University of Birmingham
Research at Birmingham

Towards a psychophysics of interoceptive processes

Brener, Jasper; Ring, Christopher

DOI:
10.1098/rstb.2016.0015

License:
None: All rights reserved

Document Version
Peer reviewed version

Citation for published version (Harvard):
Brener, J & Ring, C 2016, 'Towards a psychophysics of interoceptive processes: The measurement of heartbeat detection', *Royal Society of London. Proceedings B. Biological Sciences*, vol. 371, no. 1708, 20160015. https://doi.org/10.1098/rstb.2016.0015

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Towards a psychophysics of interoceptive processes: the measurement of heartbeat detection
Jasper Brener, Christopher Ring
Phil. Trans. R. Soc. B 2016 371 20160015; DOI: 10.1098/rstb.2016.0015. Published 10 October 2016

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 24. Apr. 2024

Towards a psychophysics of interoceptive processes: the measurement of heartbeat detection[i] [ii] [iii]

Jasper Brener[a] and Christopher Ring[b]

[a]Department of Psychology, Stony Brook University, Stony Brook, NY 11790, USA,
[b]School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham,
University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

Keywords: Interoceptive Sensitivity, Psychophysics, Heartbeat Detection, Heartbeat Counting.

Abstract:

It is difficult to collect objective evidence of interoception. Unlike exteroception, the effective stimuli for interoception are often unknown, and even when identifiable, they are difficult to control experimentally. Furthermore, direct stimulation of the interoceptors is seldom appropriate in human experimentation. Hence, non-invasive behavioral measures of accuracy in heartbeat detection have frequently been adopted to index interoceptive sensitivity. However, there has been little standardization and the two most popular methods for assessing heartbeat detection, Heartbeat Tracking and Two Alternative Forced Choice methods, appear to be biased and of questionable validity. These issues do not arise with other methods that are based on classical psychophysics and that enable subjects to indicate when during the cardiac cycle their heartbeat sensations occur. Not only are these classical methods highly reliable, but they provide continuous unbiased measures of the temporal locations of heartbeat sensations and the precision with which these sensations are detected.

Introduction:

Over the past 50 years, research on interoception has grown exponentially from 17 citations of “interocept*” in 1965 to 8,440 in 2015 (Web of Science). The early Russian work was summarized in Razran’s (1961) landmark article (1) on the subject and demonstrated, inter alia, that interoception participated fully in the inter-sensory processes of Pavlovian Conditioning. Through the conventional procedure of presenting stimuli contingently, interoceptive stimuli can acquire the capacity to signal other interoceptive stimuli (interointeroceptive conditioning), or exteroceptive stimuli (interoexteroceptive conditioning) and exteroceptive stimuli can acquire the capacity to signal interoceptive stimuli (exterointeroceptive conditioning). Such conditioning provides routes through which interoception can participate in the regulation of everyday behaviors (2), and in recent years, research has examined its role in a broad range of affective and cognitive processes as well as in personality and psychological disorders (3).

The James-Lange theory of emotion, which attributed a causal role to interoception in generating emotion provided a model for these research developments. Tests of this theory stimulated a line of psychophysiological and neuroscience research that has gathered momentum over the past half century (4, 5). As the motivational and guidance functions of interoception attracted more attention, research broadened to explore its influences on such cognitive processes as implicit and explicit memory (6, 7), decision making (8) and auditory processing (9). Individual differences in sensitivity to internal stimuli have also been investigated as potential sources of variation in the sense of self (10) and such psychosocial processes as imitation (11) and empathy (12). They have also been found to be associated with some psychological disorders (13, 14) but not others (15, 16). These research developments have been accompanied by detailed neurophysiological models that describe the pathways and processes by which interoception may achieve its behavioral and psychological effects (5, 17-22).

Despite this substantial interest in interoception, standard methods for its investigation have not been adopted. In this regard the study of interoception has diverged from the history of exteroceptive psychophysics which is grounded in standard methodologies that have provided the foundations of experimental psychology. Fechner's classical methods of adjustment, constant stimuli and limits (23) and Bekesy's "staircase" method (24) enabled thresholds to be precisely and reliably determined for different modalities and individuals. Stevens' Power Law (25), which depended on the methods of Magnitude Estimation and Production, described our differential sensitivity to features of the physical and social environments.

Recognizing the importance of standard methods in interoceptive research, Garfinkel et al (26) have recently attempted to rectify the "*inconsistency in how interoception is defined and quantified*" by proposing a three-dimensional scheme that distinguishes between the measurement of (i) interoceptive accuracy, (ii) interoceptive awareness and (iii) interoceptive sensibility. They define "interoceptive accuracy" in terms of the precision and reliability with which individuals detect internal events such as heartbeats or gastric contractions whereas "interoceptive awareness" denotes the accuracy with which subjects assess their own precision in detecting such events. Both "interoceptive accuracy" and "interoceptive awareness" may be assessed by objective performance measures. On the other hand, "interoceptive sensibility", which refers to the extent to which individuals attend to their internal states, is assessed using self-reports.

The current paper is concerned exclusively with measuring the accuracy of heartbeat detection. The methods employed to make these measurements yield most of the data on which current psychophysiological research on interoception relies. They are different from standard psychophysical methods in several respects: notably, the effective dimensions of interoceptive stimuli have not been precisely defined and are not directly controlled by the experimenter.

More conventional psychophysical methods involving direct stimulation of the viscera were employed in the early Russian research on interoception to map the sensitivities of interoceptive domains (27). This approach was recently adopted by Khalsa et al (28) in a comprehensive examination of the interoceptive effects of sympathetic stimulation. Varying doses of isoproterenol, a non-specific beta-adrenergic agonist, were administered by bolus injections and the responses of subjects were tracked using psychophysiological measures. Dose-dependent effects were found on cardio-respiratory activity and on cardio-respiratory sensations as measured by Magnitude Production (25). As dose increased, so too did feelings of physical anxiety and the specificity with which heartbeat sensations were localized in the chest.

Using the same methods on a patient who had nearly complete bilateral lesions of the insula and cingulate cortices, Khalsa et al (19) raised questions about standard views of the receptors responsible for interoceptive sensations and the central structures necessary for visceroception and emotion. This patient exhibited "*dose-dependent changes in interoceptive awareness that were comparable to healthy control participants, albeit somewhat delayed in time*". Accordingly, Khalsa and colleagues suggest "*a comprehensive redefinition of interoception involving 'afferent information that arises from anywhere and everywhere within the body'(2), including through the skin via pathways that are usually considered to support exteroception.*" Since it is challenging, if not impossible, to identify the pathways through which individuals sense their visceral activities, this redefinition seems necessary.

Direct stimulation methods of the sort used by Khalsa (28) are too intrusive to be used in most experiments concerned with the influence of interoception on emotion, cognition and/or clinical conditions. In such experiments, probes of interoceptive sensitivity should minimize influences on the subjects' affective and cognitive states and should not tire or tax them. These considerations have led to the wide adoption of non-invasive behavioral methods for assessing individual differences in sensitivity to heartbeat sensations. Such methods are minimally intrusive and the best of them provide convincing, objective, quantitative measurements of interoceptive sensitivity. However, as discussed below, the two methods that have dominated the field, Heartbeat Tracking and Two Alternative Forced Choice (2AFC) discrimination tasks, are subject to substantial criticism.

Heartbeat Tracking Tasks

Heartbeat tracking encompasses a suite of quick and easy methods designed to measure cardioception by requiring participants to report the number of heartbeats (29, 30), tap on each heartbeat (31-34), or adjust the rate of brief exteroceptive stimuli to match their heart rate (35, 36).

The heartbeat counting task introduced by Dale and Anderson (29) and popularized by Schandry (30), asks participants to detect heartbeats during short epochs. The onset and offset of each period (25/35/45 s) is signaled by a brief tone, after which the subject is *"requested to report the counted or estimated number of heartbeats*" [(30) p.484]. The absolute difference between the number of actual and reported heartbeats is divided by the number of actual heartbeats either to generate an error score, or subtracted from one to generate a perception score. Perfect detection yields an error score of zero (and a perception score of one), while under-reporting or over-reporting the actual number of heartbeats (by up to 100%) yields an error score of greater than zero (and a perception score of less than one). Schandry's (30) grand mean error score of 0.26 indicated that counted heart rate (59 bpm) underestimated actual heart rate (80 bpm) by 26%. Other studies find similar scores. Schandry and Specht's (37) participants underestimated their heart rates by 36% when resting, 32% before public speaking, and 23% after exercise. Ring et al's (38) participants underestimated their heart rates by 37% when sitting, 42% when standing, and 20% after exercise. It seems implausible that normal adults would make counting errors of this magnitude and the substantial under-reporting of the number of heartbeats implies that participants did not reliably detect heartbeat sensations.

Methods have not been devised for determining whether the reported count is based on heartbeat sensations experienced during the task or is an estimate of the number of heartbeats based on the participant's previously-acquired beliefs. As noted above, Schandry explicitly told participants to *estimate* the number of heartbeats. Accordingly, participants with knowledge about heart rate may generate accurate counting scores without detecting any heartbeat sensations.

There is convincing evidence that providing accurate information about heart rate via concurrent feedback improves subsequent heartbeat counting scores (38-40). That this improvement is also found with cardiac non-contingent feedback indicates that improved counting scores are attributable to improved knowledge rather than improved sensitivity to heartbeats (34, 38). Windmann et al's (41) research provides additional evidence that counting scores have little connection with heartbeat sensations: Changes in heart rate elicited by a cardiac pacemaker were not accompanied by changes in the number of counted heartbeats. Their participants reported heart rates of 52, 54 and 59 bpm when actual heart rates were paced at 61, 76 and 109 bpm, yielding error scores of 0.15, 0.29 and 0.46, respectively. These substantial discrepancies imply that, rather than counting heartbeat sensations, participants based their counts on beliefs about heart rate.

Further evidence against the validity of the counting task comes from experiments on the effects of body posture on counting performance. Studies consistently report that heartbeat-counting scores are better when supine than standing (37, 38, 40, 42, 43). Since stroke volume is augmented in the supine posture, this effect was initially attributed to increased cardiac stimulus intensity. However later, the increased accuracy was shown to be due to a reduction in heart rate when moving from the standing to the supine posture that reduced the difference between actual and counted heart rates. For example, Ring and Brener (40) found that counted heart rates did not differ between supine (50 bpm) and standing (48 bpm) despite large differences in actual heart rates between supine (70 bpm) and standing (86 bpm). This latter explanation is supported by the results of five experiments showing that heartbeat detection accuracy is not influenced by passive body tilt (44).

In tapping tasks, e.g. (33), instead of counting, subjects tap or press a key on each heartbeat. Like counting tasks, they may be criticized because individuals, regardless of their cardioceptive sensitivity, can generate accurate scores by tapping (counting) at frequencies that approximate their heart rates (45). Tapping does, however, provide a means, not available in the covert counting method, of verifying that subjects are detecting heartbeats rather than responding at the rate they believe their hearts to be beating. In particular, the distribution of latencies between R-waves and taps can be analyzed for preferences that are time-locked to the R-wave. For example, if a subject presses the button more frequently at around R+250 ms than at other latencies, this would indicate that he/she used heartbeat sensations as signals for tapping. While the tapping method has been used by several investigators (31, 32, 34, 36, 46, 47), results have been unconvincing.

For example, Flynn and Clemens (48) instructed participants to press a key in synchrony with their heartbeats or sounds. Based on its response latency, each key press was assigned to one of six 100-ms bins (1-100, 101-200, 201-300, 301-400, 401-500, 501-600 ms) following the R-wave or sound. Responses to heartbeats were evenly distributed across the six latency bins indicating that participants could not reliably detect heartbeats. However, this failure could not be attributed to general perceptual limitations because they exhibited non-random distributions in the auditory tapping task. Since heartbeat detection may be evidenced by other procedures, it was inferred that the demands of button pressing interfered with cardioception by competing for resources with heartbeat detection. Thus, the available evidence indicates that heartbeat tapping tasks have little to recommend them as methods for assessing cardioception.

It was noted above that in counting and tapping tasks, participants may base their responses on an assumed or believed heartbeat frequency rather than on heartbeat detection. Heart rate estimation tasks generate data on a participant’s knowledge about heart rate that might guide such guessing. In these tasks participants are explicitly asked to estimate their current heart rate rather than to process current heartbeat sensations. Essau and Jamieson (49) subtracted estimated from actual heart rates and found evidence for slight underestimation (–0.8 bpm) to modest overestimation (+5.4 bpm), indicating that participants possess accurate knowledge about resting heart rate. Using magnitude estimation, Pennebaker and Hoover (50) required participants to estimate their heart rates on a scale of 1 (*slow*) to 50 (*normal*) to 100 (*fast*), during various tasks (e.g., meditation, reading, lifting). Overall, heart rate estimates correlated positively and moderately-to-highly with actual heart rates (rs=.36-.40, ps<.05). Importantly, this association was independent of any ability to detect heartbeat sensations. Data generated by these estimation tasks suggest that participants are knowledgeable about heart rate. The implication is that tracking (counting/tapping) tasks can be solved by a combination of accurate knowledge and inaccurate interoception.

Two-Alternative-Forced-Choice (2AFC) Tasks: Signal Detection Methods

A popular method for assessing cardioception that logically requires heartbeat detection for good performance was developed by Whitehead et al (51). In their two-alternative forced-choice (2AFC) task, participants were presented with a series of cardiac-contingent light flashes that on half the trials were delayed after the R-wave by 128 ms (S+ trials) and on the other half by 384 ms (S– trials). The S+ and S– designations were based on estimates of when the pressure pulse wave generated by ventricular contraction would stimulate mechanoreceptors in and near the heart to produce heartbeat sensations. Heartbeat sensations should be simultaneous with S+ stimuli and non-simultaneous with S– stimuli. Based on signal detection theory, a decision that heartbeats and light flashes were simultaneous was classified as a *hit* on S+ trials and a *false alarm* on S– trials. Whitehead's (51) grand median d' of 0.33 (0.05-1.56) indicates that most participants struggled to discriminate between stimuli presented at these two intervals. Only one-in-four participants met the d' criterion (≥0.75) for classification as a heartbeat detector, a finding replicated by others [e.g. (52, 53)].

That only 25% of subjects could discriminate S+ from S– trials was considered an artifact of an excessively stringent criterion and demanding temporal discrimination. Accordingly, several procedural adjustments, such as increasing the delay after each R-wave by 30 ms on S- trials, were made by Katkin and others (54-56), to facilitate discrimination between S+ and S- stimuli. However, these attempts to make the Whitehead task easier were unsuccessful. Furthermore, by making the S+ and S– stimulus trains more easily discriminable [e.g. (54)], the procedural modification defeated an important feature of the Whitehead task: that S+ and S– stimuli differed only in their temporal relationship to concurrent heartbeats. In the Whitehead task, but not in the Katkin task, the distribution and sequence of inter-stimulus intervals was identical to the distribution and sequence of inter-heartbeat intervals on both S+ trials and on S- trials [cf. (57, 58)]. The Katkin task, however, provided non-cardiac temporal cues that could be used to identify S+ and S– trials [(59), p.452]: since the inter-stimulus intervals were 30 ms longer for S+ signals than S– signals, the time between the first and tenth stimuli was 300 ms longer for the S- than S+ series. Even when some of these methodological concerns were addressed, by using a constant initial delay of R+300 ms on S– trials, only one-in-five participants discriminated between the S+ and S– stimuli (56). Davis and colleagues reported that participants could not detect heartbeat sensations on the Davis, Katkin and Whitehead tasks (A' = 0.55, 0.52 and 0.53, respectively). According to Hantas et al (60) only one-in-four participants (17/63) performed better than chance and Katkin et al [(55), p.165], concluded that *"...most participants show very little ability to detect their own heartbeats without training*". In sum, none of the aforementioned 2AFC task variants can be recommended.

Not only was there a proliferation of 2AFC variants but, as noted by Kleckner et al (61), different versions have employed between 15 and 200 trials. Since classical test theory tells us that precision of measurement increases as a function of the square root of the number of observations, these investigators explored the number of trials required to achieve a sufficiently reliable measure of cardioceptive accuracy without placing excessive burdens on participants. Their analysis suggested that at least 40 trials are required to yield acceptably reliable results and a reasonable estimate of effect size. This important step towards methodological standardization does not, however, explain why only 25% of subjects are identified as heartbeat detectors by 2AFC methods.

A two-interval discrimination task should be easier, the more different are the S+ and S– delays. Stormer et al's (62) task customized the stimulus delays based on cardiac cycle duration: one quarter (S+) and three quarters (S–) of the previous interbeat interval. In this task, the S+ and S– delays will be more than 256 ms apart (i.e. the gap in the Whitehead task) for anyone with a heart rate of 116 bpm or slower. Participants judged that heartbeats were simultaneous with tones presented early (hits=69%) and non-simultaneous with tones presented later (false alarms=27%) in the cardiac cycle. Performance on this task (d'=1.14) was better than on the Whitehead (d'=0.61) and Katkin (d'=0.07) tasks. The relative ease of this task may arise from two features: greater temporal separation between the S+ and S– delays, and, later presentation in the cardiac cycle of the S+ and S–. The latter explanation is compatible with Okifuji et al (63) who compared two Whitehead task variants: Discrimination was superior with S+/S– delays of 250/550 ms than with S+/S– delays of 100/400 ms, although both delay pairs were 300 ms apart. Accordingly, the better performance with the 250/550 ms pairing may be attributed to the S+ stimulus occurring closer to and the S– stimulus occurring further from heartbeat sensations(64).

Although performance on the Stormer task is better than on other Whitehead tasks, it is not free of bias. First, individuals with slow and fast heart rates do not differ in the temporal locations of their heartbeat sensations [e.g. (65)]. Second, the customized delays make the difficulty of the discrimination dependent upon heart rate: the slower the rate, the easier the discrimination because the S+/S- gap is bigger and the S+/S- fall closer/further from heartbeat sensations.

The convention of classifying simultaneity judgments as correct only for stimuli presented at the S+ delay and incorrect for stimuli at the S- delay originated with Whitehead et al (51) who labeled R+128 ms stimuli as *immediate* and R+384 ms stimuli as *delayed* relative to the heartbeat sensation. Since then, many attempts have been made to define delays that optimize the two-interval task, including: 100/31-500 ms (54), 0/400 ms and 100/400 ms (66), 100/330-600 ms (56), 120/380 ms (67), 200/500 ms (68), 250/500 ms (69), 100/400 ms and 250/550 ms (63), and 300/50 ms (70). Although it is difficult to make comparisons because of the proliferation of discrimination indices, the tasks yield similarly low levels of discrimination. Overall, about one-in-three/four people reliably judge heartbeat sensations to be simultaneous with S+ stimuli and non-simultaneous with S- stimuli (71). This poor heartbeat detection performance may be because only this proportion of the population can detect heartbeat sensations and/or the tasks are insensitive psychophysical instruments. Since multi-interval tasks yield higher detection rates (see below), it is likely that two-interval tasks are relatively insensitive (52).

The problem originates with the flawed assumption that heartbeat sensations occur in the same temporal location relative to the R-wave in all individuals. Take the case of someone tested on the Whitehead task who feels heartbeat sensations at R+256 ms, and judges stimuli presented at R+128 ms (S+) and R+384 ms (S–) to be simultaneous with heartbeat sensations an equal number of times. It is not possible to determine whether non-discrimination between the S+ and S- stimuli is due to an inability to detect heartbeat sensations, or because the S+ and S– stimuli are equally coincident with their heartbeat sensations. This difficulty in interpreting a lack of discrimination will always arise when a heartbeat detection task uses only two intervals, but it may be avoided by using multiple intervals that span the cardiac cycle.

Multi-Interval Tasks: Classical Psychophysical Methods

Clemens (66) was the first to use classical psychophysical methods to identify the temporal location of heartbeat sensations and thereby to specify the optimal S+ and S– delays. In three studies he asked participants to press a button if stimuli presented at various intervals after the R-wave were simultaneous with heartbeat sensations. First, he found that signals at R+0 ms and R+100 ms could both be discriminated from signals at R+400 ms but not from one another. This finding was extended by a further study that used a Method of Adjustment task to show that participants could not discriminate between signals presented at R+0, R+60, R+120, R+180 and R+240 ms, i.e. during the first 240 ms of the cardiac cycle. Finally, using a five-interval Method of Constant Stimuli (MCS) task, Clemens found that signals at R+0, R+100 and R+200 ms were chosen to be simulanteous with heartbeat sensations significantly more than signals at R+300 and R+400 ms.

In a six-interval MCS task developed by Yates et al (72), participants judged whether a single light flash presented at R+0, R+100, R+200, R+300, R+400 and R+500 ms was simultaneous with their heartbeat sensations. Heartbeat sensations were more likely to be judged simultaneous with lights delivered in the middle (200, 300, 400 ms) than early (0, 100 ms) phase of the cardiac cycle, thereby challenging the assumption that heartbeat sensations dissipate before R+384 ms (51). That only eight (40%) participants exhibited modal preferences for the 0, 100 or 200 ms intervals demonstrated that individuals differ in the temporal locations of their heartbeat sensations. Surprisingly, only five (25%) participants met Yates et al.'s (72) response consistency and specificity criteria to be classified as heartbeat detectors. A later study by Brener et al (73) indicated that this poor performance was due to data limitations, with a single stimulus presentation being insufficient to make reliable simultaneity judgments.

The potential weaknesses of the previous tasks were corrected by Brener and Kluvitse (74), who developed a task based on the Method of Adjustment and MCS. By pressing one of six buttons, participants could engage an unlimited number of tones at one of six intervals (0, 100, 200, 300, 400, 500 ms) after the R-wave. Pressing a seventh button registered a choice that tones at the prevailing interval were most simultaneous with heartbeat sensations. Tones served as comparison stimuli because temporal judgments are more accurate in the auditory modality than visual modality (75). Before engaging in the heartbeat detection task, participants judged light-tone simultaneity to familiarize them with the general task demands. The overall distribution of simultaneous choices defines a "sensation envelope" (76) within which heartbeat sensations are judged to be simultaneous most often with tones presented 200 and 300 ms after the R-wave, and simultaneity was more frequent at R+100 and R+400 ms than R+0 and R+500 ms.

Unlike most other tasks, this one yields measures of the temporal locations of heartbeat sensations as well as the accuracy of heartbeat detection. Brener and Kluvitse (74) found considerable individual differences in both of these measures. The temporal locations of heartbeat sensations (Modal Preferred Interval) ranged from 100 to 400 ms, and the specificity of discrimination (Standard Deviation of the Preferred Interval) ranged from 43 to 167 ms. Importantly, both performance measures were valid (77) and reliable (65, 78). Independent replications (64, 79-82), confirmed that heartbeat sensations were perceived 100-400 ms after the R-wave.

Brener et al (1993) explored a simpler task (52) which, like the Yates method (72), was based on the MCS. Participants judged whether a series of 10 tones presented at R+0, R+100, R+200, R+300, R+400 or R+500 ms were simultaneous with heartbeat sensations. Later, it was found that reducing the number of tones to 5 on each trial did not impair the reliability of the task (73) but abbreviated the administration time considerably. Tones delivered 100, 200 and 300 ms after the R-wave were more likely to be judged simultaneous with heartbeats than tones that were delayed of 0, 400 and 500 ms after the R-wave. The reliability (split-half and test-retest) and validity (convergent and discriminant) of this task have been established (52, 73, 83).

In agreement with previous multi-interval tasks, the MCS reveals substantial individual differences in the temporal locations of heartbeat sensations, with median preferred intervals ranging from R+152 to R+373 ms. This range of values overlapped with that (R+137 to R+323 ms) exhibited by the same subjects on the Brener- Kluvitse procedure (74). In the MCS procedure the precision of heartbeat detection was indexed by a continuous performance measure, the Inter-Quartile Range (IQR) of the distribution of Preferred Intervals: smaller IQR's imply a narrower heartbeat "sensation envelope" (76), or more precise and reliable detection of heartbeats. The minimum and maximum IQR's recorded in the MCS procedure (118 & 362 ms) were somewhat greater than those recorded from the same subjects by the Brener-Kluvitse task (64 & 314 ms). However, the correlation between the IQR's on these two 6AFC tasks was high (*r*=.72), suggesting that they tap the same perceptual ability.

Studies using classical psychophysical methods find that only a quarter of participants judge heartbeat sensations to be most simultaneous with exteroceptive stimuli presented 100 ms after the R-wave. This could explain why approximately one–in-four people show evidence of heartbeat detection in two-interval tasks that present S+ stimuli around this delay. Individual differences in the timing of heartbeat sensations, a prominent and consistent finding in studies that use multi-interval tasks, could also help explain why some people cannot discriminate between the S+ and S– in two-interval Whitehead-type tasks. Support for this proposal comes from a study by Brener and Kluvitse (84).

In the first session, the multi-interval heartbeat detection task (74) was used to determine each individual's preferred interval distribution. In the second session, participants completed one of two versions of a 2AFC task. In the customized group, the S+ delay for each subject was set equal to the most frequently chosen (modal) interval on the first session, and the S– delay was their least frequently chosen interval. In the standard group, the S+ delay was R+128 ms and the S– delay was R+384 ms as proposed by Whitehead et al (51). Not surprisingly, the performance of participants on the customized task was far superior to their performance on the standard Whitehead procedure. This important finding emphasizes a key advantage of multi-interval tasks over two-interval tasks for assessing heartbeat detection. It is not possible to predict accurately when, during the cardiac cycle, individuals sense their heartbeats. Therefore, it is preferable to derive evidence of heartbeat detection using procedures, such as the MCS, that permit individuals to indicate when their heartbeat sensations occur.

While this point has not been disputed, Wiens and Palmer (85) have challenged the use of the X^2 to assess the distribution of interval choices generated by 6AFC methods, such as the MCS. On the basis of the group results of standard implementations of 6AFC methods, these investigators argue that individuals who can perceive heartbeats will show a *"∩-shaped quadratic trend across intervals*". They also justify the use of a quadratic trend test to qualify subjects as heartbeat detectors on the grounds that multimodal interval choice distributions are "*completely inconsistent with common theorizing about the utility of the MCS task*". However, the theorizing to which Wiens and Palmer (61) refer is neither referenced nor apparent in the literature. Nevertheless, they do criticize the X^2 test used with the MCS procedure for being "*needlessly insensitive*" to a quadratic trend in the interval choice distribution. While multimodal distributions of interval choices are uncommon, they may arise when, for example, a subject detects heartbeat sensations in one bodily location on some trials and in another location on other trials [(42); see also (86)].

Yates et al [(72), p.564] found that while 45% of their subjects' interval choice distributions did have quadratic trends, the remaining 55% had either linear or higher order trends. Furthermore, in analyzing the results of 109 subjects who had been run on the MCS procedure, Wiens and Palmer themselves found that of 29 subjects who met either the quadratic or X^2 criteria for classification as heartbeat detectors, 9 (31%) had significant X^2's but non-significant quadratic trends and were therefore disqualified as hearbeat detectors. Thus, by their criteria, only 18% of the 109 participants were classified as heartbeat detectors, a percentage that is notably lower than in other studies. Furthermore, 6 participants who qualified as "heartbeat detectors" by their criteria exhibited interval choice distributions that did not satisfy the X^2 criterion, implying that their distributions would occur by chance with a probability => 5%.

Using binomial probability criteria, Wiens and Palmer also assessed 2AFC performance for two pairs of intervals (S+/S- = 200/500 ms and 200/0 ms) that could provide a more efficient means of measuring the accuracy of heartbeat detection. The concurrent validities of these two methods and the MCS Quadratic Trend criterion were then informally compared to that of the MCS X^2 criterion by calculating the correlations of each of these indices with "criterion" variables (affect intensity, gender, age) found in some previous studies to be correlated with performance on heartbeat detection tasks (85). On the basis of these comparisons, the authors concluded that both 2AFC methods (0/200 ms & 500/200 ms) "*tended to be more sensitive than X^2 analysis in detecting relationships with variables previously shown to correlate with heartbeat detection*" and that this correlational analysis argued for "*the validity of two-interval tasks as measures of heartbeat detection*."

While the analysis provided by Wiens and Palmer of four distinct measures of heartbeat detection derived from a single dataset is novel and interesting, neither of these conclusions is compelling. Prior experiments using 6AFC methods have found no relationship between heartbeat detection and age, gender or body mass index (52, 65, 74) and hence the lack of correlation between MCS scores and these criterion variables observed by Wiens and Palmer was predictable. Furthermore, it is not surprising that heartbeat detection scores derived by different methods that are themselves only modestly correlated, will be differentially related to criterion variables that had been selected on the basis of their correlations with yet other tests of heartbeat detection. Thus, these correlations provide a weak case for concluding that 2AFC methods are either valid or preferable to the X^2 test normally employed as a criterion for heartbeat detection with the MCS.

Concordance between methods in the classification of heartbeat detectors.

The analysis of Wiens and Palmer revealed that the two 2AFC methods (0/200 ms & 500/200 ms) they recommend are only modestly correlated in their classifications of subjects as heartbeat detectors (r=.24). The low percent of variance shared between these methods (6%) re-emphasizes the need for common standards in the measurement of interoceptive accuracy (26, 61).

In this context, while Garfinkel et al (26) classify both the Schandry counting method and 2AFC methods as objective measures of interoceptive accuracy, they note that the methods are only modestly correlated and infer that "*they are founded on distinct (as well as potentially shared) underlying processes*" (p. 66). Schulz et al (87) found no correlation between performance on the Schandry task and two 2AFC tasks (*r*'s = .08 & .22, ns). Similarly, Phillips et al (39) found no significant correlations between performance on the Schandry task and a Whitehead 2AFC task and concluded that "that performance on one task is largely unrelated to performance on the other task" (p.508), a judgement seconded by Kleckner et al (61).

On the other hand, Hart et al (88) did find that the Schandry task and a 2AFC (250/550 ms) task were correlated (*r*=.38). Knoll and Hodapp (89) found good correspondence between the Schandry and 2AFC methods for subjects who were either very good or very poor in detecting heartbeats but little correspondence between the methods for the middle ability range of heartbeat detectors. Nevertheless, recognizing that good scores on the Schandry method could be obtained without processing heartbeat sensations, these investigators concluded that "*Schandry's mental tracking task can be used when it makes no difference whether heartbeat perception ability or the ability to estimate heart rate is being assessed*" (p.222). In contrast to the low correlations between different 2AFC methods and between 2AFC methods and the Schandry method, Brener, Liu and Ring (52) found that performance of subjects on the 6AFC Brener and Kluvitse and MCS procedures were relatively highly correlated (*r* = .72), implying that they are measuring the same or similar perceptual skills.

Conclusions:

If the ability to detect heartbeat sensations is to be used in evaluating the psychophysiological effects of variations in interoceptive sensitivity, then methodological standardization seems crucial (63). In the absence of standardization, different methods for probing the accuracy of heartbeat detection will continue to generate different, and even conflicting conclusions about the role of interoceptive sensitivity.

The 2AFC methods are biased against individuals who experience heartbeat sensations at delays after the R-wave that differ from the S+/S– delays selected by the experimenter. Such individuals may be falsely classified as non-detectors (false negatives). Nevertheless, it must be acknowledged that individuals who meet conventional statistical criteria for heartbeat detection in 2AFC tests are heartbeat detectors (true positives). On the other hand, in the heartbeat counting method, individuals may achieve high scores and be classified as heartbeat detectors on the basis of accurate beliefs but without processing heartbeat sensations. In other words, this test has a false positive bias in the classification of heartbeat detectors. The different biases of these methods coupled with the unverifiability of the heartbeat counting method question the equivalence of the methods implied in their designation by Garfinkel et al (63), as objective behavioral methods for tracking "Interoceptive Accuracy".

In contrast, the multi-interval methods provide unbiased alternatives to the 2AFC and Heartbeat Tracking methods. Of the 6AFC methods, the MCS (52) is the most efficient. A standard implementation of this procedure involves 20 trials at each of six R-wave to

Stimulus interval (R+0 ms, R+100 ms, R+200 ms, R+300 ms, R+400 ms & R+500 ms). Assuming five Heartbeat-Stimulus pairings on each trial (74) and a five second inter-trial interval, the duration of the entire procedure, including an initial 30-trial exteroceptive familiarization task, is approximately 35 minutes. The validity of the MCS procedure has not been seriously challenged and like other 6AFC methods, it has been shown to be more reliable (split-half, test-retest) than other methods. Rather than prejudging when heartbeat sensations occur during the cardiac cycle, 6AFC methods allow each individual to indicate when during the cardiac cycle his/her sensations occur. The analysis infers that the distribution of interval choices will deviate from chance only if the individual is detecting heartbeat sensations. The distribution of interval choices also provides continuous measures of precision (the Inter-Quartile Range of the distribution: IQR) and the temporal location of the heartbeat sensation (the Median Interval: MI).

Individual differences in these measures are correlated with general sensory and perceptual acuity, and sensitivity of somatosensory mechanoreceptors (90). The measures also show that contrary to common assumptions, neither hypochondriacs (15) nor “somatosensory amplifiers”(16) have elevated interoceptive sensitivity. Furthermore, heart transplant patients, who have undergone cardiac denervation, are not worse at detecting heartbeat sensations than controls with normal cardiac innervation (79). This observation reinforces the view expressed earlier that sensing visceral activity may involve not only interoceptors, but also the somatosensory mechanoreceptors and perhaps even the exteroceptors [(91), p.240/241].

Although multi-interval methods, such as MCS, were developed to correct apparent weaknesses in the Counting and 2AFC methods, they have seldom been used to investigate the affective and cognitive correlates of individual differences in Interoceptive accuracy. On the other hand, while the counting method may erroneously classify individuals as sensitive to heartbeat stimuli and the 2AFC methods may erroneously classify individuals as insensitive to heartbeat stimuli, both methods have been reported to predict a variety of affective and cognitive characteristics as well as specific electrophysiological and fMRI patterns of activation. These results could be extended and clarified by replicating the experiments from which they were derived using multi-interval tasks such as MCS.

References

1. Razran G. The Observable Unconscious and the Inferable Conscious in Current Soviet Psychophysiology. Psychological Review. 1961;68(2):81-147.
2. Cameron OG. Interoception: The Inside Story—A Model for Psychosomatic Processes. Psychosomatic Medicine. 2001;63:697-710.
3. Critchley HD, Harrison NA. Visceral influences on brain and behavior. Neuron. 2013;77(4):624-38.
4. Gendron M, Barrett LF. Reconstructing the Past: A Century of Ideas About Emotion in Psychology. Emot Rev. 2009;1(4):316-39.
5. Barrett LF, Simmons WK. Interoceptive predictions in the brain. Nat Rev Neurosci. 2015;16(7):419-29.

6. Pollatos O, Schandry R. Emotional processing and emotional memory are modulated by interoceptive awareness. Cognition & Emotion. 2008;22(2):272-87.
7. Werner NS, Peres I, Duschek S, Schandry R. Implicit memory for emotional words is modulated by cardiac perception. Biol Psychol. 2010;85(3):370-6.
8. Werner NS, Jung K, Duschek S, Schandry R. Enhanced cardiac perception is associated with benefits in decision-making. Psychophysiology. 2009;46(6):1123-9.
9. van Elk M, Lenggenhager B, Heydrich L, Blanke O. Suppression of the auditory N1-component for heartbeat-related sounds reflects interoceptive predictive coding. Biol Psychol. 2014;99:172-82.
10. Seth AK. Interoceptive inference, emotion, and the embodied self. Trends Cogn Sci. 2013;17(11):565-73.
11. Ainley V, Brass M, Tsakiris M. Heartfelt imitation: high interoceptive awareness is linked to greater automatic imitation. Neuropsychologia. 2014;60:21-8.
12. Ainley V, Maister L, Tsakiris M. Heartfelt empathy? No association between interoceptive awareness, questionnaire measures of empathy, reading the mind in the eyes task or the director task. Front Psychol. 2015;6:554.
13. Sedeno L, Couto B, Melloni M, Canales-Johnson A, Yoris A, Baez S, et al. How do you feel when you can't feel your body? Interoception, functional connectivity and emotional processing in depersonalization-derealization disorder. PLoS One. 2014;9(6):e98769.
14. Mussgay L, Klinkenberg N, Ruddel H. Heart Beat Perception in Patients with Depressive, Somatoform, and Personality Disorders. Journal of Psychophysiology. 1999;13:27-36.
15. Barsky AJ, Brener J, Coeytaux RR, Cleary PD. ACCURATE AWARENESS OF HEARTBEAT IN HYPOCHONDRIACAL AND NON-HYPOCHONDRIACAL PATIENTS. Journal of Psychosomatic Research. 1995;39(4):489-97.
16. Mailloux J, Brener J. Somatosensory Amplification and Its Relationship to Heartbeat Detection Ability. Psychosomatic Medicine. 2002;64:353-7.
17. Critchley HD, Wiens S, Rotshtein P, Ohman A, Dolan RJ. Neural systems supporting interoceptive awareness. Nat Neurosci. 2004;7(2):189-95.
18. Craig AD. How do you feel — now? The anterior insula and human awareness. Nature Reviews Neuroscience. 2009;10:59-70.
19. Khalsa SS, Rudrauf D, Feinstein JS, Tranel D. The pathways of interoceptive awareness. Nat Neurosci. 2009;12(12):1494-6.
20. Pollatos O, Schandry R, Auer DP, Kaufmann C. Brain structures mediating cardiovascular arousal and interoceptive awareness. Brain Res. 2007;1141:178-87.
21. Couto B, Adolfi F, Sedeno L, Salles A, Canales-Johnson A, Alvarez-Abut P, et al. Disentangling interoception: insights from focal strokes affecting the perception of external and internal milieus. Front Psychol. 2015;6:503.
22. Zaki J, Davis JI, Ochsner KN. Overlapping activity in anterior insula during interoception and emotional experience. Neuroimage. 2012;62(1):493-9.
23. Gescheider GA. Psychophysics: The Fundamentals. 3rd. Mahwah, NJ, USA:: Lawrence Erlbaum Associates; 1997.
24. Cornsweet TN. THE STAIRCASE-METHOD IN PSYCHOPHYSICS. The American Journal of Psychology. 1962;75(3):485-91.
25. Stevens SS. ON THE PSYCHOPHYSICAL LAW. Psychological Review. 1957;64(3):153-81.
26. Garfinkel SN, Seth AK, Barrett AB, Suzuki K, Critchley HD. Knowing your own heart: distinguishing interoceptive accuracy from interoceptive awareness. Biol Psychol. 2015;104:65-74.
27. Bykov KM. The cerebral cortex and the internal organs. New York: Chemical Publishing; 1957.
28. Khalsa SS, Rudrauf D, Sandesara C, Olshansky B, Tranel D. Bolus isoproterenol infusions provide a reliable method for assessing interoceptive awareness. Int J Psychophysiol. 2009;72(1):34-45.

29. Dale A, Anderson D. INFORMATION VARIABLES IN VOLUNTARY CONTROL AND CLASSICAL CONDITIONING OF HEART RATE- FIELD DEPENDENCE AND HEART-RATE PERCEPTION. Perceptual and Motor Skills. 1978;47:79-85.
30. Schandry R. Heart Beat Perception and Emotional Experience. Psychophysiology. 1981;18(4):483-8.
31. Hamano K. STUDIES OF SELF-REGULATION OF INTERNAL ACTIVITY: THE INTEROCEPTIVE DETECTION AND CONTROL OF CARDIAC ACTIVITY VIA TRAINING PROCEDURE OF CARDIAC-MOTOR COUPLING. Japanese Psychological Research. 1980;22(4):168-77.
32. Kleinman RA. The development of voluntary cardiovascular control. Knoxville: University of Tennessee; 1970.
33. McFarland RA. Heart rate perception and heart rate control. Psychophysiology. 1975;12(4):402-5.
34. Canales-Johnson A, Silva C, Huepe D, Rivera-Rei A, Noreika V, Garcia Mdel C, et al. Auditory Feedback Differentially Modulates Behavioral and Neural Markers of Objective and Subjective Performance When Tapping to Your Heartbeat. Cereb Cortex. 2015;25(11):4490-503.
35. Carroll D, Whellock J. Heart rate perception and voluntary control of heart rate. Biological Psychology. 1980;11:169-80.
36. Gannon L. Cardiac perception and the voluntary control of heart rate. Physiological Psychology. 1980;8:509-14.
37. Schandry R, Specht G. The influence of psychological and physical stress on the perception of heartbeats. Psychophysiology. 1981;18:154 (abstract).
38. Ring C, Brener J, Knapp K, Mailloux J. Effects of heartbeat feedback on beliefs about heart rate and heartbeat counting: a cautionary tale about interoceptive awareness. Biol Psychol. 2015;104:193-8.
39. Phillips GC, Jones GE, Rieger EJ, Snell JB. Effects of the presentation of false heart-rate feedback on the performance of two common heartbeat-detection tasks. Psychophysiology. 1999;36:594-10.
40. Ring C, Brener J. Influence of beliefs about heart rate and actual heart rate on heartbeat counting. Psychophysiology. 1996;33:541-6.
41. Windmann S, Schonecke OW, Frohlig G, Maldener G. Dissociating beliefs about heart rates and actual heart rates in patients with pacemakers. Psychophysiology. 1999;36:339-42.
42. Bestler M, Weitkunat R, Keller W, Schandry R. Heartbeat perception and body position. Journal of Psychophysiology. 1988;2:123 (Abstract).
43. Pauli P, Hartl L, Marquardt C, Stalman H, Strian F. Heartbeat and arrhythmia perception in diabetic autonomic neuropathy. Psychological Medicine. 1991;21:413-21.
44. Ring C, Liu X, Brener J. Cardiac stimulus intensity and heartbeat detection: Effects of tilt-indueed changes in stroke volume. Psychophysiology. 1994;31:553-64.
45. Reed SD, Harver A, Katkin ES. Interoception. In: Tassinary JTCLG, editor. Principles of psychophysiology: Physical, social, and inferential elements. Cambridge: Cambridge University Press; 1990.
46. Hamano K. The effect of cardiac detection upon heart rate control: An extension. Japanese Psychological Research. 1982;24:118-23.
47. Ludwick-Rosenthal R, Neufeld RWJ. Heartbeat interoception: A study of individual differences. International Journal of Psychophysiology. 1985;3:57-65.
48. Flynn DM, Clemens WJ. On the validity of heartbeat tracking tasks. Psychophysiology. 1988;25(92-96).
49. Essau CA, Jamieseon JL. Heart rate perception in the Type A personality. Health Psychology. 1987;6(1):43-54.
50. Pennebaker JW, Hoover CW. Visceral perception versus visceral detection: Disentangling methods and assumptions. Biofeedback and Seld Regulation. 1984;9:339-52.

51. Whitehead WE, Drescher VM, Heiman P, Blackwell B. Relation of heart rate control to heartbeat perception. Biofeedback and Seld Regulation. 1977;2:371-92.
52. Brener J, Liu X, Ring C. A method of constant stimuli for examining heartbeat detection - Comparison of the Brener-Kluvitse and Whitehead methods. Psychophysiology. 1993;30:657-65.
53. Wildman HE, Jones GE. Consistency of heartbeat discrimination scores on the Whitehead procedure in knowledge-of-results-trained and untrained subjects. Psychophysiology. 1982;19:592 (Abstract).
54. Katkin ES, Blascovich J, Goldband S. Empirical assessment of visceral self-perception: Individual and sex differences in the acquisition of heartbeat discrimination. Journal of Personality and Social Psychology. 1981;40:1095-101.
55. Katkin ES, Blascovich J, Reed SD, Adamec J, Jones J, Taublieb A. The effect of psychologically induced arousal on accuracy of heartbeat self-perception. Psychophysiology. 1982;19:568 (Abstract).
56. Davis MR, Langer AW, Sutterer JR, Gelling PD, Marlin M. Relative discriminability of heartbeat-contingent stimuli under three procedures for assessing cardiac perception. Psychophysiology. 1986;23(1):76-81.
57. Brener J, Jones JM. Interoceptive Discrimination in Intact Humans. Physiology and Behavior. 1974;13:763-7.
58. Ross A, Brener J. Two Procedures for Training Cardiac Discrimination. Psychophysiology. 1981;18(1):62-70.
59. Katkin ES, Reed SD, DeRoo C. A methodological analysis of three techniques for the assessment of individual differences in heartbeat detection. Psychophysiology. 1983;20:452 (Abstract).
60. Hantas M, Katkin ES, Blascovich J. Relationship between heartbeat discrimination and subjective experience of affective state. Psychophysiology. 1982;19:563 (Abstract).
61. Kleckner IR, Wormwood JB, Simmons WK, Barrett LF, Quigley KS. Methodological recommendations for a heartbeat detection-based measure of interoceptive sensitivity. Psychophysiology. 2015;52(11):1432-40.
62. Stormer SW, Heiligtag U, Knoll JF. Heartbeat detection and knowledge of results: A new method and some theoretical thoughts. Journal of Psychophysiology. 1989;3:409-17.
63. Okifuji A, Harver A, Katkin ES, Reed SD. Heartbeat perception: Assessment, symptoms, and anxiety. Psychophysiology. 1988;25:473 (Abstract).
64. Brener J, Ring C. Sensory and perceptual factors in heartbeat detection. In: Schandry DVR, editor. Interoception and cardiovascular processes. Heidelberg: Springer-Verlag; 1995.
65. Ring C, Brener J. The Temporal Locations of Heartbeat Sensations. Psychophysiology. 1992;29(5):535-45.
66. Clemens WJ. Temporal Arrangement of Signals in Heartbeat Discrimination Procedures. Psychophysiology. 1984;21(2):187-90.
67. Lombardo TW, Epstein LH. The nicotine paradox: Effect of smoking on autonomic discrimination. Addictive Behaviors. 1986;11:341-4.
68. Clemens WJ, Guethlein WG, Katkin ES. Heart Beat detection and ear bias. Psychophysiology. 1988;25:440 (Abstract).
69. Harver A, Katkin ES, Bloch E. Comparison of heartbeat and respiratory sensation among male and female subjects. Psychophysiology. 1988;26:S22 (Abstract).
70. Gardner RM, Morrell JA, Watson DN, Dandoval SL. Cardiac self-perception in obese and normal persons. Perceptual and Motor Skills. 1990;70:1179-86.
71. Ring C. The detection of cardiac activity. Stony Brook: SUNY Stony Brook; 1993.
72. Yates AJ, Jones KE, Marie GV, Hogben JH. Detection of the Heartbeat and Events in the Cardiac Cycle. Psychophysiology. 1985;22(5):561-7.

73. Brener J, Ring C, Liu X. Effects of data limitations on heartbeat detection in the method of constant stimuli. Psychophysiology. 1994;31:309-12.
74. Brener J, Kluvitse C. Heartbeat Detection: Judgments of the Simultaneity of External Stimuli and Heartbeats. Psychophysiology. 1988;25(5):554-61.
75. Doob LW. Patterning of time. New Haven: Yale University Press; 1971.
76. Efron R. The duration of the present. Annals of the New York Academy of Sciences. 1959;66:713-39.
77. Ferguson ML, Fernquist SK, Harver A, Katkin ES. Validation of a "preferred interval" heartbeat detection task. Psychophysiology. 1989;26:S22 (Abstract).
78. Kluvitse C. Discrimination of cardiac activity. Hull: University of Hull; 1987.
79. Barsky AJ, Ahern DK, Brener J, Surman OS, Ring C, Dec GW. Palpitations and Cardiac Awareness After Heart Transplantation. Psychosomatic Medicine. 1998;60:557-62.
80. Bessette PR, Scully BM, Jones GE. Test-retest reliability of the Brener-Kluvitse HB perception paradigm. Psychophysiology. 1991;28:S12 (Abstract).
81. Dedic J, Dahme B. AN EXPERIMENTAL STUDY OF HEART BEAT DETECTION IN SUBJECTS WITH HIGH VERSUS LOW SOMATIC SYMPTOM INDEX UNDER CONDITIONS FAVORING INTEROCEPTION. Psychophysiology. 1997;34(Supplement 1):S30 (Abstract).
82. Katkin ES, Cestaro VL, Weitkunat R. Individual differences in cortical evoked potentials as a function of heartbeat detection ability. . International Journal of Neuroscience. 1991;61:269-76.
83. Schneider TR, Ring C, Katkin ES. A test of the validity of the method of constant stimuli as an index of heartbeat detection. Psychophysiology. 1998;35:86-9.
84. Brener J, Kluvitse C. Temporal location of S+ and S- signals in the Whitehead heartbeat discrimination procedure. Psychophysiology. 1988;25:436-7 (Abstract).
85. Wiens S, Palmer SN. Quadratic trend analysis and heartbeat detection. Biological Psychology. 2001;58:159-75.
86. Ceunen E, Van Diest I, Vlaeyen JW. Accuracy and awareness of perception: related, yet distinct (commentary on Herbert et al., 2012). Biol Psychol. 2013;92(2):426-7.
87. Schulz A, Lass-Hennemann J, Sutterlin S, Schachinger H, Vogele C. Cold pressor stress induces opposite effects on cardioceptive accuracy dependent on assessment paradigm. Biol Psychol. 2013;93(1):167-74.
88. Hart N, McGowan J, Minati L, Critchley H. Emotional regulation and bodily sensation: interoceptive awareness is intact in borderline personality disorder. Journal of Personality Disorders. 2013;27(4):506-18.
89. Knoll JF, Hodapp V. A Comparison between Two Methods for Assessing Heartbeat Perception. Psychophysiology. 1992;29(1):218-22.
90. Knapp K, Ring C, Brener J. Sensitivity to mechanical stimuli and the role of general sensory and perceptual processes in heartbeat detection. Psychophysiology. 1997;34:467-73.
91. Brener J. Visceral Perception. Biofeedback and Behavior. New York: Plenum Press; 1977. p. 235-59.

---

[i] **Authors' contributions.** J.B. and C.R. contributed equally to the development and writing of the paper.

[ii] **Competing Interests.** We have no competing interests.

[iii] **Acknowledgements.** We thank Professors Hugo Critchley and Manos Tsakiris for inviting us to contribute our perspective on the measurement of interoception. We also thank Dr. Kelley Kline of Florida State University for her useful suggestions on the content of the paper and her help in editing it.