Cardiac-phase gating of eye movements: evidence from a gaze-contingent 'search-light' paradigm

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Abstract

Humans actively sample their environment by alternating rapid saccades for exploration with fixations for detailed perception, as high-resolution vision is restricted to the fovea. Efficient visual sampling depends on the precise coordination of these eye movements. Here, we show that this coordination is gated by the cardiac cycle. Using a gaze-contingent 'search-light' paradigm that limits visibility to a foveal window—thereby inducing frequent saccades and clearly dissociating the roles of saccades and fixations during natural-scene exploration—while simultaneously recording electrocardiography (ECG), we found that saccades occur predominantly during systole, when baroreceptors are active, whereas fixations predominate during diastole, when baroreceptor-mediated afferent signals are quiescent. These findings identify the heartbeat as an internal clock that choreographs when we explore and when we perceive, revealing a mechanism through which interoceptive signals organize spontaneous perception–action cycles.

1. Introduction

Human perception is inherently dynamic, characterized by continuous fluctuations arising from both spontaneous neural activity and the regular rhythmic patterns of our visceral organs. These inherent variations are not mere background noise but are fundamental to how sensory information is processed and integrated. In particular, the rhythmic activity of the visceral organs—interoceptive rhythms—has garnered increasing attention, as it appears to play a critical role in shaping our perceptual experiences (Engelen et al., 2023). Among the various systems generating interoceptive rhythms—such as those of the heart, respiration, and gastric activity—cardiac activity has received the most attention.

The cardiac cycle is composed of two main phases: systole, during which the heart contracts to pump blood throughout the body, and diastole, when the heart relaxes to allow blood to fill its chambers. In an electrocardiogram (ECG) waveform, the interval between consecutive R peaks represents one complete cardiac cycle, with systole commencing immediately after the R peak and diastole following thereafter. Essentially, the cardiac cycle is a perpetual sequence in which systole and diastole continuously alternate. Research on the human cardiac cycle has demonstrated that our perception and cognition are modulated by its phases. Notably, this modulation has been particularly elucidated by presenting exteroceptive stimuli—such as visual, auditory, tactile, and pain stimuli—in synchrony with distinct phases of the cardiac cycle (for a review, see Garfinkel et al., 2016; Skora et al., 2022). For example, evidence indicates that during diastole, sensory processing of visual, tactile, and painful stimuli is enhanced, whereas during systole, both sensory processing and cortical excitability are suppressed (Edwards et al., 2009; Galvez-pol et al., 2022; McIntyre et al., 2007; Pramme et al., 2016; Salomon et al., 2016; Saltafossi et al., 2023; Wilkinson et al., 2013). While the method of presenting stimuli synchronized with specific phases of the cardiac cycle has been groundbreaking and has significantly advanced interoceptive research, it is important to note that in everyday life we are not passively exposed to stimuli in this manner. Rather, we actively engage with perceiving the world by moving and adjusting our sensory organs, such as our eyes, ears, and bodies. In the case of visual perception, for instance, we deliberately move our eyes to direct objects onto the fovea—the region of the retina where visual receptors are most densely packed—to optimize image resolution. This raises the possibility that the rhythmic oscillations of the cardiac cycle might modulate the way we actively sample visual information from the world. A recent study addressed this very

possibility by demonstrating that eye movements—specifically, saccades and subsequent fixations—are significantly coupled with the cardiac cycle during a 'spot the difference' visual search task (Galvez-Pol et al., 2020). Building on these findings, we further advanced the approach to enhance the ecological validity of the task and to highlight its unique contribution to understanding how the cardiac cycle influences active visual sampling.

In the present study, we developed an original task—termed the 'search light task'—that requires participants to actively sample visual information by deliberately moving their eyes. In this task, participants viewed natural scene images, but the only central visual field was visible while the peripheral regions were masked in black using real-time, gaze-contingent manipulation. By blocking peripheral input, we intentionally created a scenario in which participants must execute eye movements to gather the necessary information, thereby clearly differentiating the functional roles of fixation and saccadic movements. Moreover, the task was self-paced, enabling participants to engage in motivation-driven visual scanning. ECG signals were recorded during the task to test the coupling between cardiac phase and eye movements. We hypothesized that fixations—periods during which visual information is sampled—would occur more frequently during the diastolic phase, whereas saccadic movements—which, although they transiently impair visual perception, are essential for directing the gaze toward the fovea—would occur more frequently during systole.

2. Results

A total of 41 participants performed the searchlight task, in which they were required to report the content of each image. Because only the central visual field was made visible—using a custom-written, real-time, gaze-contingent algorithm (see Methods for details)— participants had to actively move their eyes to scan the entire image, much like a search light (Figure 1A). Each participant completed 21 test trials, each lasting 40 seconds. Simultaneously, their ECG was recorded during the task, and we computed the coupling between cardiac phase and various ocular behaviors, including saccades, fixations, and blinks (Figure 1B).

The mean R-R interval across participants during the task was 819 msec (SD = 32.12, range: 691–942 msec). During each 40-second trial, participants made an average of 28 saccades (SD = 5.19, range: 17–46 times), 44 fixations (SD = 12.22, range: 21–69 times), and 8 blinks (SD = 4.80, range: 2–19 times). To statistically test

the hypothesis that eye-movements are coupled with cardiac cycles, we employed circular statistics to take advantage of the cyclical nature of cardiac cycle. For each oculomotor event, we first calculated the times of the preceding and subsequent R-peaks. We then computed the phase of each event as a function of the R-R interval. For each participant, the median phase (in degrees) for each type of oculomotor event (saccades, fixations, and blinks) was calculated and used as a representative value for an individual participant.

At the group level, saccades occurred on average at 119.83°—within the R-R interval, as indicated by the red arrow in Figure 2A. To statistically test whether the distribution was skewed toward a specific phase of the cardiac cycle, we performed a Rayleigh test with the null hypothesis that the distribution is uniform. The result indicated that this distribution significantly deviated from uniformity (z = 0.34, p = 0.009). This skewed distribution, which peaked at 119.83°, corresponds, the early stage of the cardiac cycle—, the systolic phase (Fig. 2A). The same analysis was conducted for fixations and blinks. For fixations, the results indicated that they occurred on average at 204.32°—within the R-R interval, with a significant deviation from uniformity (z = 0.33, p = 0.013). This skewed distribution, corresponds to the mid phase of the cardiac cycle—, the early diastolic phase (Fig. 2B). In contrast, blinks occurred on average at 297.31°—within the R-R interval. Although the Rayleigh test for blinks did not reach statistical significance (z = 0.26, p = 0.063), it showed a trend toward non-uniformity, suggesting that blink timing corresponds, to the late period of the cardiac cycle—, the diastolic phase (Fig. 2C).

3. Discussion

Humans actively explore their environment by moving sensory organs to gather information. In vision, we incessantly shift our gaze because only the fovea—a small retinal region densely packed with cone photoreceptors—supports high-acuity color vision. To place an object of interest onto the fovea, the oculomotor system generates rapid ballistic eye movements known as saccades. Although such movements should blur incoming input, perceptual stability is preserved by saccadic suppression, a predictive inhibitory mechanism by which the brain transiently attenuates visual processing around each saccade. Perception resumes as soon as the eye comes to rest in the ensuing fixation (Hamker et al., 2008; Ibbotson et al., 2011; Poletti et al., 2013).

Efficient operation of this system benefits from the coordinated timing of

saccades and fixations. Here, we show that the cardiac cycle gates active visual sampling. Eye-movement timing was coupled with the cardiac cycle: saccades occurred predominantly during systole, whereas fixations predominated during diastole. These findings suggest that the cardiac cycle acts as an internal clock that choreographs when we explore and when we perceive.

Each heartbeat triggers baroreceptors in the aortic arch and carotid sinus, sending a burst of afferent activity to brainstem and insular networks that maintain cardio-visceral homeostasis (Critchley et al., 2013; Khalsa et al., 2018; Engelen et al., 2023). Like the blur induced by saccades, this baroreceptor volley can act as internal noise that competes with incoming exteroceptive information. For stable perception of the world, the neural predictive processes would need to suppress sensory gain during systole, the baroreceptor-active phase, and release that suppression during diastole.

Within a predictive-coding framework, the heartbeat entrains cortical rhythms such that precision—the confidence assigned to prediction errors—is rhythmically weighted. During systole, high interoceptive precision biases processing toward self-related bodily signals and away from external input, creating a favorable window for action initiation, which also generates self-originating somatosensory feedback that should be damped. During diastole, interoceptive precision drops, exteroceptive channels are up-weighted, and perceptual sampling is enhanced (Skora et al., 2022). In this view, the cardiac cycle dynamically toggles the brain between 'action-centered' and 'perception-centered' modes, explaining why we observed saccade clustering in systole and fixation-based information gathering in diastole.

Converging behavioral evidence supports this heartbeat-gated principle across diverse active tasks, including saccades during a spot-the-difference visual-search paradigm (Galvez-Pol et al., 2020); microsaccades during stable fixations (Ohl et al., 2016); self-paced button presses in a memory-recall task (Kunzendorf et al., 2019). Other studies report that, although the timing of spontaneous actions itself is not always modulated, the perceptual or cognitive consequences of those actions depend on whether they were initiated in systole or diastole (Herman & Tsakiris., 2020; Galvez-Pol et al., 2022). Our findings extend this literature to more ecologically valid form of visual exploration and further strengthen the case a heartbeat-locked mechanisms that coordinates action with perception. We also observed that blinks tended to occur late in diastole, consistent with their putative role in toggling activity between the default-mode and attention networks

(Nakano et al., 2012), thereby resetting processing before the next exploratory episode.

In sum, the present study is the first to show cardiac modulation of active visual sampling during natural-scene viewing, using a novel gaze-contingent 'search-light' paradigm that exaggerates the fovea–periphery contrast. This approach opens a path to studying how interoception orchestrates spontaneous perception–action cycles under ecologically valid conditions. Because the task is non-verbal, it can be applied to animals, infants, or clinical populations, offering a powerful tool for probing the biological basis—and potentially the causal architecture—of interoceptive–exteroceptive coupling across the lifespan.

4. Methods

4.1 Participants

The final sample consisted of 41 healthy adults (25 females; mean age = 21.0 years, SD = 1.93), all with normal vision (corrected or uncorrected) and no known cardiac abnormalities. One additional participant was excluded from the analysis due to an error in the ECG recordings. This study was approved by the Ethics Committee of the Department of Psychology at Nagoya University (approval number: NUPSY -240305-L-01), and all participants provided informed consent.

4.2 Stimulus and Apparatus

Stimulus images (26 in total) used for the task were selected from Pixabay, a royalty-free repository. These images contained information about animals and their backgrounds (e.g., three goats in a meadow), and were edited to a resolution of 1920 (W) by 1282 (H) pixels. The task was presented on a 24.5-inch LCD monitor (240 Hz refresh rate) and controlled by custom-written script in MATLAB R2019b (MathWorks, Inc.) with Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007). A Tobii TX300 eye tracker (Tobii AB) was positioned below the monitor, allowing us to record participants' gaze during the task at a sampling rate of 300 Hz. For real-time, gaze-contingent control of the task, we used the Tobii Pro SDK to interface with MATLAB. ECG data were recorded using the BIOPAC MP160 system and ECG100C amplifier (BIOPAC Systems, Inc.) at a sampling rate of 1000 Hz.

4.3 Task and procedure

Upon the arrival, participants provided informed consent and had disposal

electrodes attached for ECG recordings using a 3-lead configuration. Participants sat 56 cm away from the display with chin rest, and performed the 'searchlight task,' in which they were required to report the content of each image. Because only the central visual field was made visible, participants had to actively move their eyes to scan the entire image, much like a search light. The visible area was limited to a circle with a 40 pixels radius, centered on the foveal region; areas outside this circle were masked in black (see Figure 1). To calculate the coordinates of the visible area, we calculated the average of the coordinates sampled 0.01 milliseconds by the right and left eyes, multiplied each value by the vertical and horizontal dimensions of the display, and then found the median value of the results. We then substituted this value into circle formula to determine the coordinates of the visible area. After 40 seconds of scanning, participants were instructed to verbally report the number of animals and the background context. No feedback was given. The task consisted of 5 practice trials and 21 main trials (one trial per image), which were divided into 3 blocks of 7 trials. A 9-point calibration was conducted before each block, and short breaks were provided between trials. During these short breaks, participants were instructed to remove their chin from the chin rest and sit in a relaxed posture. The total experiment duration was approximately 45 minutes.

4.4 Data Analysis

Physiological signal pre-processing was performed using MATLAB 2023a (Mathworks, Inc.). Statistical analysis was conducted using RStudio (RStudio Team, 2023) with R version 4.4.0 (R Core Team, 2023).

2.4.1 ECG Data Analysis:

We first applied a 5 Hz high-pass, first-order Butterworth filter on the raw ECG data to remove body-movement-related artifacts. R-wave peaks were then identified as local maxima with a minimum peak distance of 500 msec, and R–R intervals were computed as the differences between consecutive peaks. The analysis was automated with a custom-written MATLAB program and visually inspected for accuracy.

2.4.2 Gaze Data Analysis:

Gaze data analysis focused on detecting the timing of events, including saccades, fixations, and blinks. We first converted left eye gaze coordinates from

pixels to millimeters, then applied an 11-point moving average filter, and performed differentiation to calculate the eye-movement velocity. A saccade event was detected when the velocity exceeded a threshold of 2.5°/sec. From the consecutive points meeting this criterion, the point corresponding to the maximal velocity was marked as the saccade timepoint. Fixations were identified when the velocity was between a 0 and –50°and lasted over 200 ms, with the midpoint of these data points designated as the fixation timepoint. Blinks were detected when consecutive NaN sequences persisted for more than 150 msec, with the onset of these sequences marked as the blink timepoint. Eye movement data that did not exceed these thresholds or criteria were not involved in the further analysis.

2.4.3 Circular Analysis:

We examined the relationship between oculomotor events and the cardiac cycle by creating a circular representation in which vertices were defined by R–R intervals. The timing of each oculomotor event was calculated using the following formula:

$$Circular\ timing\ of\ eye\ movements = \left(\frac{Timing\ of\ eye\ movements}{R - peak\ to\ R - peak\ duration}\right) \times 360$$

We then obtained an median phase (in degrees) for each type of oculomotor event for each participant. Using each participant's representative value, we obtained a group-level distribution of the circular timing of the evets. To test uniformity of phase distribution, we employed a Rayleigh test for each oculomotor type separately.

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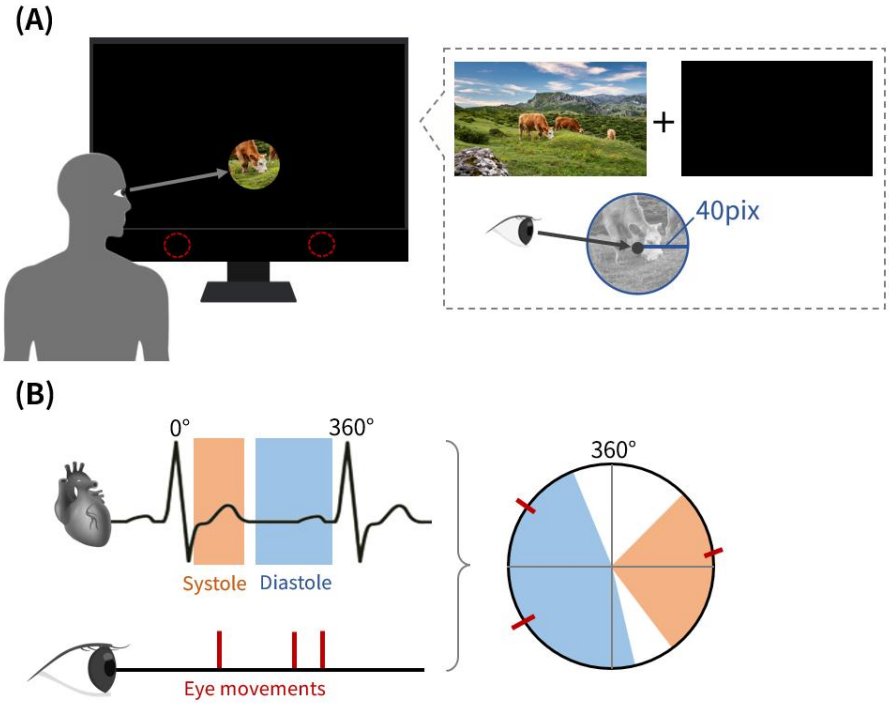

Fig.1. Schematic diagram of task and analysis. (A) Example of a single trial. Participants were required to report the content of stimulus images hidden behind black masks. As they moved their eyes to scan the stimulus images on the display, a portion of the stimulus image became visible within a circular area (40-pixel radius) centered on their gaze position. (B) Schematic overview of the analysis. The top-left panel shows the ECG waveform, with the systole phase indicated in orange and the diastole phase in blue. The bottom-left panel shows the timing of eye movements, indicated by a red line. The right panel shows a clockwise circle with R-peaks set to 0 degrees. The timing of eye movements is plotted as red lines along the circumference.

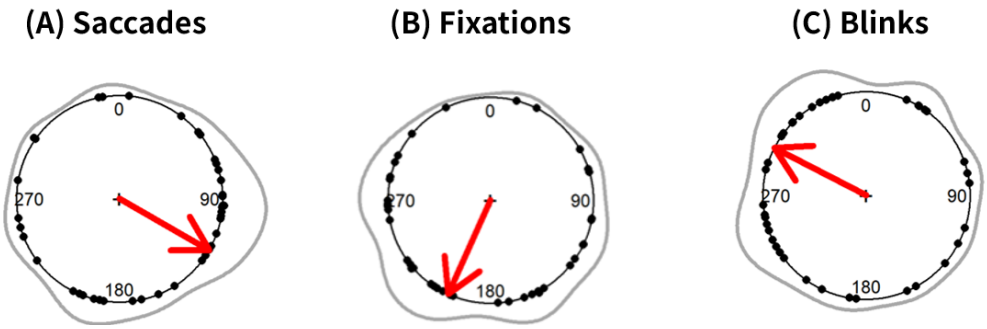

Fig.2. Relationship between eye movement timing and the cardiac cycle. In each panel, the timing of eye movements is plotted on a circular scale with the R-peaks as the vertex. Black dots indicate the median timing of saccades, fixations, and blinks for each participant across all trials. The red line indicates phase bias vectors. The gray wavy line represents the kernel density estimation. (A) shows the relationship between the timing of saccades and the phase of the R-R interval. (B) shows the relationship between the timing of fixations and the phase of the R-R interval. (C) shows the relationship between the timing of blinks and the phase of the R-R interval.

Reference

Brainard, D. H. 1997. The psychophysics toolbox. *Spatial Vision* 10(4): 433–436. DOI: https://doi.org/10.1163/156856897X00357.

Critchley, H.D. and Harrison, N.A. 2013. Visceral influences on brain and behavior. *Neuron* 77: 624–638. DOI: 10.1016/j.neuron.2013.02.008

Edwards, L., Ring, C., McIntyre, D., Winer, J. B., & Martin, U. 2009. Sensory detection thresholds are modulated across the cardiac cycle: Evidence that cutaneous sensibility is greatest for systolic stimulation. *Psychophysiology* 46(2): 252–256. DOI: https://doi.org/10.1111/j.1469-8986.2008.00769.x

Engelen T, Solcà M, Tallon-Baudry C. 2023. Interoceptive rhythms in the Brain. *Nature Neuroscience* 26 (10): 1670–84. DOI: https://doi.org/10.1038/s41593-023-01425-1

Galvez-Pol, A., McConnell, R., & Kilner, J. M. 2020. Active sampling in visual search is coupled to the cardiac cycle. *Cognition* 196: 104149. DOI: https://doi.org/10.1016/j .cognition.2019.104149

Galvez-Pol, A., Virdee, P., Villacampa, J., & Kilner, J. M. 2022. Active tactile discrimination is coupled with and modulated by the cardiac cycle. *eLife* 11. DOI: https://doi.org/10.7554/eLife.78126

Garfinkel, S. N., & Critchley, H. D. 2016. Threat and the body: How the heart supports fear processing. *Trends in Cognitive Sciences* 20(1): 34–46. DOI: http://dx.doi.org/10.1016/j.tics.2015.10.005

Hamker, F. H., Zirnsak, M., Calow, D., & Lappe, M. 2008. The peri-saccadic perception of objects and space. *PLoS Computational Biology* 4(2). DOI: https://doi.org/10.1371/journal.pcbi.0040031

Herman, A. M., & Tsakiris, M. 2020. Feeling in control: The role of cardiac timing in the sense of agency. *Affective Science* 1: 155–171. DOI: https://doi.org/10.1007/s42761-020-00013-x

Ibbotson, M., & Krekelberg, B. 2011. Visual perception and saccadic eye movements. *Current Opinion in Neurobiology* 21(4): 553–558. DOI: https://doi.org/10.1016/j.conb.2011.05.012

Khalsa, S.S., Adolphs, R., Cameron, O.G., Critchley, H.D., Davenport, P.W., Feinstein, J. S., Feusner, J.D., Garfinkel, S.N., Lane, R.D., Mehling, W.E., Meuret, A.E., Nemeroff, C.B., Oppenheimer, S., Petzschner, F.H., Pollatos, O., Rhudy, J.L., Schramm, L.P., Simmons, W.K., Stein, M.B., Stephan, K.E., Van den Bergh, O., Van Diest, I., von Leupoldt, A., Paulus, M.P., 2018. Interoception and Mental Health: A Roadmap. *Biological psychiatry. Cognitive neuroscience and neuroimaging* 501–513. DOI: https://doi.org/10.1016/j.bpsc.2017.12.004

Kleiner, M., Brainard, D. H., Pelli, D. G., Broussard, C., Wolf, T., & Niehorster, D. 2007. What's new in psychtoolbox-3? *Perception* 36: S14. DOI: https://doi.org/10.1068/

Kunzendorf, S., Klotzsche, F., Akbal, M., Villringer, A., Ohl, S., & Gaebler, M. 2019. Active information sampling varies across the cardiac cycle. *Psychophysiology*, 1–16. DOI: https://doi.org/10.1111/psyp.13322.

McIntyre, D., Ring, C., Hamer, M., & Carroll, D. 2007. Effects of arterial and cardiopulmonary baroreceptor activation on simple and choice reac- tion times. *Psychophysiology* 44: 874–879. DOI: https://doi.org/10.1111/j.1469-8986.2007.00547.x

Nakano, T., Kato, M., Morito, Y., Itoi, S., Kitazawa, S. 2012. Blink-related momentary activation of the default mode network while viewing videos. *Proceedings of the National Academy of Sciences* 110(2): 702-706. DOI: https://doi.org/10.1073/pnas.1214804110

Ohl, S., Wohltat, C., Kliegl, R., Pollatos, O., & Engbert, R. 2016. Microsaccades are coupled to heartbeat. *Journal of Neuroscience* 36(4): 1237–1241. DOI: https://doi.org/10. 1523/JNEUROSCI.2211-15.2016.

Pelli, D. G. 1997. The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*. DOI: https://doi.org/10.1163/156856897X00366

Poletti M, Listorti C, Rucci M. 2013. Microscopic eye movements compensate for nonhomogeneous vision within the fovea. *Current Biology* 23: 1691–1695. DOI: https://doi.org/10.1016/j.cub.2013.07.007

Pramme, L., Larra, M. F., Schächinger, H., & Frings, C. 2016. Cardiac cycle time effects on selection efficiency in vision. *Psychophysiology* 53(11): 1702–1711. DOI: https://doi.org/10.1111/psyp.12728

Salomon, R., Ronchi, R., Donz, J., Bello-Ruiz, J., Herbelin, B., Martet, R., Faivre, N., Schaller, K., Blanke, O., 2016. The insula mediates access to awareness of visual stimuli presented synchronously to the heartbeat. *Journal of Neuroscience* 36: 5115–5127. DOI: https://doi.org/10.1523/JNEUROSCI.4262-15.2016

Saltafossi, M., Zaccaro, A., Perrucci, M. G., Ferri, F., & Costantini, M. 2023. The impact of cardiac phases on multisensory integration. *Biological Psychology* 182: 108642. DOI: https://doi.org/10.1016/j.biopsycho.2023.108642

Skora, L. I., Livermore, J. J. A., & Roelofs, K. 2022. The funcutional role of cardiac activity in perception and action. *Neuroscience and Biobehavioral Reviews* 137: 104655. DOI: https://doi.org/10.1016/j.neubiorev.2022.104655

Wilkinson, M., McIntyre, D. & Edwards, L. 2013. Electrocutaneous pain thresholds are

higher during systole than diastole. *Biological Psychology* 94: 71-73. DOI: https://doi.org/10.1016/j.biopsycho.2013.05.002