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Heartbeat Counting is Unrelated to Heartbeat Detection: A Comparison of Methods to Quantify Interoception

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Abstract

Recent research has identified individual differences in interoceptive sensitivity as a key source of variation in action, cognition and emotion. This research has relied heavily on a single method for assessing interoceptive sensitivity: the accuracy of counting heartbeats while at rest. The validity of this method was assessed here by comparing the Heartbeat Counting (HBC) performance of 48 individuals with their Heartbeat Detection (HBD) performance. The Heartbeat Counting (HBC) task required participants to report the numbers of heartbeats counted during brief signaled periods and indexed cardioceptive accuracy based on the difference between the numbers of reported and actual heartbeats. In the Heartbeat Detection (HBD) task, participants indicated the temporal location of heartbeat sensations relative to the onset of ventricular contraction. On each trial they judged whether heartbeat sensations were or were not simultaneous with brief tones presented at one of six fixed delays following R-waves of the ECG. In this method, cardioceptive accuracy or precision was indexed by variability in the temporal location, relative to the R-wave, of tones judged to be simultaneous with heartbeat sensations. Although intra-task correlations indicated that each method yielded reliable scores, inter-task correlations showed that HBC scores were unrelated to HBD scores. These results, which indicate that heartbeat detection and heartbeat counting are distinct processes, raise important questions about the assessment of interoceptive sensitivity and the involvement of this attribute in the psychological processes that have been associated with it on the basis of their correlations with HBC performance.

Heartbeat Counting is Unrelated to Heartbeat Detection: A Comparison of Methods to Quantify Interoception

A rapidly-growing body of research has identified individual differences in interoceptive sensitivity as a key source of variation in a wide range of affective, cognitive, conative and clinical processes (Shivkumar*, et al.*, 2016; Tsakiris & Critchley, 2016). This research has relied heavily on measuring sensitivity to heartbeat sensations as a means of assessing interoceptive sensitivity, presumably because of the simplicity and unintrusiveness of the associated methods. While several techniques for measuring sensitivity to heartbeat sensations are no longer used because of flawed methodology and/or poor psychometrics, others have survived despite their apparent flaws (Brener & Ring, 2016). With this issue in mind, the current study evaluated and compared two different methods for assessing sensitivity to heartbeat sensations – Heartbeat Counting (HBC) and Heartbeat Detection (HBD). According to Garfinkel et al (2015) these two methods, which are claimed by their proponents to yield valid objective measures of cardioceptive accuracy, are "*founded on distinct (as well as potentially shared) underlying processes*".

Heartbeat Counting

In the Heartbeat Counting (HBC) task participants are instructed to report the number of counted *or estimated* heartbeats during several signaled periods, each generally lasting less than a minute (Dale & Anderson, 1978; Schandry, 1981). Sensitivity to heartbeat sensations is indexed by a perception score calculated from the difference between the numbers of actual and reported heartbeats. Evidence shows that the accuracy of heartbeat counting is unrelated to the abilities to estimate time (Antony*, et al.*, 1994) or to count accurately (Ring & Brener, 1996), leaving open the possibility that individual differences in the accuracy of heartbeat counting are due to individual differences in sensitivity to stimuli produced by the beating of the heart.

Mechanoreceptors in the heart, the pericardium, and other parts of the body generate afferent signals on each heartbeat (see Ring & Brener, 1992). Hence, it seems plausible that individuals, particularly those with high mechanoreceptive sensitivity, will develop an ability to recognize and count their heartbeats and to estimate their heart rates accurately. As research on interoceptive processes has grown (Shivkumar, et al., 2016; Tsakiris & Critchley, 2016), the Schandry (1981) heartbeat counting procedure, which is simple to implement and quick to execute, has become the main method used to assess individual differences in interoceptive sensitivity [1].

However, the face validity of the counting task has been challenged repeatedly on the grounds that individuals may perform accurately by counting at a rate that approximates their heart rates but without actually detecting any heartbeat sensations (Flynn & Clemens, 1988; Jones, 1994; Katkin & Reed, 1988 ; Kleckner*, et al.*, 2015; Weisz*, et al.*, 1988; Yates*, et al.*, 1985). This criticism has been supported by the publication of a series of experimental findings showing that counts are based more on beliefs about heart rate than on sensations generated by heartbeats (Pennebaker, 1981; Pennebaker & Hoover, 1984; Phillips*, et al.*, 1999; Ring & Brener, 1996; Ring*, et al.*, 2015; Windmann*, et al.*, 1999). For example, the numbers of reported heartbeats change little despite substantial changes in heart rates elicited by postural (Ring & Brener, 1996) and pacemaker (Windmann, et al., 1999) manipulations.

These data indicate that high scores on the heartbeat counting task may be earned by a combination of accurate knowledge of heart rate and inaccurate perception of cardiac activity (Brener & Ring, 2016). Nevertheless, the "Predictive Coding", "Bayesian Inference" viewpoint that has been adopted by several researchers in the field (Ainley, *et al.*, 2016; Barrett, *et al.*, 2016; Seth & Friston, 2016) appears to accommodate the possibility that while beliefs about heart rate can be experimentally manipulated (e.g. Ring et al, 2015), the "prior" content of such beliefs reflects knowledge based on a life time's experience of heartbeat sensations. Hence, individuals who are more sensitive to heartbeat sensations will develop more accurate implicit and/or explicit knowledge of their cardiac activity from which they can generate more accurate counts of heart beats as well as better estimates of heart rate and hence, higher perception scores on the Schandry HBC task.

In addition, proponents of the HBC method point to a number of heart evoked potential (HEP) studies that purport to show significant differences in heart-related neural activity between accurate and inaccurate heartbeat counters (Canales-Johnson, *et al.*, 2015; Katkin, *et al.*, 1991; Pollatos, *et al.*, 2005; Pollatos & Schandry, 2004; Schandry, *et al.*, 1986; Yuan, *et al.*, 2007). These data appear to support the validity of the counting method by showing that the accuracy of heartbeat perception as measured by the Schandry HBC method taps neural processes associated with heartbeat sensations. An fMRI study (Pollatos, *et al.*, 2007) also purports to show a significant relationship between heartbeat counting accuracy and the BOLD signal in the right insula. Another fMRI study has shown specificity in insula activity from interoceptive versus exteroceptive information (Simmons, Avery, Barcalow, Bodurka, Drevets, & Bellgowan, 2013). However, a more recent report, using an arguably more completely-balanced control design (Pfleiderer*, et al.*, 2014), failed to find a significantly greater BOLD signal in the right insula when attention was directed to interoceptive stimuli (heartbeats) rather than exteroceptive stimuli (tones): both types of stimuli giving rise to similar right insula activation.

Furthermore, it is possible that variations in HEP amplitude that have been attributed to individual differences in interoceptive sensitivity on the basis of the Schandry counting task are actually due to one or more of the many covariates of interoceptive sensitivity that have been reported. For example, individual differences in attentional focus (Babo-Rebelo*, et al.*, 2016; Garcia-Cordero*, et al.*, 2016; Montoya*, et al.*, 1993), emotion/stress/arousal (Couto*, et al.*, 2015; Gray*, et al.*, 2007; Luft & Bhattacharya, 2015; MacKinnon*, et al.*, 2013) and motivation (Schulz*, et al.*, 2015; Weitkunat & Schandry, 1990) have all been reported to be associated with HEP amplitude. It seems plausible that any or all of these processes may predispose individuals to acquire more or less accurate, albeit indirect, knowledge of their heart rates and thereby to achieve higher or lower scores on the Schandry HBC test. In other words, a third variable (e.g., attention, effort) may be responsible for the relationship reported between HBC performance and HEP amplitudes.

Heartbeat Detection

Unlike heartbeat counting tasks, in which high performance scores may be achieved through indirectly-acquired knowledge of cardiac performance, good performance on Heart Beat Detection (HBD) tasks appears unequivocally to depend on the detection of heartbeat sensations (for review see Brener & Ring, 2016). These tasks require participants to judge whether heartbeat sensations are or are not simultaneous with exteroceptive stimuli presented at different delays (at least two) following the onset of the electromechanical systole. In most two-interval HBD procedures, both the positive (HB-coincident) and negative (HB-noncoincident) delays have been chosen on the basis of estimates of when, following the R-wave of the ECG, the pressure pulse wave generated by ventricular contraction will stimulate mechanoreceptors in or adjacent to the heart or major vessels of the circulatory system, see (Whitehead*, et al.*, 1977).

However, recognizing that individuals show wide variation in the timing of their heartbeat sensations, some heartbeat discrimination methods (Brener & Kluvitse, 1988; Brener*, et al.*, 1993; Yates, et al., 1985) require individuals to judge the simultaneity of heartbeat sensations and exteroceptive stimuli presented at six delays following the R-wave (R+0, R+100, R+200, R+300, R+400, R+500 ms). These six-interval tasks span the cardiac cycle more completely thereby permitting participants to identify the temporal location of their heartbeat sensations with fewer restrictions than two interval tasks. Two-interval tasks assume that heartbeat sensations occur at the same temporal location in the cardiac cycle in all individuals and seek to answer the question of whether or not individuals can detect such sensations. In contrast, six-interval HBD tasks are able to answer the question of when during the cardiac cycle each participant senses heartbeat sensations.

On each trial of the six-interval task, a series of brief exteroceptive stimuli (say, tones) is presented at one of the six intervals following each R-wave of the ECG. At the end of the trial the participant renders a judgment of whether or not those tones were simultaneous with heartbeat sensations. Over a large number of trials, a distribution of simultaneous judgments across the six intervals is generated. If this observed distribution of simultaneous judgments differs significantly by chi-square from a rectangular distribution, in which judgments are expected to be equiprobable across the six intervals, then that participant is classified as a heartbeat detector. The dispersion of the distribution of simultaneous judgments across the six intervals, as measured by the interquartile range, provides a continuous measure of the precision or accuracy of heartbeat detection; this is what is referred to as the interval of uncertainty in the method of constant stimuli (Gescheider, 2013). The logic of these multi-interval HBD tasks, as well as the standard statistical methods that are employed to assess performance, provide such tasks with high face validity. Furthermore, the reliability (split-half and test-retest) as well as the convergent[2] and discriminant validity of the tasks have been thoroughly tested (Brener, et al., 1993; Brener*, et al.*, 1994; Jones*, et al.*, 1990; Schneider*, et al.*, 1998), thereby providing a defensible standard for assessing heartbeat detection accuracy using non-invasive methods.

Nevertheless, the method has been criticized by Wiens and Palmer (2001) on the grounds that the chi-square test is "needlessly insensitive" to their preferred criterion of heartbeat discrimination which is that the distribution of simultaneous judgments across the six R-Wave-to-Stimulus intervals is best described by a quadratic or inverted-U shaped function. In such a function, stimuli presented at R+0 and R+500 ms are judged to be least simultaneous with heartbeat sensation, stimuli at R+200 and R+300 ms most simultaneous, and stimuli at R+100 and R+400 ms between these two extremes. While this ∩-shaped function does accurately describe the group averages for heartbeat detectors in published reports of performance on the MCS (See Figure 2 in Brener & Ring, 1995), it does not best describe the choice distributions of a substantial proportion of the individual members of these groups who meet standard statistical criteria for classification as heartbeat detectors (Yates et al, 1985; Brener & Ring, 2016). Furthermore, not all datasets that exhibit significant quadratic (∩) trends have distributions of simultaneous judgments that differ significantly from chance (Yates et al, 1985; Wiens & Palmer, 2001).

Wiens and Palmer (2001) also argue that certain two-interval HBD tasks are preferable to six-interval tasks because they "tended to be more sensitive than chi-square analysis in detecting relationships with "criterion" variables (better detectors have less affect, a lower age, and tend to be male) that have been shown to correlate with heartbeat detection. This inference is questionable on the grounds that the criterion variables employed by Wiens and Palmer to judge the validity of their favored indices were identified on the basis of their correlations with yet other tests of cardiac detection that are themselves of dubious validity (for review see Brener & Ring, 2016).

Another criticism of heartbeat detection tasks is that the simultaneity paradigm is impaired because it requires participants to attend "simultaneously to cardiac sensation and external stimuli" (Couto, et al., 2015). However, since the nervous system is continuously engaged in parallel processing of sensory inputs from internal and external receptors, e.g. (Molholm, *et al.*, 2002) and our ability to judge simultaneity is very precise indeed – we can tell whether two stimuli presented to different modalities are simultaneous or not with a resolution of less than 20 milliseconds (Zampini, *et al.*, 2005) – performance on HBD tasks is not limited by this general perceptual ability.

Thus, cases for the validity of both the HBC and 6-interval HBD measures have been presented by proponents of these methods while questions of their validity have been raised by critics of each of the methods. Some investigators have reported that performance on the HBC task is related to HBD performance on two-alternative forced-choice tasks (Hart*, et al.*, 2013; Knoll & Hodapp, 1992), but others have found performance on the two tasks to be uncorrelated (Forkmann*, et al.*, 2016; Kandasamy*, et al.*, 2016; Phillips, et al., 1999; Schulz*, et al.*, 2013; Weisz, et al., 1988), also see Knoll & Hodapp (1992) [3]. In this context, the current experiment was undertaken in order to clarify the extent to which the HBC task (Schandry; 1981) and the six-interval HBD task (Brener et al; 1993) measure the same or different abilities. Further information about the current implementation of the HBC task can be found in a previous report by Ring and Brener (1996).

Method

Participants

Forty-eight undergraduates (18 males, 30 females) aged 18-20 (M = 18.69, SD = 0.78) years participated for course credit. Their mean height was 1.67 (SD = 0.08) m, mean weight was 61.45 (SD = 9.94) kg, and mean body mass index was 21.93 (SD = 2.63) kg/m^2. In terms of fitness, on average, they exercised for 5.39 (SD = 4.36) hours per week, completed 2.26 (SD = 1.38) athletic activities per week, and had a resting heart rate (beats per minute) of 70.00 (SD = 10.62) when supine, 75.50 (SD = 11.50) when sitting, and 86.87 (SD = 12.69) when standing.

Apparatus

A computer presented experimental stimuli and collected responses. It also detected and processed heartbeats (R-waves) from an electrocardiogram recorded using a lead II electrode configuration. During a familiarization task, supra-threshold vibrotactile stimuli

(250 Hz, 10 ms) were delivered to the finger using a piezo-oscillator and during the heartbeat and familiarization tasks, auditory stimuli (1000 Hz, 10 ms, 75 dB) were delivered through speakers.

Procedure

Participants completed one task per session in counterbalanced order. Each laboratory session, which lasted less than one hour, was scheduled on a separate day. The amount of time separating the heartbeat counting task session and the heartbeat detection task session ranged from 1 to 8 days. During the session, participants sat upright in a sound-and-light-attenuated room and were told that direct palpation of their pulse was not allowed.

Heartbeat counting task (Schandry, 1981). Participants were instructed to count heartbeats silently during three periods (25, 35, 45 s). A single tone signaled the start and two tones signaled the end of each period. Specifically, they were instructed to "*count your heartbeats silently without taking your pulse, beginning with the single tone and ending with the double tone*". Participants then reported the number of counted heartbeats. A 45 s interval separated each period. Participants were told that the periods varied in length but were not told the duration of each period. This sequence of three counting periods was later repeated to compute test-retest reliability across the two parts of the heartbeat counting task [4].

Heartbeat detection task (Brener, et al., 1993). On each trial participants were presented with 10 tones at one of six R-wave to tone intervals (0, 100, 200, 300, 400, 500 ms). Following the tenth tone they were instructed to press the appropriate button to indicate whether the tones had or had not been simultaneous with heartbeat sensations. The next trial started five seconds after each simultaneous/non-simultaneous button press. A quasi-random sequence of intervals was used, with the constraints that each interval occurred 10 times in each block of 60 trials, 10 times on odd-numbered trials, and 10 times on even-numbered trials. Each interval occurred 20 times. Prior to the heartbeat detection task, participants judged the simultaneity of vibrations and tones during a 30-trial familiarization task that acquainted them with the general demands of intermodal simultaneity judgments (Brener, et al., 1993).

Measures

The accuracy of heartbeat detection was indexed by the interquartile range of the distribution of simultaneous judgments across the six intervals of the HBD task (Brener, et al., 1993). Figure 1 shows how this measure was computed. The accuracy of heartbeat counting was indexed by the perception score, calculated from differences in the numbers of actual and counted heartbeats across the three counting periods in the HBC task (Schandry, 1981). A perfect perception score equals one; the score declines as more heartbeats are reported or unreported than actually occurred.

Data Analysis

The dataset was examined for missing values, outliers and normality (Tabachnick & Fidell (2007). No missing values were found. No extreme outliers, defined as three standard deviations from the mean, were detected. The kurtosis and skewness values for each variable indicated normal distributions (–0.71 to 1.23 and –1.18 to –0.68, respectively) based on cutoff values of 10 for kurtosis and 3 for skewness. As illustrated in Figure 2, MCS performance was in line with previous reports. By X^2 analysis ($p < .05$), the percentage of detectors in this study (27%) fell within the range reported in independent studies using the MCS method: 19% (Wiens & Palmer, 2001), 29% (Schneider et al, 1998) and 32% (Young et al, (2017).

Results

Validity and Reliability

The convergent validity of the two tasks was assessed by examining the correlation between the two accuracy measures (see Figure 3). The interquartile range (M = 265, SD = 48 ms) was not significantly correlated with the perception score (M = 0.61, SD = 0.29), $r(46)$ = –.04, p = .77. This null finding was confirmed by a corresponding Spearman rank order correlation: = .02, p = .90.

The performances of participants who satisfied the X2 criterion ($p < .05$) for classification as "detectors" on the MCS procedure are identified in Figure 3 by filled-in black squares. Since heartbeat detection is a prerequisite to heartbeat counting, it is to be expected that detectors would be well represented among participants who had high Perception Scores on the HBC procedure. However, it will be seen that of the 17 participants who have Perception Scores equal to or greater than 0.80, nine (53%) were detectors. It is inferred that the remaining eight participants (47%) achieved their high Perception Scores on the basis of beliefs. This suggests that while participants with good heartbeat detection scores should be good at counting heartbeats whereas participants with good heartbeat counting scores may not necessarily be good at detecting heartbeats.

Split-half reliability was assessed by correlating the interquartile range computed on the first half of the trials (i.e., 1-60) with the interquartile range computed on the second half of the trials (i.e. 61-120), $r(46) = .60$, $p < .001$. Odd-even reliability was assessed by correlating the interquartile ranges computed on odd-numbered trials (i.e., 1, 3, 5, …. , 119) and with the interquartile ranges computed on even-numbered trials (i.e., 2, 4, 6, …, 120), $r(46) = .50$, $p < .001$. Test-retest reliability was assessed by correlating the perception scores associated with the three counting periods in Part 1 with perception scores in Part 3, $r(46) = .67$, $p < .001$. These significant positive intra-task correlation coefficients indicate that the heartbeat detection and heartbeat counting tasks yielded reliable measures of detection and counting, respectively.

Supplementary Analyses

Correlational analyses indicated that the perception score and IQR were not significantly related to gender (r = .27 & -.25), age (r = -.14 & -.16), body mass index (r = -.01 & -.18), exercise hours (r = -.08 & .19), exercise frequency (r = -.07 & -.05), and resting heart rate (r = .22 & -.10), respectively.

Discussion

Our purposes were to evaluate the reliability of two tasks designed to assess the ability to detect heartbeat sensations and to examine the relationship between performance on them. It was found that, although both tasks yielded reliable accuracy measures, heartbeat counting scores were unrelated to heartbeat detection scores in this sample of university students. This evidence adds to previous findings that heartbeat counting scores are uncorrelated with heartbeat detection scores on two-alternative forced-choice tasks (Forkmann, et al., 2016; Kandasamy, et al., 2016; Knoll & Hodapp, 1992; Phillips, et al., 1999; Schulz, et al., 2013; Weisz, et al., 1988).

Unlike heartbeat detection tasks, the heartbeat counting task can yield high, and, by implication, accurate, perception scores without participants detecting heartbeat sensations. That individuals' verbal reports about their cardiac activity may be based on prior knowledge of heart rate as well as on heartbeat sensations has been demonstrated in several experiments (e.g., Pennebaker & Epstein, 1983; Phillips, et al., 1999; Ring & Brener, 1996; Ring et al., 2015; Windmann, et al., 1999). Therefore, counting performance may be stable over time without necessarily reflecting sensitivity to cardiac sensations. Indeed, the current findings indicated that the ability to count heartbeats is not a valid indicator of the ability to detect heartbeat sensations as measured by the six-interval task used in this study. In this connection it may be noted that despite substantial differences in the MCS X^2s of the Good and Poor subjects (X^2_{Good} = 68.24; X^2_{Poor} = 2.27) displayed in Figure 1, their heartbeat Counting Perception Scores (PS) were very similar (PS_{Good} = 0.83; PS_{Poor} = 0.88).

This six-interval heartbeat detection task, which is based on the Method of Constant Stimuli, yields a distribution of simultaneous judgments across the intervals on each session from which an index of precision – the interquartile range - may be computed. The interquartile range has been found to be reliable over sessions (Ring, et al., 1994; Schneider, et al., 1998) and within a session (Brener, et al., 1993; current study). Furthermore, the distribution of simultaneous judgments for each participant may be submitted to statistical analysis to determine whether or not that participant's performance deviates from chance and therefore qualifies the participant as a heartbeat detector. It is worth noting that no such criterion is available to distinguish between high Perception Scores in the HBC task that are based on detecting the pulsatile action of the heart and high Perception Scores that are based on some other process that does not involve cardiac interoception. Therefore, the influence of guessing on counting performance cannot be determined using the standard instructions and assessments of task performance (cf. Brener & Ring, 2016).

Performance on the heartbeat detection task also meets the criteria for internal (Schneider, et al., 1998), construct (Brener, et al., 1993; Jones, et al., 1990), and face validity. No other procedures for measuring the accuracy of heartbeat detection have shown comparable psychometric properties.

In contrast, accumulating evidence questions the validity of the heartbeat counting task as a method for assessing the ability to detect heartbeat sensations. Its continued popularity among researchers may be due to its simplicity and brevity. However, since performance on the task may reflect estimating, guessing or inferring the number of heartbeats rather than counting them, it would seem ill-advised to use the HBC method to index sensitivity to heartbeat sensations and, even less, interoceptive sensitivity (Knoll & Hodapp, 1992).

Nevertheless performance on the HBC task has been reported to predict a broad range of emotional, perceptual, cognitive, psychosocial and clinical processes as well neural activity recorded by heart evoked potentials and MRIs. (see Tsakiris & Critchley, 2016 for an overview of current work). If these predictions, mostly made on the basis of HBC performance, are really due to variations in interoceptive sensitivity, then it is to be expected that they will be confirmed by predictions based on other established tests of interoceptive accuracy. In the absence of such confirmation, further work will be needed to reveal what the predictive characteristic is that is being tapped by the HBC test.

A factor that could limit the generalizability of the results of this study is that while the participant sample was of a reasonable size (48 participants), it comprised only young college students. Whether the same results would be obtained in other populations remains to be determined. Another consideration related to the generalizability of the results is that the MCS task, by requiring judgments of the simultaneity of exteroceptive and interoceptive stimuli, is thought by some (e.g. Couto et al., 2015) to be too difficult. If this view is accurate, then the zero correlation between the MCS IQR and the Schandry et al (1981) Perception Score reported here may be an underestimate. However, the conjecture that the MCS is too difficult has yet to to be fully articulated or tested. According to Couto et al (1981) the difficulty of heartbeat detection tasks that rely on judging the simultaneity of external stimuli and heartbeat sensations is that ".. interference (is) generated by attending simultaneously to cardiac sensation and external stimuli …".

However, this hypothesis is inconsistent with the substantial experimental literature on judging intersensory (intermodal) simultaneity and order. The work indicates that such judgments are involved in a broad range of everyday behaviors (Vroomen & Keetels, 2010) and confer numerous behavioral and perceptual benefits (Noel et al, 2016). While interoception has not commonly been examined in the intersensory context, phenomena such as bait shyness (Garcia & Koelling, 1966), food preferences and aversions (Booth, 1985) and interoceptive conditioning (Razran, 1961) make clear the functional importance and ubiquity of processing interoceptive-exteroceptive contingencies.

In conclusion, the current study adds to the accumulating body of evidence that questions the validity of the HBC counting task as measure of cardioception. Unlike two-interval HBD tests of sensitivity to heartbeat sensations, the MCS test used here does not make unjustifiable assumptions about when during the cardiac cycle, the heartbeat sensation occurs. As suggested earlier, research employing a multi-interval heartbeat detection task such as the MCS could help to resolve whether the numerous cognitive, psychosocial, clinical and emotional correlates of heartbeat counting performance are due to cardioceptive sensitivity or some other, yet-to-be-identified, characteristic.

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Notes

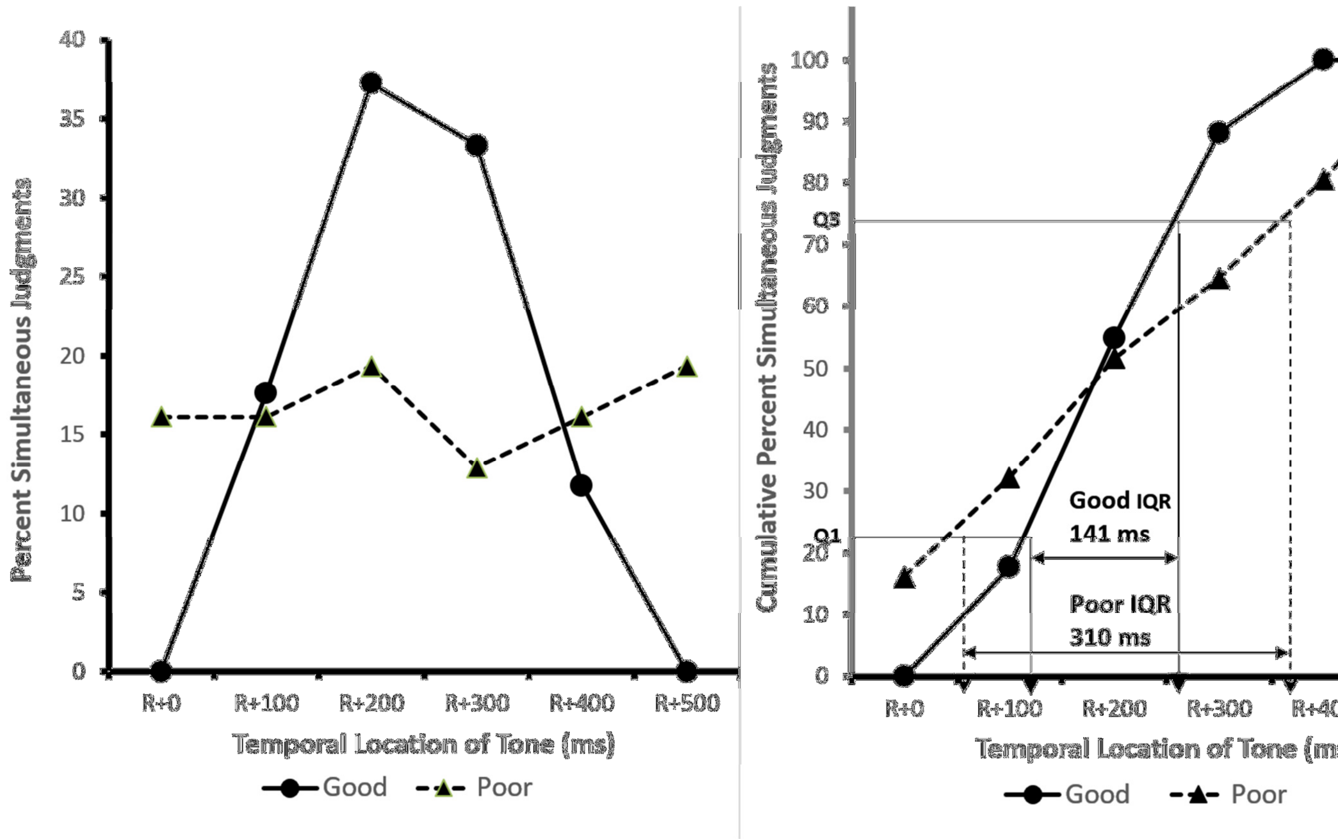
1. We do not deal here with evidence for a general interoceptive sensitivity or, if it exists, whether cardioceptive sensitivity is a valid index of this general sensory characteristic. However, several researchers have presented evidence on this issue, (e.g., Garfinkel, et al., 2016; Herbert, et al., 2012; Kollenbaum, et al., 1996; Steptoe & Noll, 1997; Whitehead & Drescher, 1980).

2. Brener, Liu and Ring (1993) found that performance accuracy on the MCS task, measured by the IQR, was significantly correlated (*rho* = -.59) with performance accuracy on the Whitehead task, measured using A', a non-parametric index which is preferred over d' when there is only one pair of hit and false alarm rates. The full dataset, including d' and several other statistics that have been reported in the experimental literature, are presented in their appendix.

3. The study by Knoll and Hodapp (1992) is often cited as evidence that HBC and HBD methods yield similar results. However, while these investigators did find that good and poor heartbeat detectors on the two methods were classified similarly, the performance of those in the middle range was uncorrelated. Furthermore these authors also advised using HBD methods when the interest is in assessing heartbeat detection and only using the HBC methods "when it makes no difference whether heartbeat perception ability or the ability to estimate heart rate is being assessed."

4. The session comprised three parts. In Part 1, participants counted heartbeats for three counting periods while sitting, standing, supine, and post-exercise. In Part 2, they counted vibrations for three periods. In Part 3, they repeated Part 1. The data from periods 1-3 (Part 1), during which participants performed the task while sitting, were used to compute a perception score. This perception score from Part 1 was correlated with the IQR measure from the HBD task to assess validity and correlated with the perception score from periods 25-27 (Part 3) to assess reliability. The full dataset was analyzed in a previous report (Ring & Brener, 1996).

Figure 1. The left diagram shows the percentages of all simultaneous judgments for tones presented at each of the six R wave to Tone intervals for a Good heartbeat detector and a Poor heartbeat detector from the current experiment. The Good participant most frequently judged tones presented at R+200 ms to be simultaneous with heartbeat sensations and never judge tones presented at R+0 and R+500 ms to be simultaneous with heartbeats. The Poor participant, however, judged tones at each of the six intervals to be simultaneous with heartbeats with approximately the same probability. The right diagram illustrates cumulative percentage frequency distributions corresponding to the distributions for the Good and Poor participants shown on the left. The calculation of IQRs for those two participants is also illustrated here. This entailed calculating the R-wave to Tone intervals corresponding to the first quartile (Q1 or 25^{th} percentile) and third quartile (Q3 or 75^{th} percentile) of the Cumulative Percentage Frequency distributions of simultaneous judgments for each participant. The IQR for each participant was then calculated by subtracting their Q1 interval from their Q3 interval. This procedure yielded an IQR of 310 ms for the Poor participant and IQR of 141 ms for the Good participant.



Percent Simultaneous Judgments
40
35
30
25
20
15
10
5
0
R+0
R+100
R+200
R+300
R+400
R+500
Temporal Location of Tone (ms)
Good
Poor
Cumulative Percent Simultaneous Judgments
100
90
80
Q3
70
60
50
40
30
Q1
20
10
0
Good IQR
141 ms
Poor IQR
310 ms
R+0
R+100
R+200
R+300
Good
Poor

Figure 2. The combined distribution of simultaneity judgments of detectors (Chi-square *p* < .01) in the Current Experiment (CE) displayed as a heavy line over the distributions reported in six previous replications (1-6) of the MCS procedure. (1) Ring & Brener 1989, 1992; (2) Brener & Ring, 1989; (3) Ring & Brener, 1990; (4) Brener, Ring & Wilmers, 1990; (5) Ring & Brener, 1991; (6) Jones, personal Communication). Note that in all datasets most simultaneous judgments are for stimuli at R+200 ms and fewest at R+0 ms and R+400 ms.

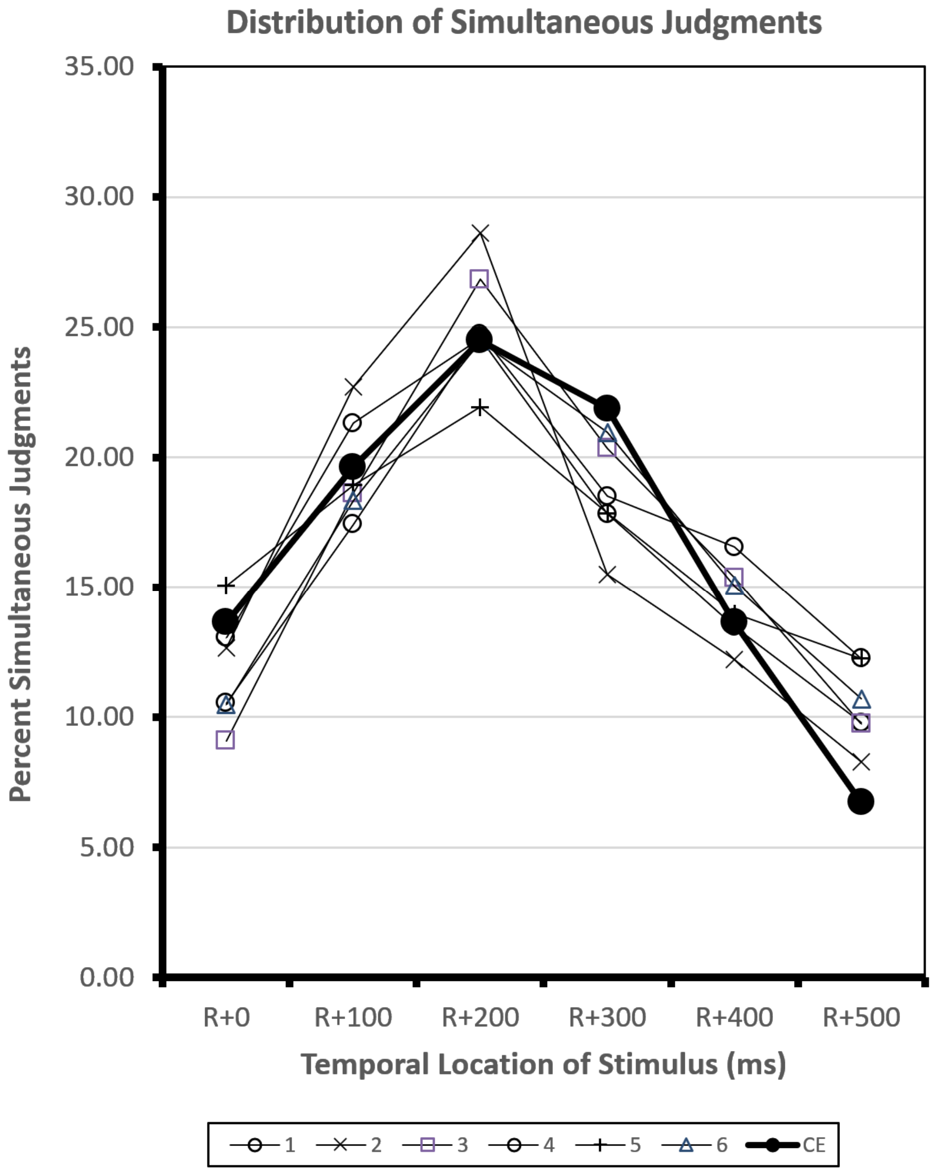


Figure 3. Heartbeat detection performance in relation to heartbeat counting performance. The interquartile range was unrelated to the perception score: $r(46) = -.04$, $p = .77$; rho(46) = .02, p = .90. The data points of participants classified as "detectors" by Chi-square ($p<.05$) are filled in black. Since heartbeat detection is prerequisite to counting heartbeats accurately, it is to be expected that a relatively high proportion of participants (9/17) who have HBC Perception Scores >= 0.80 will be heartbeat detectors. However, the observation that approximately half the participants (8/17) whose Perception Scores were >= 0.80 failed to meet the statistical criteria for classification as heartbeat detectors suggests that their Perception Scores were based on processes other than heartbeat counting.