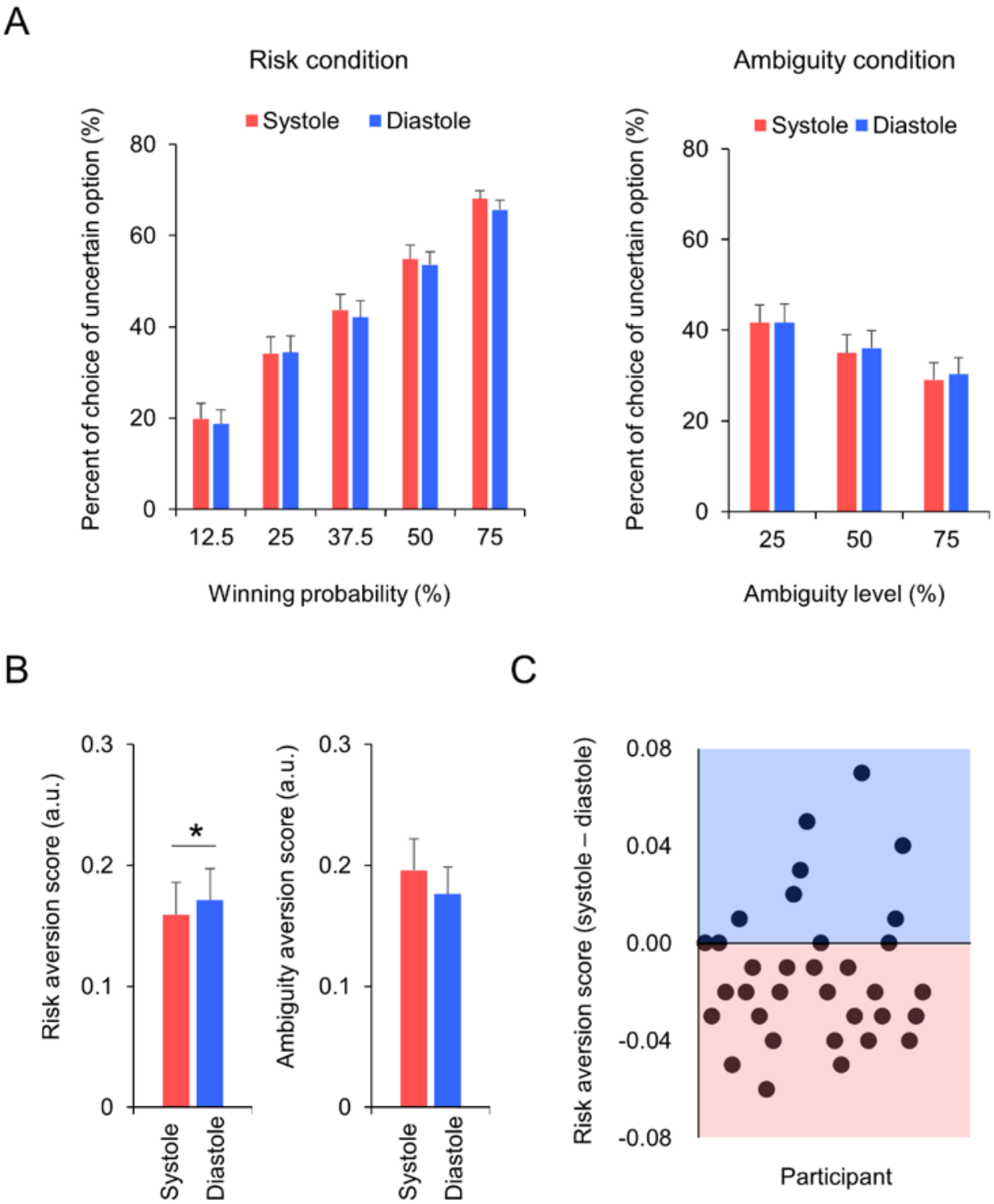

Figure 2

(A) Mean percentages of the uncertain options chosen in the systole and diastole trials in the risk and ambiguity conditions. Error bars indicate *SE*. **(B)** Means of the risk and ambiguity aversion scores in the systole and diastole trials. Error bars indicate *SE*. An asterisk indicates a significant difference in the risk aversion score between the systole and diastole trials (*: $p < .05$). **(C)** In 22 of the 33 participants, there was a lower risk aversion score in the systole trial compared with that in the diastole trial.

Supplementary Files

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- SupplementaryMaterial21227.docx
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