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A heartbeat away from a valid tracking task. An empirical comparison of the mental and the motor tracking task

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ABSTRACT

Individuals' ability to perceive their heartbeats, called cardioceptive accuracy, is assessed with various paradigms. Performance in the mental and a novel motor tracking task that eliminates disturbing tactile sensations was assessed at rest and during walking with the participation of 45 young people. Significantly higher scores in the mental tracking task than in the motor tracking task were found. Scores obtained at rest were consistently higher than their walking counterparts. Motor responses showed no temporal association with heartbeats for 84% of participants at rest and 95% during walking. Overall, participants' cardioceptive accuracy at rest and under slight physical activity was poor. Even if people rely on their heartbeat-related sensations during their daily activity, it is either not the ability that is assessed by the tracking tasks, or it is a relatively poor source of information about the actual state of the body.

1. Introduction

Cardioceptive accuracy (CAc), i.e., the acuity of perception of cardiac activity, represents perhaps the most widely studied modality of interoception (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). This popularity can be explained partly by the availability of a simple and quick method for its assessment, partly by the assumption that the perception of cardiac activity as an indicator of internal changes plays an important role in a variety of different psychological phenomena, e.g., emotion (Pollatos, Kirsch, & Schandry, 2005a; Schandry, 1981), mental disorders (Bornemann & Singer, 2017; Domschke, Stevens, Pfleiderer, & Gerlach, 2010; Furman, Waugh, Bhattacharjee, Thompson, & Gotlib, 2013; Herbert, Herbert, & Pollatos, 2011; Murphy, Brewer, Hobson, Catmur, & Bird, 2018; Pollatos, Traut-Mattausch, & Schandry, 2009; Terhaar, Viola, Bär, & Debener, 2012; Van der Does, Antony, Ehlers, & Barsky, 2000), or the sense of the self (Allen & Tsakiris, 2018; Apps & Tsakiris, 2014; Tsakiris, 2017). The method widely used for the assessment of CAc, dubbed mental tracking task (also called heartbeat counting task or Schandry task), takes only several minutes and requires relatively simple technical and computational background. Participants are asked to silently count their perceived heartbeats under resting conditions for brief periods of time (typically each is shorter than one minute), and the number of reported and actual (usually measured with electrocardiography, ECG) heartbeats are compared (Dale & Anderson, 1978; Schandry, 1981). This paradigm has its origin in the 70 s (Carroll, 1977); the recently widely used version was developed by Schandry (1981). It has received methodological criticism from early on (Carroll, 1977; Ehlers & Breuer, 1996; Ring & Brener, 1996); recently, the critiques became more pronounced, even questioning the validity of the method as a measure of cardioceptive accuracy (Brener & Ring, 2016; Ring & Brener, 2018; Zamariola, Maurage, Luminet, & Corneille, 2018; Zimprich, Nusser, & Pollatos, 2020). Critique of the Schandry task focuses on its malleability to non-interoceptive (mainly top-down) influences, which lead to the estimation of heartbeats based on expectation, knowledge of heart rate (HR), and similar cognitive factors (Brener & Ring, 2016; Körmendi, Ferentzi, & Köteles, 2021; Ludwick-Rosenthal & Neufeld, 1985; Pennebaker & Hoover, 1984; Phillips, Jones, Rieger, & Snell, 1999; Ring, Brener, Knapp, & Mailloux, 2015; Ring & Brener, 1996, 2018; Windmann, Schonecke, Fröhlig, & Maldener, 1999). It is important to see, however, that (1) the impact of certain top-down factors can be reduced with the use of a strict instruction that explicitly prohibits estimation (Desmedt, Luminet, & Corneille, 2018; Ehlers, Breuer, Dohn, & Fiegenbaum, 1995), and (2) perception in general necessarily involves top-down (in this case: non-interoceptive) factors (Clark, 2015; Gregory, 1980; Pennebaker, 1982, 1995), which might even play a dominant role if the incoming

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(bottom-up) signal is vague (Pennebaker, 1982; Van den Bergh, Witthöft, Petersen, & Brown, 2017).

As a huge body of empirical findings obtained with the use of the Schandry task from a wide variety of fields of research is available (for a review, see (Köteles, 2021)), a better understanding of the factors that impact participants' performance might help to reconsider the findings of previous studies. Individual differences in the contribution of the aforementioned top-down factors are particularly relevant here. If the contribution shows comparatively small or negligible individual variability, i.e., the Schandry score can be considered a linear transformation of really sensed heart beats, then the majority of findings and conclusions of empirical studies from the last 40 years can still be considered valid. Available studies demonstrating the impact of non-interoceptive factors manipulated various variables at the group level, i.e., participants received different instructions or information on HR, and the difference in performance was calculated (Desmedt et al., 2018; Ehlers et al., 1995; Ring & Brener, 1996). Individual differences in the contribution of interoceptive (detection of actual heart beats) and non-interoceptive (e.g. estimation-related) factors can be revealed by comparing performance in the Schandry task to that obtained from a task that minimizes the impact of non-interoceptive factors.

The direct antecedent of the mental tracking task is the so-called motor tracking task. In this task, participants are asked to press a button immediately after sensing a heartbeat. In the original version, which is still used recently, simply the total score of button presses and actual heartbeats are compared (Brener, 1974; Dobrushina et al., 2020; McFarland, 1975; Weisz, Balázs, & Ádám, 1988). As it was realized quite early that not all button presses represent actual cardiac events, i.e., participants sometimes "had 'seen' a heart beat that had not occurred" (Brener, 1974, p. 381), more sophisticated calculation methods that take into account the temporal relationship between cardiac events and subsequent button presses were developed (Brener, 1974; Fittipaldi et al., 2020). However, these modifications do not eliminate a highly problematic aspect of the motor tracking task, namely, that motor response and particularly the tactile sensation evoked by the button presses can disturb the perception of heartbeats (Pennebaker & Epstein, 1983; Pennebaker & Hoover, 1984). The mental tracking task entirely eliminates the disturbing motor response and the accompanying tactile sensation. In return, as only the sum of the counted heartbeats is reported, the temporal congruence between actual and counted cardiac events cannot be checked (Flynn & Clemens, 1988), i.e., counted heartbeats evoked by bottom-up and top-down factors cannot be discriminated. Thus, a method that (1) is able to differentiate responses to actual cardiac events from those evoked by top-down information, and (2) is characterized by minimal disturbing sensory input would be necessary to shed more light on the background of the Schandry task.

Heartbeat represents a very weak signal, which is barely perceivable under resting conditions in the laboratory, focusing exclusively on cardiac sensations (Köteles, 2021). A rarely mentioned issue is how it can be perceived under more active everyday circumstances, when internal noise is increased due to physical activity and attention dominantly focuses on external cues. In other words, to which extent the outcome of a measurement carried out under sterile laboratory conditions can be generalized to other situations for a very weak signal (Pennebaker & Hoover, 1984). Concerning the increase of internal noise due to physical activity (including the slight activation caused by everyday activities, such as walking, gardening, etc.), the available empirical evidence is far from conclusive. A recent study reported a moderate association between the Schandry score assessed at rest and another indicator of awareness of cardiac activity, i.e., the acuity of reproduction of a previously presented level of very lightweight physical activity (Köteles *et al.* 2020). However, the association disappeared for more intense levels of physical exertion. Also, findings on the association between the Schandry score and perceived fatigue and actual physical exertion are equivocal (Kósa et al., 2021). Findings of a recent study indicate that perceived arousal component of the affective experience under various levels of physical exertion is associated with the Schandry score assessed under resting conditions (Köteles, Teufel, Körmendi, Ferentzi, & Szemerszky, 2020). However, no direct evidence is available on the impact of ongoing physical activity on cardioceptive accuracy.

In the study reported in this paper, the issues of the heartbeat counting task are approached from a novel direction: instead of demonstrating the impact of non-interoceptive information, we attempt to demonstrate the inherent limitations of processing cardioceptive information itself. We present a new motor tracking task which considerably reduces the limitations of both the classic motor and mental tracking approaches and makes them directly comparable. In more details, it minimizes the somatic sensation caused by the motor response with the use of electromyography (EMG) instead of direct button presses. This way, the tactile component of the response can completely be eliminated. Further, it enables us to disentangle possibly heartbeat-related finger movements from non heartbeat-related ones based on the temporal relationship between responses and actual heartbeats. To the authors' knowledge, no such heartbeat perception task has been developed and tested yet and no direct comparison between the outcome of the mental tracking and the motor tracking task has been carried out to date. In this study, we compare participants' performance shown in this novel motor tracking task and the Schandry task, which can shed more light on the variance of bias in the Schandry paradigm. Moreover, both assessments were conducted at rest and under walking conditions, which enables us to draw conclusions on the generalizability (external validity) of both tracking tasks.

2. Methods

2.1. Participants

A priori sample size calculation for a strong positive association ($r = 0.5$, one-tailed; $\alpha = 0.05$, $\beta = 0.9$) was conducted with the G*Power software (Version: 3.1.9.4.; Faul, Erdfelder, Lang, & Buchner, 2007). It resulted in a minimum sample size of $N = 31$. Our sample consisted of 45 young individuals (23 male; $M_{age} = 23.3$ yrs; $SD_{age} = 4.93$ yrs;), with normal body composition ($M = 24.5\%$, $SD = 8.2\%$) and blood pressure values ($M_{systolic} = 121.7$ Hgmm, $SD_{systolic} = 17.1$ Hgmm; $M_{diastolic} = 73.4$ Hgmm, $SD_{diastolic} = 10.7$ Hgmm). Participants were recruited via local advertisements and personal contacts (i.e., they represent a convenience sample of young individuals); they received no reward for their participation. The study was approved by the Ethics Board of the Faculty. All participants signed an informed consent before starting the study.

2.2. ECG and EMG measurement

Physiological measurements were carried out with the NeXus recording system (NeXus Wireless Physiological Monitoring and Feedback: NeXus-10 Mark II, Version 1.02; BioTrace + Software for NeXus-10 Version: V201581; Mind Media BV, Herten, the Netherlands) with a sample rate of 1024 Hz. Cardiac activity was recorded between the left costal arch (positive) and the right collarbone (negative), while the ground electrode was placed on the left collarbone (modified Lead II design). EMG was recorded between two electrodes placed on the anterior (palmar) surface of the right forearm over the belly of the flexor digitorum superficialis muscle. In order to minimize the movement of other muscles of the arm, participants' forearm was lying on their thigh in a relaxed position with the palm facing upward during the sitting measurement. During the walking measurement, the forearm was fixed with the palm facing upward using an arm sling made of a triangular bandage. Identification of R-R peaks (ECG) and the starting point of finger movements (EMG) was conducted with custom algorithms implemented in Matlab (Version: R2016a; The MathWorks, Inc., Natick, MA, USA). The outcome of the algorithms was checked by visual inspection in all cases.

2.3. Mental tracking task

Assessment of heartbeat perception was conducted under seated and walking circumstances (for the exact instructions, see Supplementary material). Participants were asked to count their heart beats silently during three randomly presented intervals (25, 35 and 50 s) after a 15 s long practice phase. The counting started with a verbal NOW signal and stopped by a STOP signal, after which participants reported the number of counted heart beats. Participants were explicitly encouraged to say zero if they did not feel any heartbeats, but also encouraged to count if they have a slight sensation only. Individual heartbeat perception scores were calculated for each interval using the following formula: $1 - |(HB_{recorded} - HB_{counted})/ HB_{recorded}|$, followed by the calculation of the average ($CAc_{mental\_resting}$; $CAc_{mental\_walking}$). Cronbach's alpha for the three trials of the Schandry-task was.96 for the resting, and.97 for the walking condition.

2.4. Motor tracking task

Participants performance in the motor tracking task was estimated in two ways. First, the formula used in the mental tracking task (see above) was used with the inclusion of all finger movements ($CAc_{motor\_resting\_all}$; $CAc_{motor\_walking\_all}$). Cronbach's alpha for the three trials was.98 for the resting, and.96 for the walking condition. Second, a time frame (from 350 to 650 ms from the preceding R-peak, see below) for acceptable finger movements was determined (see below), and only those finger movement were considered that occurred in this time frame. The delay between the R-peak of the ECG and the heartbeat sensed in the chest is approximately 150 ms (Whitehead, Drescher, Heiman, & Blackwell, 1977); it can be considerably longer (up to 350 ms) if the pulse in the distal parts of the arm is sensed. Thus, the stimulus to be processed (detected) occurs 150–350 ms after the R-peak. Motor response-based simple reaction time experiments usually report a delay of 200–300 ms from the presentation of the stimulus (Der & Deary, 2006; Jain, Bansal, Kumar, & Singh, 2015), this should be added to the aforementioned delay. Overall, a response quicker than 350 ms (150 ms + 200 ms) after the R-peak cannot be considered valid even for a person with above average reaction time. In a similar vein, the response should be within 650 ms (350 ms + 300 ms) after the R-peak even if the worst scenario (perception on the wrist accompanied by a slow reaction) is taken into consideration. Overall, the time frame of 350–650 ms represents a reasonable but quite relaxed criterion. We have good theoretical reasons to regard finger movements before or after this time frame as not indicating an actual heartbeat, just an expected or an illusory sensation. Thus, our second indicator of performance ($CAc_{motor\_resting\_acceptable}$; $CAc_{motor\_walking\_acceptable}$) was calculated using the formula described above with the inclusion of the responses within the 350–650 ms time frame (in the case of multiple responses, only the first response was accepted). Cronbach's alpha for the three trials of this strict formula was.92 for the resting and.94 for the walking condition.

The application of a time frame does not mean that all finger movements occurring within the acceptable range refer to actual heartbeats. Completely random guessing also leads to apparent hits; however, in this case the ratio of finger movements within and outside the time frame does not differ from the ratio of the length of the two intervals. Therefore, the distribution of the start of the finger movements relative to the R-R peaks was examined to determine whether the finger movements are to some extent synchronous with the heartbeats or not. Although heartbeat is not completely regular, i.e., it can be regarded as a quasi periodic activity, the circular statistics approach was used (Berens, 2009). The time distance of each finger movement from the preceding R-peak was converted to angles in degrees; the average R-R distance of the entire time interval (data obtained from the three trials was merged) was regarded as 360 degree. The dispersion of the angles is calculated as the vectorial average of the unit vectors at the angle with x-axis (horizontal axis) in the two-dimensional plane, called mean resultant vector (Berens, 2009). The length of the mean resultant vector is between 0 and 1; values close to zero reflects high variability of angles, whereas values close to 1 indicate less variability.

2.5. Procedure

Upon arrival, participants read and signed an informed consent form. Their body composition was measured with an Omron BF511 body composition monitor (OMRON Healthcare Group, Kyoto, Japan), blood pressure was measured with Omron BP7100 upper arm blood pressure monitor (OMRON Healthcare Group, Kyoto, Japan). Spontaneous walking speed was assessed in an appr. 15 m long corridor within the building, followed by the placement of ECG and EMG electrodes. The measurement started with the resting or the walking condition in a randomized order (Fig. 1); there was a 10 min resting period between the two conditions. The resting measurements were completed in a sitting position after a 3-minute-long resting period. At the end of the resting period, participants were asked to estimate their actual HR in bpm. Concerning the walking measurements, participants' were asked to walk on a treadmill (h/p/cosmos mercury med; h/p/cosmos Sports & Medical GmbH, Nussdorf–Traunstein, Germany) set to their spontaneous walking speed assessed before the experiment. Before the heartbeat perception measurements, they walked for 3 min on the treadmill in order to become physiologically and psychologically adjusted to this condition. At the end of this period, actual HR was estimated again. Each condition consisted of a mental and a motor tracking task, administered in randomized order. In each task, participants received the instruction from an audio tape (see Supplementary material), verbally reported their expectation, completed a 15 s trial and three real measurements (25, 35, and 50 s in random order).

2.6. Statistical analysis

Statistical analysis was conducted using the JASP software (Version: 0.14.3; University of Amsterdam, The Netherlands; JASP Team, 2021). Association between estimated and actual HR was estimated with Spearman's rho coefficient; the difference between the two was checked with paired-samples t-test. Associations between estimated HR and various indices of cardioceptive accuracy were estimated with Spearman correlation. Differences among indices of the mental and motor tracking tasks were checked with repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser correction; in the post hoc analysis, Holm correction was applied. Finally, differences between the analogous indices calculated for the resting and the walking condition were investigated using Wilcoxon signed-rand tests with rank-biserial correlation as indicator of effect size. For the calculations of circular statistics, the circ_r function of the Circular Statistics toolbox (Berens, 2009) of the

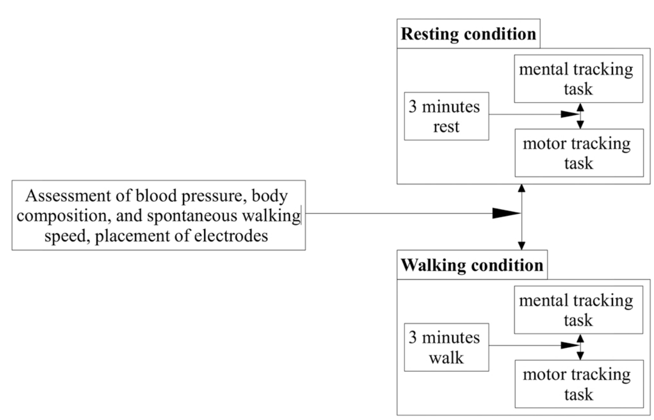

Fig. 1. Protocol of the study. Double-headed arrows between conditions and tasks indicate randomization steps.

Matlab System was used. The Rayleigh test was applied to indicate how large the mean resultant vector length must be to indicate a non-uniform distribution. A *p*-value above the $p = .05$ limit indicates that the distribution of the finger movements with respect to the R-R peaks can be considered random, i.e., there is no temporal association between finger movements and the preceding heartbeat. Group-level differences between those with non-random and random distribution were estimated with Wilcoxon tests.

3. Results

Descriptive statistics of the calculated indices are summarized in Table 1 and Fig. 2. The average values of indices of cardioceptive accuracy were well below.5, indicating a relatively poor average performance. This is also shown by the distribution of individual scores: even under resting condition, a substantial proportion of our participants reported/indicated only the minority of their actual heartbeats (Table 1). The Rayleigh test further supported this finding. The statistic was below the $p = .05$ limit only for seven participants of 45 (15.6%) for the resting condition and for two participants (4.4%) for the walking condition (for details, see Supplementary material). These participants can be considered heartbeat detectors (this does not refer to perfect accuracy though). In other words, there was no association between heartbeats and finger movements for the vast majority of participants. Descriptive statistics for the detector and non-detector group are presented in Table 2.

Paired-samples t-test indicated a significant difference between the actual and estimated HR both for the resting ($t(44) = 3.69$, $p < .001$, $d = 0.55$) and the walking ($t(44) = 5.17$, $p < .001$, $d = 0.77$) condition. Participants underestimated their actual HR in both cases. Correlation between the actual and estimated HR was $r_s = 0.30$, $p = .049$ for the resting and $r_s = 0.38$, $p = .009$ for the walking condition.

For the resting condition, estimated HR was not associated with $CAc_{mental\_resting}$ (r_s =0.11, $p = .460$), $CAc_{motor\_resting\_all}$ (r_s =0.19, $p = .222$), and $CAc_{motor\_resting\_acceptable}$ (r_s =0.20, $p = .197$). For the walking condition, however, HR was significantly positively correlated with $CAc_{mental\_walking}$ (r_s =0.29, $p = .051$), $CAc_{motor\_walking\_all}$ (r_s =0.35, $p = .017$), and $CAc_{motor\_walking\_acceptable}$ (r_s =0.41, $p = .006$).

Repeated measures ANOVA indicated significant differences between the indices in both resting ($F(2,70) = 56.93$, $p < .001$, $\eta^2 = 0.564$) and walking ($F(1,61) = 13.95$, $p < .001$, $\eta^2 = 0.241$) conditions (Fig. 3). *Post hoc* analysis showed significant (p_{Holm} <0.05) differences between each pair for both conditions.

Also, Wilcoxon signed-rand tests indicated a significant difference between $CAc_{mental\_resting}$ and $CAc_{mental\_walking}$ ($W = 886$, $p < .001$, $r_{rank\text{-}biserial}$ =0.79), between $CAc_{motor\_resting\_all}$ and $CAc_{motor\_walking\_all}$ ($W = 804$, $p < .001$, $r_{rank\text{-}biserial}$ =0.69), and between $CAc_{motor\_resting\_acceptable}$ and $CAc_{motor\_walking\_acceptable}$ ($W = 617$, $p < .001$, $r_{rank\text{-}biserial}$ =0.43) (Fig. 4). The average resting CAc score was larger than the average walking score for all cases.

For the resting condition, significant differences with large effect size between heartbeat detectors and non-detectors with respect to all three indices were found (Table 2). Mean of the detector group was uniformly higher than that of the non-detector group in all cases. Finally, the Schandry-score ($CAc_{mental\_resting}$) showed strong positive correlations with all other indices of cardioceptive accuracy (Table 3; for a visual presentation, see Supplementary material)).

4. Discussion

With the participation of 45 young individuals, the associations between measures of cardioceptive accuracy (as assessed with the mental and the motor tracking method) were investigated under resting and walking conditions. Participants achieved substantially higher scores in the mental tracking task than in the motor tracking task in both conditions. Also, indices obtained under resting conditions were consistently higher than their walking counterparts. The Schandry-score, i.e., the score achieved in the mental tracking task at rest, was strongly positively associated with all other indices of cardioceptive accuracy but not with estimated HR. Participants whose motor responses were associated with their heartbeats under resting conditions ("detectors") showed better performance than those with random motor responses. However, the vast majority of our participants (84.4%) belonged to the latter group.

As expected, participants' mental tracking scores were higher than the motor tracking scores in both the resting and walking conditions. This can be explained in two ways. First, interference between cardiac and motor events might have reduced the detectability of heartbeats (Köteles, 2021; Pennebaker & Epstein, 1983; Pennebaker & Hoover, 1984), even if our paradigm eliminates the disturbing effect of tactile sensations. Second, participants might have applied a more strict decision criterion in the motor tracking task, i.e., probably only the comparatively strong and well detectable heartbeats were indicated. Taking into consideration finger movements within the predetermined time frame only further reduced the index. A possible interpretation of this pattern suggests that the vast majority of the heartbeats that are counted in the mental tracking task cannot be regarded as a response to a cardiac event. As the association between the mental tracking score at rest and the estimated HR was weak and non-significant, these illusory heartbeats cannot be explained by estimation that is simply based on knowledge or belief about HR. On the one hand, our results suggest that the vast majority of counted and reported heartbeats in the Schandry task do not correspond to actual heartbeats, which questions the validity of the Schandry-score as an indicator of cardioceptive accuracy. On the other hand, however, the association between the mental tracking score and both motor tracking scores was very strong (r above 0.8). In other words, those who counted more heartbeats in the mental tracking task tended to indicate more (and more actual) heartbeats in the motor tracking task and the other way around. Also, performance of "detectors" in the Schandry task was significantly higher than that of non-detectors. This indicates that the performances in various tracking tasks differ mainly in their magnitude, but they require more or less the same ability by classifying people's heartbeat perception ability similarly. Also, the latter result is in concert with the finding of a recently reported study, where heartbeat discrimination scores were associated

Table 1
Descriptive statistics of the assessed and calculated variables.

Index of cardioceptive accuracy (N = 45)	M	SD	min	max	% of values under 0.5	% of values under 0.25	% of values under 0.1	% of zero values
$CAc_{mental\_resting}$	.38	0.28	0	.96	66.7	37.8	24.4	8.9
$CAc_{motor\_resting\_all}$	.25	0.23	0	.84	84.4	53.3	31.1	4.4
$CAc_{motor\_resting\_acceptable}$	.10	0.10	0	.35	100	91.1	60	11.1
$CAc_{mental\_walking}$	.20	0.25	0	.87	82.2	68.9	55.6	17.8
$CAc_{motor\_walking\_all}$	.15	0.20	0	.86	95.6	80	55.6	26.7
$CAc_{motor\_walking\_acceptable}$	.08	0.11	0	.53	97.8	95.6	82.2	31.1
resting HR (bpm)	74.1	12.4	52.3	96.4	–	–	–	
resting estimated HR (bpm)	65.8	11.5	30	110	–	–	–	
walking HR (bpm)	89.6	14.6	64.5	146.0	–	–	–	
walking estimated HR (bpm)	77.7	12.1	50	110	–	–	–	

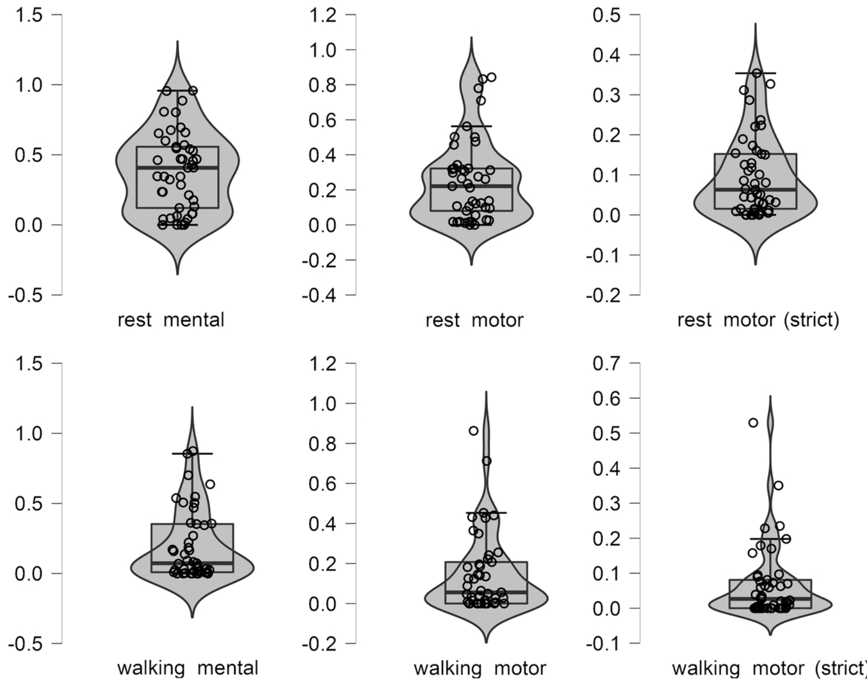

Fig. 2. Distribution of indices in the four cardioceptive tasks.

Table 2
Descriptive statistics of the heartbeat detector and non-detector group and results of group-level comparison (Wilcoxon test).

	Heartbeat detectors (n = 7)	Non-detectors (n = 38)	W	*p*	rank-biserial correlation
$CAc_{mental\_resting}$	0.64 ± 0.22	.33 ± 0.27	51.000	.011	.62
$CAc_{motor\_resting\_all}$	.42 ± 0.20	.22 ± 0.23	55.000	.015	.59
$CAc_{motor\_resting\_acceptable}$	.17 ± 0.07	.08 ± 0.98	57.000	.018	.57

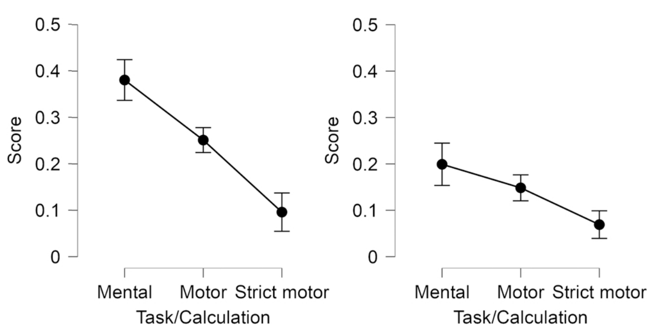

Fig. 3. Average scores achieved by participants in the mental and motor tracking task at rest (left-hand side) and during walking (right-hand side). All differences are significant ($p < .05$), error bars indicate 95% confidence intervals.

with mental tracking scores across different conditions (Schulz, Back, Schaan, Bertsch, & Vögele, 2021). A recent review (Hickman, Seyedsalehi, Cook, Bird, & Murphy, 2020) also found only a weak association between the two paradigms. These results must be considered with reservations, however, as a meta-analysis is not necessarily informative if one or two of the compared methods is not reliable.

If one has a closer look at the absolute values of the indices, however, it turns out that only a minority of actual heartbeats might have been sensed (10% on average, as indicated by $CAc_{motor\_resting\_acceptable}$). More than 90% of our participants responded to only every fourth heartbeat or even less, and 11% did not indicate one single heartbeat. Finally, there was no association between the heartbeats and the timing of finger movements for the vast majority of our participants (as shown by the Rayleigh test). This indicates that finger movements within the acceptable range can be considered false alarms rather than hits for 84.4% of our participants.

4.1. Ecological validity

The issue of ecological validity of the cardioceptive tasks was already raised in the 80′s; it was concluded that people rely on exteroceptive information and knowledge rather than poorly available internal cues when they need to judge the internal physiological state of their body (Pennebaker, 1995; Pennebaker & Hoover, 1984; Pennebaker & Roberts, 1992; Roberts & Pennebaker, 1995). Our findings support this idea, demonstrating the small, probably often negligible contribution of bottom-up (cardiac) input to the perception of heartbeats even under resting conditions. In addition, CAc was consistently and substantially lower during walking than at rest. Physical activity is characterized by the increase of interoceptive (including proprioceptive) and exteroceptive input (e.g. higher level of arousal, perception of rhythmic movements and their auditory concomitants). From the viewpoint of the cardioceptive tasks, these stimuli represent noise, which further impairs the perception of heartbeats (Köteles, Éliás, et al., 2020). Also, as stated by the principle of competition of cues (Pennebaker & Lightner, 1980), exteroceptive stimuli usually attract attention more effectively than interoceptive stimuli (Ádám, 1998), which leads to reduced perception of the latter. The weak to moderate association between actual and estimated HR, and between estimated HR and indices of cardioceptive accuracy in the walking condition suggest that estimation might have played a role in the completion of the task. However, the walking

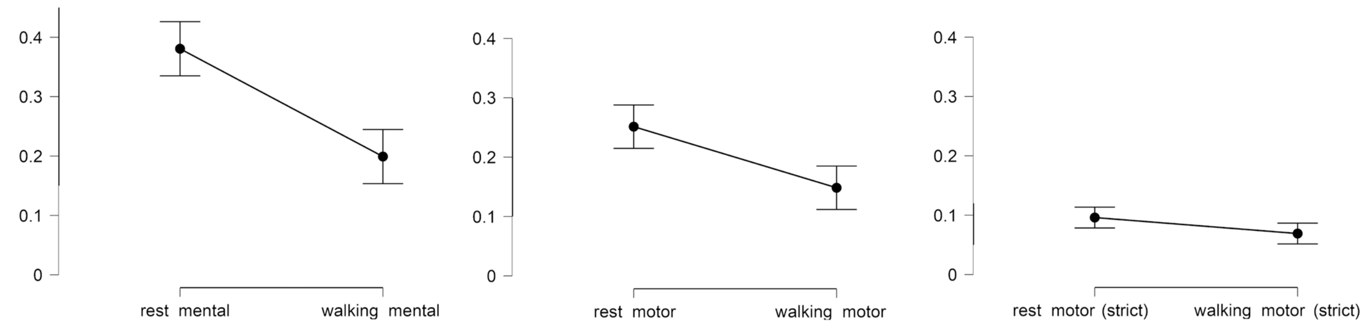

Fig. 4. Average scores of the three indices of cardioceptive accuracy obtained under resting and walking conditions. All differences are significant ($p < .001$), error bars indicate 95% confidence intervals.

Table 3
Associations (Spearman's rho coefficients) between indices of cardioceptive accuracy for the entire sample.

N = 45	$CAc_{motor\_resting\_all}$	$CAc_{motor\_resting\_acceptable}$	$CAc_{mental\_walking}$	$CAc_{motor\_walking\_all}$	$CAc_{motor\_walking\_acceptable}$
$CAc_{mental\_resting}$	.85	.81	.67	.63	.58
$CAc_{motor\_resting\_all}$		.95	.73	.73	.69
$CAc_{motor\_resting\_acceptable}$			.73	.66	.61
$CAc_{mental\_walking}$				.70	.68
$CAc_{motor\_walking\_all}$					.97

Note: $p < .001$ for all. $CAc_{mental\_resting}$ stands for the classic Schandry score

condition further reduced the absolute value of each cardioceptive index; on average, only 8% of the heartbeats were indicated correctly, more than 80% of our participants indicated only every 10th heartbeat or less, and 31% did sense no heartbeat at all. Finally, only two participants out of 45 showed a finger movement pattern that was to some extent synchronous with the actual heartbeats. This is a surprisingly low ratio of "heartbeat detectors". The fact that very slight physical activity already reduces the ability to perceive the heartbeats questions the ecological validity of the tracking tasks in general. If cardioceptive accuracy plays a crucial role in a variety of significant psychological phenomena (see introduction), it is at least surprising that noisy environment prevents heartbeat perception. From this point of view, the assessment of CAc during everyday activities and development of novel tasks that can be completed under non-resting circumstances appears a promising step forward.

In summary, our findings suggest that the vast majority of people are barely able to sense their actual heartbeats even at rest, not to speak of slight physical activity. As the bottom-up sensation of cardiac activity is so poor, its perception must necessarily be determined by non-interoceptive (e.g. situational, knowledge-related) factors (Desmedt et al., 2018; Desmedt et al., 2020; Köteles, 2021; Pennebaker, 1982, 1994); under everyday circumstances (but not necessarily in the laboratory), such external cues might in fact improve the acuity of perception (Pennebaker, 1995; Pennebaker & Roberts, 1992). From this point of view, the mental tracking task appears to measure the outcome of a "perceptual heuristics", with the dominance of top-down cues.

Even for the minority whose finger movements were associated with heartbeats, the absolute value of the respective index was very low ($CAc_{motor\_resting\_acceptable}$ =.17). On average, these people were able to perceive only approximately one sixth of their heartbeats. HR is typically assumed to indicate the actual condition (activation, arousal) of the body (Köteles, Éliás, et al., 2020; Pollatos, Kirsch, & Schandry, 2005b; Pollatos, Herbert, Kaufmann, Auer, & Schandry, 2007; Pollatos, Traut-Mattausch, Schroeder, & Schandry, 2007). However, if only every sixth heartbeat is sensed on average at rest and even less in a slightly activated state, the question arises how people could draw a realistic conclusion on their actual HR and activation state based on such a rare and irregular signal. Taken together, the ability to consciously sense actual cardiac events (i.e. a dominantly bottom-up process) is not necessarily an adaptive feature that helps to interpret internal events and thus improves psychological functioning. From an evolutionary point of view, it might be a simple by-product of the interaction between the rhythmic activity of the heart and the occurrence of tactile receptors in the chest wall (Köteles, 2021).

Findings of the present study should be generalized with caution only, as the sample was not representative of the general population. Analysis involving comparisons between detectors and non-detectors should be interpreted cautiously given the low sample size (N = 7) in the latter condition. Furthermore, the power of the Rayleigh test might have been reduced due to the small number of motor responses in certain measurements. Also, interaction between finger movements and the perception of heartbeats might have reduced participants' performance in the motor tracking task. Thus, it is a question, whether the detectability of cardiac events during the motor tracking task can be generalised to the detectability of cardiac events during the mental tracking task. Although the high correlation between the measures supports this assumption, it cannot be excluded that the mental tracking task allows the perception of more actual heartbeats. Finally, validity of the novel motor tracking task presented in this paper should be further investigated. For example, its relation to an established heartbeat discrimination task would be informative.

5. Conclusion

The ability to perceive heartbeats at rest and under slight physical activity is poor. Scores reported with the use of the mental tracking task are inflated. Based on our results, it can be assumed that even if people rely on their heartbeat-related sensations during their daily activity, it is either not the ability that is assessed by the tracking tasks, or it is a relatively poor source of information on the actual state of the body.

Declaration of Competing Interest

The authors have no competing interest to report.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2022.108328.

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