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WACARDIA: Graphical MATLAB software for Wireless Assessment of CARDiac Interoceptive Accuracy

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ABSTRACT

Many theories of psychological function emphasize the importance of bodily sensations and the ability to accurately detect them, known as interoceptive accuracy. The most common measure of interoceptive accuracy uses heartbeat detection tasks such as the Whitehead Task, yet to our knowledge there are no freely accessible programs to conduct this task. In this paper, we present novel software called WACARDIA (Wireless Assessment of CARDiac Interoceptive Accuracy), which is free, open-source software that conducts the heartbeat detection task using Matlab and Psychtoolbox. WACARDIA contains several key features supporting participant engagement, operator convenience, and measurement accuracy. First, the program includes an optional practice trial of unlimited duration, a participant-facing graphical interface, and the ability to perform heartbeat detection training. Second, the operator is provided with a graphical user interface, live trial feedback, an accurate wireless electrocardiogram device, and a separate program to conduct the related Heartbeat Tracking task. Finally, the program ensures the accuracy of collected data by scheduling the delivery of tones with high precision and implementing fail-safes to automatically reset erroneous measurements. This paper includes flowcharts that help create transparency by describing our algorithm. We also outline customizable aspects of the program with the intent to have WACARDIA's algorithm expanded to accommodate more situations and applications. With this paper, we hope to encourage the practice of publicizing research software to contribute to the transparency, rigor, and reproducibility of scientific studies. WACARDIA and video tutorials are available at www.github.com/iankleckner/wacardia and http://wacardia.iankleckner.com.

1. Introduction

Interoception refers to the process by which the nervous system senses, interprets, and integrates signals originating from within the body (Khalsa, Adolphs, et al., 2018). Research on interoception has grown exponentially in the past decades (Khalsa, Adolphs, et al., 2018) given the central role of bodily sensations in mental processes and allostasis/homeostasis (Quigley et al., 2021; Sennesh et al., 2022). Indeed, studies have linked the interoception to emotion (Critchley & Garfinkel, 2017), decision-making (Dunn et al., 2010), memory (Messina et al., 2022), pain (Di Lernia et al., 2016), anxiety (Paulus & Stein, 2010), depression (Barrett et al., 2016), energy regulation (Quigley et al., 2021) and other processes in various populations including patients with anxiety (Smith et al., 2020), depression (Smith et al., 2020), eating disorders (Khalsa, Hassanpour, et al., 2018), psychopathology (Murphy et al., 2017), autism (Garfinkel et al., 2016), cancer (Manuweera et al., 2024; Omran et al., 2021; Kleckner et al., 2024), and others. Studies have also investigated neural mechanisms that support interoception in a variety of contexts (Barrett & Simmons, 2015; Khalsa, Adolphs, et al., 2018; Kleckner et al., 2017; Quadt et al., 2018).

Though as many as eight distinct dimensions of interoception have been described (Suksasilp & Garfinkel, 2022), much research orients around interoceptive accuracy, which is defined as the ability to precisely and correctly monitor changes in internal events. One of the most common measures is cardiac interoceptive accuracy, predominantly assessed by measuring an individual's performance in the Heartbeat Tracking (HBT) task (Schandry, 1981) or the Heartbeat Detection (HBD)

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task (Whitehead et al., 1977). The former, which requires participants to count the number of heartbeats they feel in a certain interval, has been criticized for its strong association with knowledge about one's own heartrate (Brener & Ring, 2016; Desmedt et al., 2020; Murphy et al., 2018; Ring et al., 2015). In the latter, participants are exposed to a series of auditory stimuli at intervals to their R-spikes meant to be perceived as synchronous or asynchronous to their heartbeat. Participants are asked to determine whether the stimuli were coincident or noncoincident with their own heartbeats while focusing on their internal sensations, without touching themselves or other objects to allow them to feel their pulse. This is repeated for typically at least 40 trials (Kleckner et al., 2015). HBD is a more valid measure of interoceptive accuracy considering that participants can only obtain a high score on the test if they can indeed feel their own heartbeats, as opposed to merely updating the knowledge of their heartrate (Phillips et al., 1999). We focus on HBD in this paper (for a comprehensive comparison of these tasks, see: (Hickman et al., 2020; Ring & Brener, 2018).

Although the Whitehead HBD task is widely used, there is little consensus or availability of programs to conduct this task. Most studies utilizing HBD simply describe their procedure, including details such as the wave-to-tone delay for synchronous and asynchronous trials (e.g., (Garfinkel et al., 2016; Koreki et al., 2021; Leganes-Fonteneau et al., 2022)). Several others mention "in-house software" that produces stimuli in response to R-wave peaks (e.g., (Aspell et al., 2013; Hina & Aspell, 2019; Kleckner et al., 2015)). While measures are taken to create transparency and rigor in these studies, per NIH guidelines (National Institutes of Health, 2021), complete reproducibility is difficult without making these programs widely available. Barker et al. extend FAIR (Findable, Accessible, Interoperable, Reusable) principles to research software, further emphasizing the need for open publication (Barker et al., 2022). To our knowledge, there are no freely available programs to run HBD, which makes it hard for researchers to consistently run the task and for smaller scale studies to be conducted due to the resources required to program this task from scratch.

In this paper, we present WACARDIA (Wireless Assessment of CARDiac Interoceptive Accuracy), a free, open-source software to conduct the Whitehead HBD task using a wireless electrocardiogram device. The program utilizes MATLAB and Psychtoolbox functions to detect peaks in the ECG R-wave and prepare audio in a way that produces minimal lag, which is crucial for the highly precise operation. It also implements helpful features and fail-safes that significantly reduce the burden on researchers. We intend the code to be highly customizable via the open-source MIT license and thus provide a thorough description of the algorithm's processes here. For a free download, video tutorials, and additional information, visit www.github.com/iankleckner/wacardia and http://wacardia.iankleckner.com.

2. Materials and methods

2.1. Requisite software

WACARDIA is written in the MATLAB programming language and runs through the MATLAB R2023a v9.14 application (MathWorks, Natick, MA). The software requires the Signal Processing Toolbox v9.2 and Statistics and Machine Learning Toolbox v12.5, MATLAB products. WACARDIA may run on other versions of these packages as well, but these were not rigorously evaluated. In addition, the graphical user interface relies on the Psychtoolbox-3 extension (Brainard & Vision, 1997; Kleiner et al., 2007; Pelli & Vision, 1997). The program is designed to run with a Shimmer3 ECG Unit (Shimmer Sensing, Dublin, Ireland) which uses Consensys to set up the ECG device initially and RealTerm to communicate with the computer, along with MATLAB libraries offered by Shimmer Sensing. Although WACARDIA has been developed and runs exclusively on the Windows operating system, because MATLAB and Psychtoolbox are also compatible with macOS and Linux, the program may also function on other operating systems.

2.1.1. Heartbeat detection settings

The Shimmer ECG device was set up with Bluetooth signal transfer and data collection at 1024 Hz. For HBD and HBT, we recommend ECG leads are connected in a modified Lead-II configuration, as shown in Fig. 1**a** to maximize the height and narrowness of the R-spike while reducing the amplitude of the T-wave. We recommend standard Ag/AgCl ECG electrodes. Finally, we recommend an external USB Bluetooth dongle (antenna) and USB extension cable to improve signal quality and ensure line of sight from the Shimmer ECG to the Bluetooth antenna.

WACARDIA uses a MATLAB findpeaks function to identify the ECG R spike in real time with other criteria including a minimum prominence (amplitude compared to the surrounding baseline signal) and minimum time since the prior R spike, if there was one. Once the R spike is found, WACARDIA prepares to deliver an audio stimulus (a beep, with user-defined parameters including tone/frequency and duration). The audio stimulus is set to occur either 200 msec or 500 msec after each R spike (delays are user-defined options), for 10 R spikes in a row (the number of R spikes is a user-modifiable option).

The main settings for WACARDIA are as follows: (1) Sampling rate of ECG—we recommend 1024 Hz to have msec-level precision in determination of the R spike. (2) Minimum duration of consecutive R spikes—we recommend 0.5 sec to allow heart rates up to 120 beats per minute, but the minimum R-R interval may need to be reduced if HBD is conducted during physical activity. (3) Minimum prominence of R spike—we recommend 1 mV as this works for most participants we have measured, but this should be checked for each participant based on the ECG reading obtained from them. The R spike prominence is displayed in the View and Record module and detailed instructions are provided in our Standard Operating Procedures on GitHub. (4) Number of trials—we have a publication discussing this issue (Kleckner et al., 2015) and the final number depends on many factors. We recommend at least 40 trials in total, but often 80–100 will be time well spent if cardiac interoceptive accuracy is very important to the study. We recommend using sets of no more than 25 trials at a time to prevent participant fatigue.

2.1.2. Calculating lag in Bluetooth signal transfer

To determine the amount of time it takes from an actual R-spike from the heart to the R-spike reading by MATLAB in WACARDIA, we designed a hardware circuit and "simulated heart" driven by a module within WACARDIA. The basic schematic is shown in Fig. 1b with a wiring diagrams in Fig. 1c and Fig. 1d. The products used include the following (1) Elegoo Uno R3 board, (2) breadboard, (3) 100 kΩ and 220 Ω breadboard-compatible resistors, (4) 4 male to male breadboard-compatible wires, (5) electrical tape, and (6) snap to pin connectors. The total cost is approximately $50 USD at the time of publication with all parts readily available from a large online retailer. The circuit is designed to carry a 10-mV signal that can be measured by the Shimmer ECG, as this voltage value is similar to the voltages detected across the heart in an actual ECG. We also recommend a multimeter for testing the circuit before connecting to the ECG device to prevent overloading the ECG device. We recommend specific vendor links in our Standard Operating Procedures at www.github.com/iankleckner/wacardia and http://wacardia.iankleckner.com.

Once this hardware circuit is set up and plugged in, the user should enter the relevant COM ports for the Arduino board and Shimmer ECG, then choose Bluetooth Lag Detection from the main menu of WACARDIA and run the program. This will send a square wave signal from the Arduino to the ECG with signal duration of 0.5 sec. WACARDIA's Bluetooth Lag Detection uses PsychToolbox's timing functions to calculate the time from triggering the Arduino signal (the simulated heart) to the time it is read back via the Shimmer Bluetooth connection as a change in square wave amplitude (see Fig. 4). After 400 changes in amplitude (the user can change the actual number), the array of lag values recorded will quantify the mean lag and variability in lag values. The researcher should place the Shimmer ECG and computer in a similar physical arrangement as the HBD task to ensure an accurate assessment

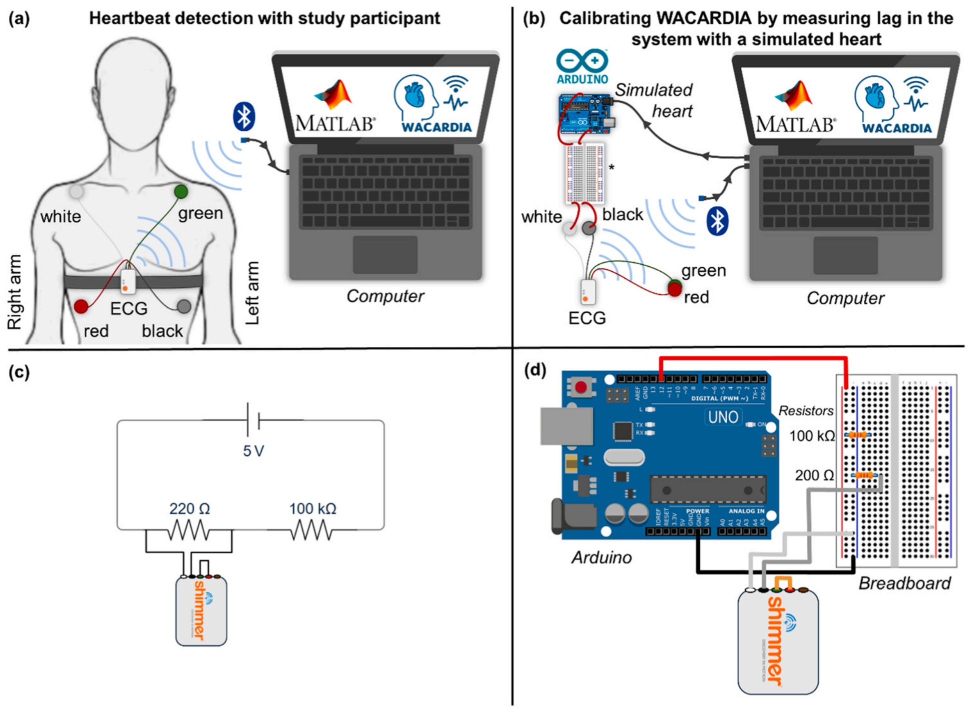

Fig. 1. Experimental setup for conducting the heartbeat detection (HBD) task with high temporal precision. (a) The electrocardiogram (ECG) is connected to the study participant in a modified lead II configuration. The WACARDIA program streams data from the ECG wirelessly using Bluetooth sampled at 1024 Hz (researchers can adjust sampling frequency if desired). (b) To maximize timing accuracy during the HBD task, WACARDIA can measure the lag in the system by simulating a heartbeat using an external circuit (Arduino board) that connects to the ECG device. The WACARDIA program reads back the simulated ECG signal that it generated and calculates the mean and distribution of the lag times between reference points in the outgoing and incoming signals (Fig. 4). The researcher enters the mean lag time in the main HBD program, which warns the user if the lag time is prohibitively long or unstable. The red and green leads are connected to ensure a stable baseline ECG. (c) Schematic wiring circuit diagram of the simulated heart. (d) Full wiring diagram of simulated heart. Details in Methods.

of the lag. This should not need to be repeated, but can be checked periodically or if the physical arrangement of the HBD task is altered.

WACARDIA can save the mean and variability of the lag times to make the HBD task more accurate. The mean lag is adjusted for with high temporal precision and is not problematic so long as it is less than approximately 150 msec; this is because WACARDIA is typically ready to deliver the 200-msec-delay beep 155–180 msec ahead of time. However, the variability in the lag time is a key determinant of temporal precision because although the lag can be measured with the Bluetooth Lag Detection module of WACARDIA, the actual lag at the time of each beep may vary stochastically. Because the HBD task relies on clearly separating 200 msec and 500 msec delay times, we reasoned that the lag times should generally not vary by more than ±50 msec on any given beep (i.e., a 99 % confidence interval width of less than ± 50 msec). In this case, 99 % of the beeps would have a delay of either 150–250 msec or 450–550 msec after the actual R-spike. This ±50 msec suggestion is based on findings of only small differences in judgments of simultaneity comparing beeps delayed by 100, 200, 300, 400, and 500 msec after the R-spike in 22 participants deemed good heartbeat detectors (Wiens & Palmer, 2001).

2.1.3. Participant instructions

WACARDIA includes participant instructions delivered to the screen one sentence at a time as image files that can be modified by the researcher. The instructions are as follows: "The goal of this task is to assess how well you can detect your heartbeat. You will hear a series of 10 beeps, each of which is triggered by your heartbeat. Sometimes, the 10 beeps occur <u>during</u> your heartbeats. Other times, the 10 beeps occur <u>in between</u> your heartbeats. For each series of 10 beeps, indicate whether you heard the beeps <u>during</u> or <u>between</u> your heartbeats. You will also be asked to rate how <u>confident</u> you are in your response. Please do not take your pulse directly using your hands or other objects. Instead, focus on your heart and chest. Finally, please remain still during each trial (the beeping). Do you have any questions?" The participant has an opportunity to practice using the input device (mouse, keyboard, etc.). The researcher also has an opportunity to allow the participant to use an extended practice trial with unlimited beeps presented during the participant's heartbeat.

3. Results

3.1. Key features of the program

WACARDIA is uniquely effective in performing the Whitehead HBD task because it integrates many practical features spanning participant engagement, operator convenience, and measurement accuracy.

3.1.1. Participant engagement

It is well known that the HBD task may be difficult for participants to understand because cardiac sensations might be weak or difficult to feel, and the task itself involves integration of both interoceptive and exteroceptive stimuli with very precise timing (Kleckner et al., 2015). Some studies make it easier for participants to learn how to follow task instructions by including practice trials, which are excluded from the final data (Schulz et al., 2021). WACARDIA includes the option for a practice trial of unlimited duration, which allows participants to experience a series of heartbeat-synchronous beeps until they feel ready to start the actual experiment. During this time, the researcher could use a set of instructions or guide the participant through the process of attempting to feel heartbeats, thereby accounting for individual differences in knowledge of strategies to improve heartbeat detection.

Second, WACARDIA offers the option of a participant-facing graphical interface with Psychtoolbox (Brainard & Vision, 1997; Kleiner et al., 2007; Pelli & Vision, 1997). Research participants are presented with self-paced steps and visual instruction slides, which are more intuitive than simply text-based instructions. Research participants have the choice to respond to each trial by mouse and keyboard or to verbalize their response to the operator.

Finally, WACARDIA is also able to carry out heartbeat detection training, in which individuals try to improve their ability to accurately feel their heartbeats. This is accomplished by allowing participants to view their accuracy directly after each trial, allowing them to adjust their decision-making process accordingly. This is a growing area of application, as heartbeat detection training has been suggested as a novel therapy, with one study suggesting it can reduce anxiety in adults with autism (Quadt et al., 2021). HBD training can also be used to experimentally manipulate interoceptive accuracy to assess its causal effects on related phenomena such as affective experience, attention, decision-making, symptom reporting, etc.

3.1.2. *Operator convenience*

WACARDIA's graphical user interface allows the operator to adjust certain task parameters before launching the program (Fig. 2). We name and describe every pertinent variable in the program, with the option to adjust each one (e.g., the number of trials, tone frequency, and whether to show the participant their progress in the experiment). For details about editing the default values in the main window, see the section below on *Customizability*.

WACARDIA has the option of providing the operator with several forms of live feedback throughout each trial, which allows operators to quickly react to unexpected issues. First, the program displays the ECG in real-time along with indications of where R-spike peaks were detected Fig. 3**b**. This is accompanied by debugging output at every stage of the algorithm, which will immediately notify the operator of malfunctions. In the event of an interruption or abnormal trial data (e.g., ECG artifacts from excessive participant movement), a keyboard command (Shift + Escape) can stop and allow the operator to repeat the trial when they are ready (e.g., after reminding the participant to remain still, helping the participant feel more comfortable, or after adjusting the ECG electrodes). Furthermore, summary graphs saved for each trial allow

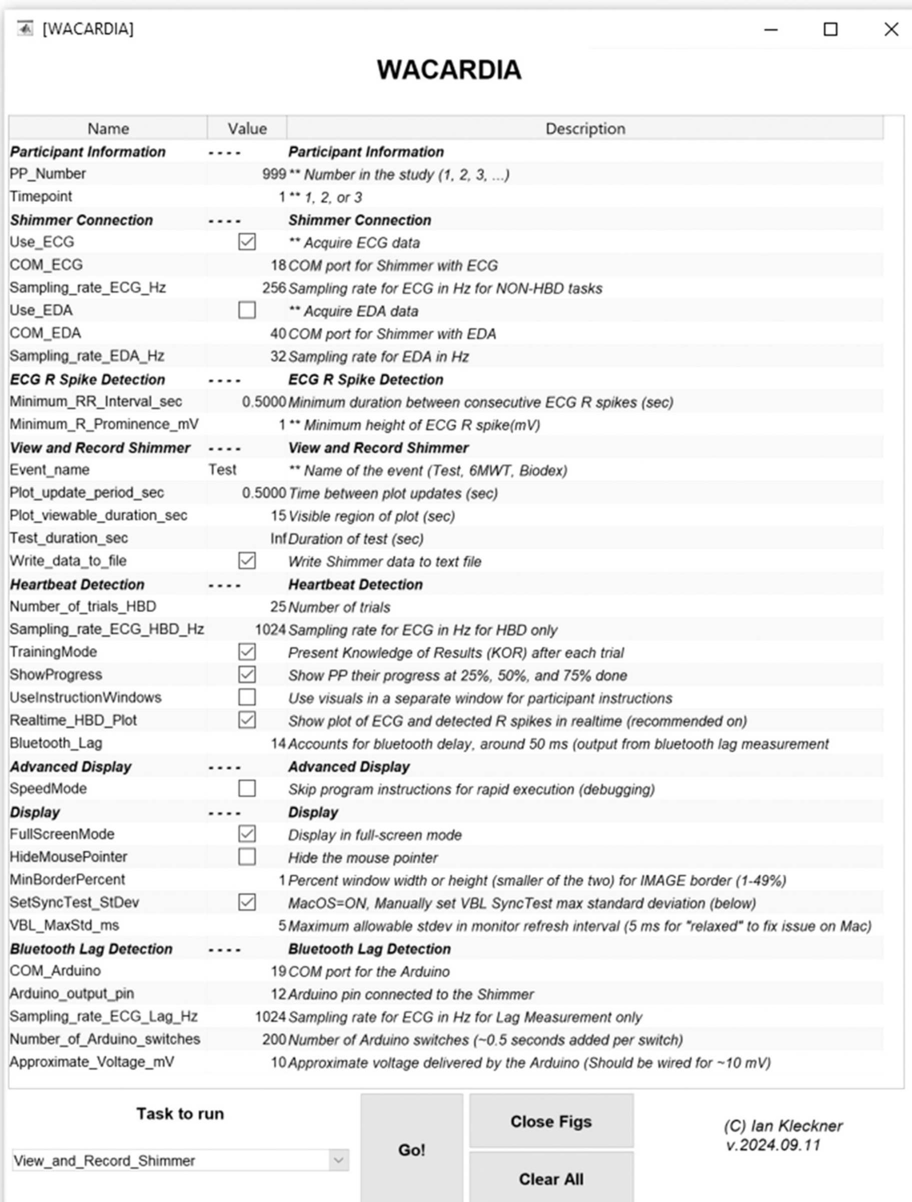

Fig. 2. WACARDIA's main window from which the operator can customize aspects of the HBD task on an individual-by-individual basis.

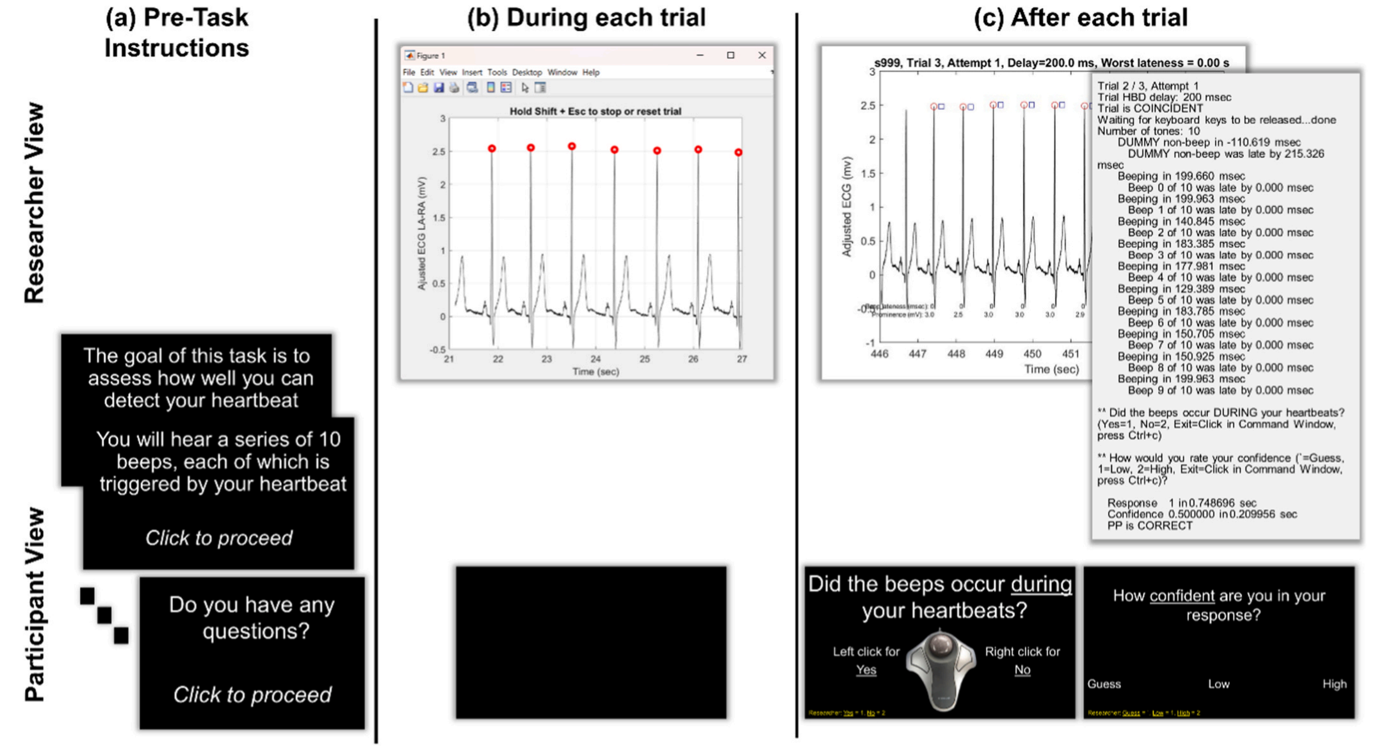

Fig. 3. Researcher and participant views while running WACARDIA. (a) The participant and researcher both see the instruction slides (only showing the first two slides and the last slide; full instructions are in the Methods). (b) During each trial, the participant sees a black screen while the researcher sees a live graph of R-wave from adjusted ECG over time. Detected R-spike peaks are marked by red circles, while T-waves below the minimum prominence threshold (1 mV) are disregarded. The live graphs within trials allow operators to stop the trial immediately using a keyboard command (Shift + Esc) if there are any issues, and then repeat the trial when they have corrected the issue. (c) At the end of each trial, the participant sees questions presented to them while the researcher sees a summary graph for a completed trial automatically saved as an output file. The title displays participant number, trial number, number of times the trial was attempted (if it was repeated due to an error), the audio delay (200 msec for synchronous, 500 msec for asynchronous), and how late the latest beep was presented to assess for any timing issues. The detected peaks are indicated by red circles and beeps are indicated by blue squares. The numbers below each peak show the lateness in delivering the beep from its desired time and the maximum ECG prominence (all of these were delivered with sub-millisecond precision, indicating there were no timing errors). The researcher also sees text output in the MATLAB Command Window for each trial (also saved to a text file). This displays trial information, beep timing, and participant responses. For each beep, both its anticipated timing and its lateness are displayed. Note that the initial "dummy beep" would have been delivered 215 msec late if it had been audible, while the ten true beeps were precisely on time.

abnormal data to be considered post-experiment to help with quality assessment (Fig. 3**c**).

In addition, WACARDIA is configured for a Bluetooth wireless ECG device, which allows for more freedom in the physical arrangement of the research including allowing the participant to move while performing the task, if desired and if the appropriate measures are taken to ensure signal quality (i.e., avoiding tugging on ECG electrodes or leads) and Bluetooth connection fidelity. The operator can be far away or in a separate room if the Bluetooth signal is strong enough. We suggest that computers add an external Bluetooth antenna using a USB extension cable and USB Bluetooth dongle; these are typically very small and inexpensive yet outperform integrated Bluetooth antennae in laptop and desktop computers. High quality Bluetooth communication is important because the algorithm needs to deliver consistent auditory stimuli taking account of delays due to wireless data transfer.

The software can also quantify multiple dimensions of interoception, including interoceptive accuracy (correct and precise monitoring of internal events; e.g., percent correct across all trials, or sensitivity from signal detection theory analyses), interoceptive sensibility (prior beliefs concerning ability to detect interoceptive sensations; e.g. trial-by-trial confidence ratings), and interoceptive insight (metacognitive evaluation of performance on interoceptive tasks; e.g., correlation between confidence and accuracy overall or trial-by-trial) (Critchley & Garfinkel, 2017; Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022). To assess interoceptive sensibility and insight, the program can collect confidence ratings from the participant after every trial. These ratings are formatted for statistical analysis along with summary statistics in the output data.

Finally, WACARDIA includes a program to conduct the heartbeat tracking task, with a graphical interface and similar output data features, supplemental to the main Whitehead heartbeat detection task. The inclusion of HBT is not widely discussed in this paper because HBT has been strongly criticized (Desmedt et al., 2018; Zamariola et al., 2018) and programming HBT is a much easier than programming HBD.

3.1.3. *Measurement accuracy*

Because the HBD procedure deals with precise timing to the msec, eliminating lag in the delivery of auditory stimuli is critical. One of our primary motivations for using Psychtoolbox was its powerful library with functions for producing audio with extremely low onset latency. Specifically, we utilized PsychPortAudio, a high precision sound driver from Psychtoolbox-3. PsychPortAudio allows the program to schedule tones for certain times with sub-millisecond accuracy (Fig. 3**c**).

WACARDIA also includes a module for quantifying the lag inherent in the recording system (Shimmer device, Bluetooth signal transfer, MATLAB software, etc.). The Bluetooth Lag Detection module involves additional hardware shown in Fig. 1b. The results in Fig. 4 show 400 simulated "heartbeats" (signal changes)—the lag has a mean of 14 msec, and a 99 % CI of 3.7–22.4 msec. This amount of lag is easily accounted for in WACARDIA to deliver precisely timed delays (e.g., 200 or 500 msec after each R spike). The 99 % confidence interval corresponds to a temporal precision of ±9.3 msec, which is well within the ±50 msec that would reasonably yield consistent results in conducting the HBD

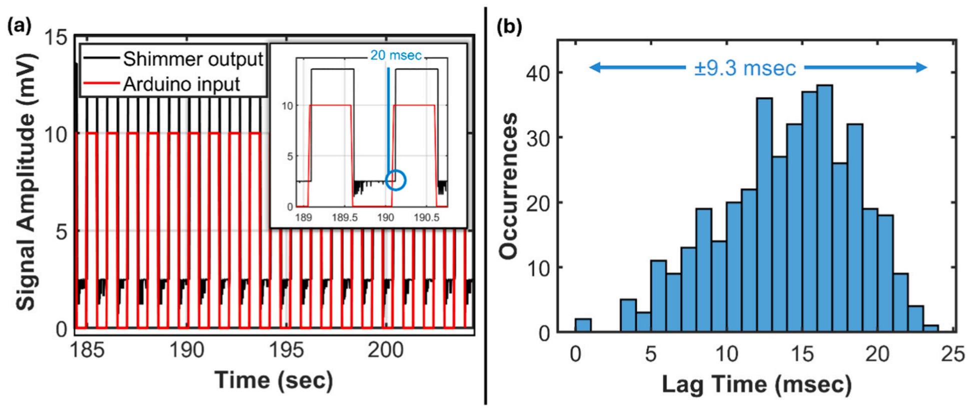

Fig. 4. Output from WACARDIA's Bluetooth Lag Detection module. (a) Example portion of square wave data with Arduino input to the Shimmer (red) and Shimmer detection (black). The inset portion shows the lag itself. There is some noise in the Shimmer measurement seen at the bottom of the trace. (b) Histogram across all 400 lag values, wherein the full width of ±9.3 msec in this example shows the temporal precision in which beeps can be presented (the average lag value of 14 msec can be accounted for to within a fraction of a msec).

task. WACARDIA reminds the user that the lag distribution should be provided in publications using WACARDIA.

Aside from the operator escape key to abort and later restart a trial, WACARDIA has several fail-safes that automatically stop trials if a step in the process malfunctions, allowing the operator to repeat them when they are ready. For example, the trial will automatically end if data acquisition from the ECG device is not successful, if an R-spike is not detected in a reasonable amount of time, or if the system attempts to schedule a tone for too far into the future. The first could be triggered by a malfunctioning Shimmer sensor or weak Bluetooth connection, the second by a misaligned electrode or excessive participant movement, and the third by a miscalculation in the timers or if the computer is running other processes in the background.

WACARDIA contains several other features that improve the reliability of trials by excluding consistently irregular data. In our experimentation, we found that the onset latency in initiating Bluetooth communication with the Shimmer sensor resulted in irregular readings for the first tenth of a second of each trial's ECG readings. This may not be an issue if the program is rewritten for a different ECG device, see the section below on *Customizability*. Thus, we implemented an initial delay in measurement to circumvent the unpredictable amount of missing or lagged data. We also found a consistent tendency to lag in the first tone delivered. The program accounts for this by releasing an inaudible "dummy beep" after the earliest detected R-spike (Fig. 3**c**). These two aspects of WACARDIA's algorithm contribute to the accuracy of auditory stimuli and ensure consistency between trials and participants.

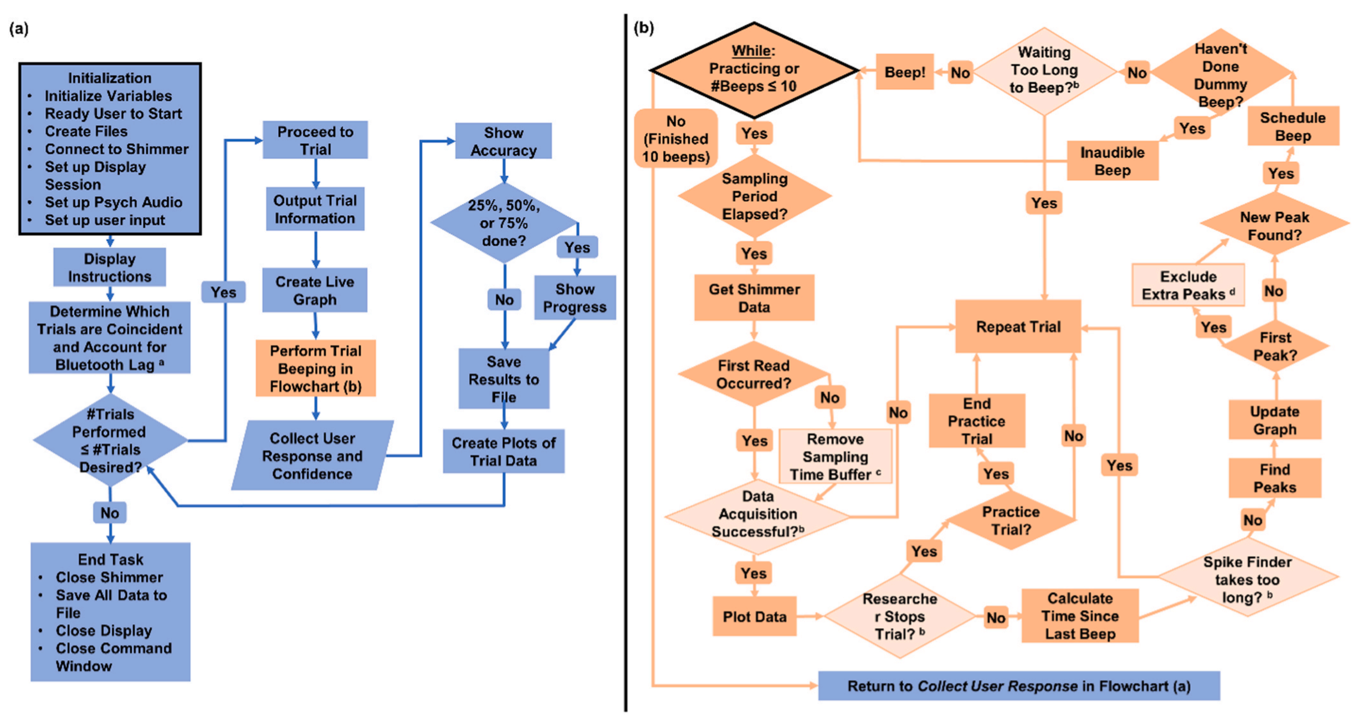

Fig. 5. The flowchart for WACARDIA shows the key components and logic gates that control the sequence of all processes. (a) The program begins at the outlined box in the top left. The orange box in the middle is shown in the second flow chart in (b) The detailed flowchart describes the logical process of producing ten tones after detected heartbeats within each trial, and begins at the outlined diamond-shaped gate in the top-left. Notes: [a] The lag is estimated by the Bluetooth Lag Detection module that can be run prior to starting the HBD program, and may be unique to each laboratory's setup (computer, Bluetooth signal, physical arrangement of devices, etc.). [b] a series of fail-safes that all result in repeating the abnormal trial. [c] removes initial delay in Shimmer measurement (defaults 0.1 s) after the first starting data collection. [d] ignores false peaks from initially noisy measurement on the beginning of each data collection epoch.

3.2. How the program works

This section elucidates the inner workings of our algorithm to conduct HBD. The following information is not necessary for general usage of WACARDIA. However, a reasonable understanding of the code is requisite for efficient debugging and customization (see *Customizability* section below). For example, a stream of trial information is automatically output by the program in the MATLAB command window (Fig. 3**c**), notably in circumstances which prompt the need to repeat a trial. Understanding the precise conditions under which the command window yields certain statements is essential towards isolating the problem with a trial. The flowcharts contained in this section illustrate the abstract components of the program and can be used as a roadmap in interpreting the complete code, with key details provided in the figure captions (Fig. 5).

3.3. Customizability

We intend for WACARDIA to be readily customizable to accommodate the current and future variations of HBD. However, for researchers who want to make changes, in this section we suggest and illustrate basic settings and more advanced modifications that can be made to WACARDIA.

On a basic level, program parameters can be manipulated to adjust certain task features within the existing infrastructure. Much freedom is already permitted by editing variables in the main WACARDIA window (Fig. 2). Through the graphical interface, the operator can manipulate the number of trials, the delay time for synchronous and asynchronous beeps, the sensor sampling rate, and whether knowledge of results is presented to participants after trials. In particular, 'Minimum_RR_Interval_sec' and 'Minimum_R_Prominence_mV' have a key role in peak detection. The former determines the minimum interval of time that must separate consecutive R-spikes to be detected, and the latter determines the minimum spike prominence that will be considered an R-spike. These values are calibrated to accommodate natural variation in heartbeats across research participants and ECG electrode configurations. In addition to the Task Starter, other variables in the source code can be easily adjusted. These include 'USE_PTB' to use the participant-side graphical interface, 'Nbeeps_per_trial' to choose the number of tones in a trial, and 'delay_HBD_(non)coincident_sec' to determine the delay between R-spikes and delivering tones, to name a few. Further detail describing the function of each pertinent variable can be found in the source code file "HeartbeatDetection_expt_Shimmer.m" under the heading "Initialization." Finally, the default values for the main WACARDIA window can be edited in "Task_Starter.m" in the section labeled "Input specs table."

In general, we expect others to make additions to the code to accommodate different variations of the standard Whitehead task. For example, one prominent example of an HBD variation is the method of constant stimuli (MCS), where tones are delivered at six distinct intervals from the heartbeat (i.e., six distinct locations in the cardiac cycle) (Brener & Kluvitse, 1988; Brener et al., 1993; Wiens & Palmer, 2001). WACARDIA could be naturally altered to perform MCS by quantifying six different delay times rather than just two. Some other simple adjustments to the program could be made to change the ECG device or the mode of stimuli; for example, using visual stimuli instead of audio beeps (Salomon et al., 2016; Wittkamp et al., 2018). A slightly more involved task would be changing the trials to run for a certain duration rather than a certain number of heartbeats (Asmundson et al., 1993; O'Brien et al., 1998; Suzuki et al., 2013). The entire code could also be rewritten in a different language to eliminate the reliance on MATLAB, a process which would be assisted by the flowcharts in this paper. In general, the algorithm can theoretically accomplish any function based on performing an action between a person's heartbeats, regardless of relation to interoception (e.g., relating respiratory and cardiac cycles to conscious tactile perception; (Grund et al., 2022). By contrast, converting the frequency of asynchronous tones to 120 % of the actual heartrate (e.g., (Mul et al., 2018) is not compatible with the algorithm and would require more substantial modification.

3.4. Other features

WACARDIA can also record ECG data at a user-defined sampling rate for use in other analyses such as resting HR or HRV, or changes in those values during different tasks (e.g., heart rate before, during, and after physical activity). WACARDIA simply saves the ECG data to a text file for analyses in a separate program.

4. Discussion

Here, we have introduced Wireless Assessment of CARDiac Interoceptive Accuracy (WACARDIA), a freely accessible open-source program to perform the Whitehead heartbeat detection task. This paper has described key features, underlying mechanisms, and future variations of WACARDIA. With this open-source software, we hope to make research on interoception more accessible by reducing the burden of researchers of having to write their own code from scratch. While a superior, standardized method of measuring cardiac interoceptive accuracy beyond the Whitehead heartbeat detection task is still sought after (Brener & Ring, 2016), WACARDIA may help offer a foundation for other researchers to explore those options to further the field of psychophysiology. This is important because, to our knowledge, this is the first and only freely available and open-source software to run the Whitehead heartbeat detection task.

WACARDIA has several key strengths. First, the software is free and open source. This defining characteristic makes it unique to our knowledge and easy to apply in clinical research. Second, the program implements a robust algorithm to run the task accurately and effectively, including critical components which ensure the accuracy of the collected data. The use of Psychtoolbox audio scheduling functions contributes to the precision of auditory stimuli delivery. In addition, we incorporated an initial measurement buffer and inaudible "dummy" beep to exclude potentially inaccurate sensor readings at the start of recording epochs. WACARDIA provides the operator with a live updated ECG for real-time quality assessment and the ability to use a keyboard command to repeat the trial. To guarantee proper performance, we implemented additional fail-safes protecting against malfunctions and interruptions throughout the process, such as checking the time between R spikes and checking for delays in delivering audio beeps. Finally, WACARDIA is particularly flexible and versatile. As described in the section on *Customizability,* basic adjustments in the operator's Task Starter can produce a range of desired effects to perform alternative variations of HBD without the need to edit the source code. Furthermore, WACARDIA offers immediate feedback enabling heartbeat detection training similar to that performed by Quadt et al. (2021) and an entirely separate program to run HBT. These features make WACARDIA's useful in clinical applications as well. Finally, the fact that these tasks can be run wirelessly makes the setup and conduct more convenient and safer by avoiding long wires that may be tripping hazards for some participants. The wireless format also allows easier transitions from HBD/HBT tasks to other tasks, including ambulatory tasks such as walk tests or exercise before or after HBD that involve moving to a different room in a lab, for example without having to disconnect and re-connect wires.

WACARDIA also contains a few limitations. First, WACARDIA currently operates exclusively with Shimmer sensors and MATLAB, chosen because Shimmer Sensing developed libraries for use with MATLAB. The program also depends on several additional MATLAB toolboxes, including the Signal Processing Toolbox and Statistics and Machine Learning Toolbox. This places WACARDIA at a higher price point than other toolboxes such as the Systole package for Python using the Nonin finger pulse oximeter device (Legrand & Allen, 2022).

However, we believe these are all at a modest price point compared to other hardware options for measuring high-quality ECG signals and other software options (e.g., custom written code). In addition, WACARDIA itself is free and could be modified for use with other ECG sensors or programming environments such as Python. Second, because WACARDIA uses the Whitehead heartbeat detection task, any weaknesses of that HBD task itself would also apply to WACARDIA (for discussion, see (Brener & Ring, 2016; Ring & Brener, 2018). That said, this task is still among the most widely used and well validated tasks of interoceptive accuracy.

To contextualize this paper within the literature, we compare it to the body of publications regarding methods of measuring cardiac interoceptive accuracy. One method uses infusions of the beta adrenergic agonist isoproterenol to increase heart rate exogenously and asks participants to rate their perceived heart rate second-by-second using a dial (Khalsa et al., 2009). Recent examples of tasks without exogenous physiological stimulation include the Heartbeat Matching Task (HMT) (Palmer et al., 2019), the Phase Adjustment Task (PAT) (Plans et al., 2021), and the Heart Rate Discrimination Task (HRD) (Legrand et al., 2022). The first, HMT, requires participants to match the rate of a visual pulse to their own heartbeat using a sliding scale. Similarly, PAT participants adjust the offset between external tones and their heartbeats until they feel the two as coincident. Finally, HRD is an adaptation of HBD that applies 2-Interval Forced Choice design, an exteroceptive control condition, and dynamic adjustment of the asynchronous feedback rate. While all three papers present novel and compelling ideas, only Legrand et al. accompany their description of the procedure with source code. Although we did not develop the Whitehead heartbeat detection task, we hope to normalize the behavior of publishing code and describing algorithms in accordance with the FAIR (Findable, Accessible, Interoperable, Reusable) principles for research software (Barker et al., 2022).

In future work, we aim to expand WACARDIA's functionality. First, we aim to synchronize stimulus presentation to certain portions of the heartbeat cycle (e.g., (Leganes-Fonteneau et al., 2021)). This could occur through researchers providing their own stimuli presented at different delays from each heartbeat (e.g., end of diastole immediately after the R spike vs. end of systole 300 msec after the R spike). This could also include communication with other devices through COM port communication (e.g., to deliver a shock or other sensory stimulus; (Edwards et al., 2002)). Second, we can incorporate other devices such as other brands of wireless ECG, traditional wired ECG devices, respiration, EDA, etc. to trigger stimuli based on physiological data. The Bluetooth Lag module can also be adapted to test the lag in any wireless (or wired) device. These additional modules can be completed in the coming years to get the next generation of scientists helping with interoception research (e.g., annual updates with summer interns programming a single module, or students working longer programming multiple modules).

WACARDIA could also be reshaped to incorporate emerging technologies in the measurement of heartbeats. The program is currently configured to operate on a wireless Shimmer ECG Unit, but finger pulse oximeters have also been utilized in interoceptive tasks (e.g., (Caseras et al., 2013; Haruki & Ogawa, 2021)); however, results have suggested that the device causes increased heartbeat sensation in the finger and influences interoceptive accuracy (Murphy et al., 2018). Alternatively, recent studies have investigated the reliability of mobile photoplethysmography (PPG) for analyzing heart rate variability through wearable bands and phone cameras (Bolanos et al., 2006; Jeyhani et al., 2015; Morelli et al., 2018). PPG sensors are also viable recording devices for cardiac interoceptive accuracy (Murphy et al., 2018) and have become more prevalent in recent interoception tasks (Plans et al., 2021; Ponzo et al., 2021). We have opted to implement the wireless ECG device because of the EGC's established accuracy and wide acceptance in scientific labs. Still, upcoming revisions to our HBD program can accommodate these substitute measurement instruments or other physiological recording devices, provided they are benchmarked for accuracy (Kleckner et al., 2021).

In conclusion, this paper described the key features, algorithms, and customizable properties of WACARDIA, the Wireless Assessment of CARDiac Interoceptive Accuracy. WACARDIA is a novel, free, open-source MATLAB program to administer the Whitehead HBD, which is the most widely used and well validated assessment of cardiac interoceptive accuracy. Although HBD is widely used, to our knowledge there is no established and available software to run the task, which requires researchers to write their own code or simply prevents them from conducting HBD at all. By publishing this software as open source, we hope to contribute to scientific transparency and reduce the burden on researchers conducting studies in the growing literature on cardiac interoceptive accuracy. Researchers can access WACARDIA for free along with video tutorials and additional information at www.github.com/iankleckner/wacardia and http://wacardia.iankleckner.com.

Author contributions

The program was conceived and developed by IRK with additional coding of the Bluetooth Lag Detection module by JJC. The manuscript was written by JJC and IRK. All authors approved the final version of the manuscript.

AI Statement

The authors did not use any generative AI or AI-assisted technologies in working on this project or writing this manuscript.

CRediT authorship contribution statement

Jacob J. Chung: Writing – review & editing, Writing – original draft, Visualization. **Ian Kleckner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Ian Kleckner reports financial support was provided by University of Maryland Baltimore. Ian Kleckner reports a relationship with National Cancer Institute that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

https://github.com/iankleckner/WACARDIA

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