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Cardioceptive accuracy is associated with arousal but not with valence and perceived exertion under physical load

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Abstract

Under resting conditions, cardioceptive accuracy—the acuity of the perception of heartbeats—is associated with the self-reported intensity of affective states but not with reported valence. Physical exertion elicits positive affect below the anaerobic threshold and negative affect above the threshold while arousal gradually increases. The current research aimed to study the associations between cardioceptive accuracy and characteristics of the affective response (arousal and valence) during physical activity. About 67 undergraduate students completed the Schandry task and rated their perceived exertion (Borg-scale) and affective experience (arousal and valence) under three physical loads (running on a treadmill below, around, and above the anaerobic threshold). Cardioceptive accuracy was associated with the arousal component of the affective states during physical activity but not with valence and perceived exertion.

KEYWORDS

affect, arousal, heartbeat perception, interoception, physical activity, valence

1 | INTRODUCTION

Interoception refers to the processing of internal bodily stimuli by the nervous system (Khalsa et al., 2018). Conscious aspects of interoceptive processing compose three dimensions, that is, interoceptive accuracy (IAc; acuity of perception of interoceptive stimuli as assessed with behavioral tests), interoceptive sensibility (self-reported attentiveness to and awareness of interoceptive stimuli), and interoceptive awareness (metacognitive awareness of interoceptive accuracy) (Critchley, Eccles, & Garfinkel, 2013; Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Beyond these sensory-perceptual aspects, the inclusion of the affective-evaluative aspect, called interoceptive affective evaluation or interoceptive appraisal, was proposed (Farb & Logie, 2018; Herbert & Pollatos, 2018). The associations between interoception and pathological and non-pathological affective processes, such as anxiety, depression, and the intensity of emotional response to affective stimulation, have received considerable research attention (Avery et al., 2014; Barrett, Quigley, & Hamilton, 2016; Domschke, Stevens, Pfleiderer, & Gerlach, 2010; Dunn, Galton, et al., 2010; Dunn, Stefanovitch, et al., 2010; Herbert, Herbert, & Pollatos, 2011; Herbert, Pollatos, Flor, Enck, & Schandry, 2010; Khalsa & Feinstein, 2018; Pollatos, Herbert, Matthias, Herbert, Matthias, & Schandry, 2007). The vast majority of these studies were conducted under resting (i.e., physically inactive) conditions thus much less is known about the associations between physical activity, interoception, and affect.

Physical activity was part of the original lifestyle of *Homo sapiens*. Our anatomy and physiology have primarily been adapted to long-term physical activity in the aerobic domain (Bramble & Lieberman, 2004). Endurance was useful while chasing the prey or exploring new areas; it is even assumed that the latter was associated with increased cognitive load (e.g., due to building up and storing the internal map of the new environment), thus, it facilitates the generation of new neurons in the brain (Raichlen & Alexander, 2017). Physical activity in the aerobic domain is sustainable for many hours, sometimes even days. If the load is overly high and the oxygen supply carried by the cardiovascular system is insufficient, however, metabolism turns into anaerobic mode. This leads to the accumulation of lactate in the muscles and other local and systemic changes. Overall, these changes render physical activity unsustainable in the long run (Powers & Howley, 2014), which manifests itself as fatigue and exhaustion at the subjective level.

Perceived fatigue during physical activity is a complex phenomenon; it is a blend of local (e.g., fatigue of the muscles, pain in the joints) and more systemic (e.g., hunger for air, increased heart rate (HR), and respiration rate) body sensations (Borg, 1982; Jameson & Ring, 2000; Mihevic, 1981; St Clair Gibson & Noakes, 2004). Once this state is reached, it is difficult to reverse; thus, the constant monitoring of the actual level of physical activity is necessary to predict overload. As in other areas of human functioning, including the maintenance of homeostasis, this regulation heavily relies on affective-motivational changes. Physical activity in the aerobic domain typically generates positive affect, which starts to deteriorate around the anaerobic threshold; further increase of the load leads to negative affective states (Ekkekakis, Hall, Hall, & Petruzzello, 2008; Ekkekakis, Parfitt, & Petruzzello, 2011; Ekkekakis & Petruzzello, 1999). Thus, the regulation is bidirectional: the positive affective state motivates the individual to maintain the actual exertion, whereas the demotivating effect of the negative affective state leads to the decrease of the load. Accordingly, both (positive or negative) valence and intensity of the affective state play a role in the fine-tuning of the sustainable load. In line with this approach, the use of the so-called circumplex model of affect (Russell, 1980) is recommended in sports psychophysiology (Ekkekakis et al., 2011; Ekkekakis & Petruzzello, 1999), as it conceptualizes affect along the more or less independent dimensions of valence and arousal (Barrett & Russell, 1999; Kuppens, Tuerlinckx, Russell, & Barrett, 2013; Russell, 1980).

The subjectively sensed physical load or perceived exertion (i.e., the perceived sensory-discriminative aspect of activity) is routinely assessed using the rating of perceived exertion (RPE) scale by Borg (1982). Although the values of the Borg-scale were chosen to refer to the normal range of HR, from 60 to 200 bpm, this does not mean that people's ratings exclusively rely on cardiac stimuli (Borg, 1982; Ekblom & Goldbarg, 1971). Indeed, it was shown that muscle and respiratory sensations play a particularly important role in the perception of exertion (Jameson & Ring, 2000). Concerning HR, it can be sensed and reproduced quite reliably under physical loading; however, the reproduced load was systematically higher than the originally presented load. This was interpreted as a tendency to underestimate the actual load compared to the originally presented load (Kollenbaum, Dahme, & Kirchner, 1996; Kollenbaum, Dahme, Kirchner, Katenkamp, & Wagner, 1994; Köteles et al., 2020).

Perceived exertion, fatigue, cardiac activation, and the actual state of the respiratory system and the muscles belong to the umbrella of interoception. The view that conscious aspects of physical exertion are of homeostatic relevance is in line with the theory of Craig (2003, 2015), that emphasizes the role of interoception in the maintenance of homeostasis. The major dimensions of interoception, including IAc, show considerable individual differences (Brener & Ring, 2016; Garfinkel et al., 2015; Jones, 1995; Schandry, 1981). The most frequently used indicator of IAc is cardioceptive accuracy, the acuity of perception of heartbeats. Considering the fact that accuracy of cardioception cannot be generalized to other interoceptive modalities (Ferentzi et al., 2017, 2018; Garfinkel et al., 2016), this practice is not always advisable. In the context of physical exertion and affect, however, it can be considered an appropriate indicator as the cardiovascular system plays a prominent role in the physiological response to such stimuli (Herbert, Ulbrich, Ulbrich, & Schandry, 2007; Pollatos, Herbert, Matthias, et al., 2007; Schandry, 1981).

Higher levels of cardioceptive accuracy, as assessed with the mental tracking task of Schandry (1981) under resting conditions, were associated with lower physical performance when participants could freely choose their pedaling pace on a bicycle ergometer (Herbert, Ulbrich, et al., 2007). According to the explanation of the authors, better cardioceptive accuracy leads to the fine-tuning of the behavior. However, accuracy measured under resting conditions was associated with acuity of replication for very slight physical load but not for higher loads in another study (Köteles et al., 2020). The authors drew the conclusion that cardioceptive accuracy at rest and under physical load might rely on partly different interoceptive channels; for example, information from the respiratory system and the muscles, as well as affective state, might also be involved in the latter.

Cardioceptive accuracy plays a role in the experience of emotions too (Wiens, 2005). Relying on Russel's circumplex model of emotions (1980), empirical evidence shows that cardiac IAc is associated with the intensity of emotions (i.e., felt arousal), but not with valence (Barrett, Quigley, Bliss-Moreau, & Aronson, 2004; Herbert et al., 2010; Herbert, Pollatos, Pollatos, & Schandry, 2007; Pollatos, Herbert, Matthias, et al., 2007; Pollatos, Kirsch, & Schandry, 2005b; Wiens, Mezzacappa, & Katkin, 2000). Higher levels of cardioceptive accuracy were associated with higher arousal ratings in these studies. As the accuracy of perception of heartbeats plays a role in the experience and regulation of physical exertion as well as in emotional experience at rest, and physical activity generates affective changes, it is reasonable to assume that cardiac IAc is also associated with aspects of emotional experience evoked by physical activity.

The present research aimed to study associations between cardioceptive accuracy and aspects of subjective experience during physical activity. It was expected that cardioceptive accuracy, as assessed by heartbeat tracking ability, would show a positive association with perceived exertion (*Hypothesis 1*) and felt arousal during various intensities of physical activity (*Hypothesis 2*), however, it would not be related to valence (*Hypothesis 3*).

2 | METHOD

2.1 | Participants

Required sample size was calculated using the G-Power v3.1.9.4. Software (Faul, Erdfelder, Lang, & Buchner, 2007) based on the following considerations. The lowest effect size with respect to the correlation between heartbeat tracking ability and subjective arousal ratings reported in the literature (Herbert, Pollatos, et al., 2007; Pollatos, Herbert, Matthias, et al., 2007) was $r = .31$. This effect size was transformed to f and was applied to the between-subject main effect of a mixed analysis of variance (2 groups × 3 measurements); α was set to .05, 1-β was set to .8. Average correlation among repeated measures with respect to arousal ratings was calculated for the first 10 participants ($r = .592$). Using these parameters, the minimum required sample size was $N = 56$.

The final sample consisted of 67 undergraduates studying recreation or sports management (40 males; age: 20.67 ± 1.46 years). Participation was voluntary but rewarded with partial course credit. Participants gave signed informed consent; the study was allowed by the ethics board of the university.

2.2 | Measurements

2.2.1 | Anaerobic threshold

Anaerobic threshold ($HR_{threshold}$) was determined for each participant in a separate session before the experiment using a graded exercise test. A spiroergometer (Cosmed Fitmate Med, Cosmed The Metabolic Company, Italy) and a bicycle ergometer (Ergo Bike Premium 8, Daum Electronic GmbH, Germany) were used to measure oxygen consumption during exercise. HR was measured using the Firstbeat system (Firstbeat Heartrate monitoring belts and Sports software v4.7.2.1; Firstbeat Technologies Ltd., Jyväskylä, Finland), a valid and widely used system designed to monitor HR (Bogdány, Boros, Szemerszky, & Köteles, 2016; Hallman, Mathiassen, & Lyskov, 2015; Kos et al., 2017; Parak & Korhonen, 2013; Parak, Uuskoski, Machek, & Korhonen, 2017). After a short warm-up period (3 min, 25 Watt), the resistance of the ergometer was increased by 25 Watt/min until the subject reached his or her limit of tolerance. The pedal rate was maintained at 80 ± 5 rpm throughout the test (i.e., if the pedal rate dropped permanently under 75 rpm, the test was finished). During the test protocol, ventilation, O_2 consumption (VO_2), and HR were simultaneously measured. Anaerobic threshold was estimated as the point at which ventilation started to disproportionately increase compared to oxygen uptake (for more details, see Supporting Information, Part 1). This break point was determined by the consensus of three experts. Experts considered the results of an algorithm written in Matlab to detect the break point and also the slope of the ventilation-oxygen consumption curve (Szabolcs, Körmendi, Ihász, Köteles, & Szemerszky, 2018). The detection algorithm implements the sixth method described in the article of Ekkekakis and colleagues (Ekkekakis, Lind, Lind, Hall, & Petruzzello, 2008), that is, the break point was determined on the [VE/VO_2 versus. VO_2] diagram by the statistical method of Jones and Molitoris (Jones & Molitoris, 1984). Using the calculated anaerobic VO_2 threshold values, the corresponding anaerobic HR threshold values were obtained from the [HR versus. VO_2] diagram by another Matlab program.

2.2.2 | Schandry task

Assessment of heartbeat perception was conducted in seated position, with both feet on the ground, hands on the legs. Participants were asked to count their heartbeats silently during three randomly presented intervals (25, 35, and 55 s) after a 15 s long practicing phase. The counting started with a verbal START signal and stopped by a STOP signal, after which participants reported the number of felt heartbeats. Participants were explicitly encouraged to say 0 if they did not feel any heartbeats, but also encouraged to count if they have a slight sensation only. Actual heartbeats (ECG) were recorded 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). 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. Cronbach's alpha for the three trials of the Schandry task was .917.

2.2.3 | Self-report scales

Following the recommendations of Ekkekakis and colleagues (Ekkekakis, 2003; Ekkekakis et al., 2011; Ekkekakis, Hall, & Petruzzello, 2004), experiential aspects of physical exercise were assessed using one-item scales that can be rated verbally without interrupting the ongoing activity.

Perceived exertion was measured using the Rating of Perceived Exertion scale (RPE, aka Borg-scale) (Borg, 1982). This scale assesses the level of felt exertion ("Please rate the extent of your physical exertion at this moment") from 6 ("no exertion at all") to 20 ("maximal exertion"). The Borg-scale is the most widely used measure of perceived exertion (Borg, 1982, 1998; Lox, Martin Ginis, & Petruzzello, 2010).

Perceived level of arousal was measured using the Felt Arousal Scale (FAS) (Svebak & Murgatroyd, 1985). Participants are asked to rate their actual arousal level ("Please estimate how aroused you actually feel") on a 6-point scale from 1 ("very low arousal") to 6 ("very activated").

Valence was assessed using the Feeling Scale (FS) (Hardy & Rejeski, 1989). This 11-point scale measures affective state ("Please estimate how do you feel at this moment") with the anchor points of −5 ("very bad"), 0 ("neutral"), and +5 ("very good"). The FS is commonly used for the assessment of affective responses during exercise (Ekkekakis et al., 2004).

2.3 | Procedure

Major steps of the study are presented in Figure 1. Participants were examined one by one in a laboratory room. First, they completed the Schandry task. Second, they were equipped with the Firstbeat chest belt to monitor their HR during the physical loadings. Third, a short (3 min long) unloading period was included to reduce sympathetic activation evoked by the novel experimental setting (Kollenbaum et al., 1996; Köteles et al., 2020). This treatment is used in exercise and other settings when actual HR is a dependent variable. People with high levels of cardiovascular reactivity are prone to respond to the novel experimental situation with increased HR and blood pressure due to unusually high sympathetic activation. Thus, as described by Kollenbaum and colleagues (1996, p. 187), this period, was intended to "unload" excessive sympathetic drive so that the postexercise values could be regarded as basal values. For this unloading period, participants were asked to step on a treadmill (h/p/cosmos mercury med; h/p/cosmos Sports & Medical GmbH, Nussdorf–Traunstein, Germany). Speed was set to 3 km/h and participants were allowed to freely adjust the speed within the range of 3–6 km/h. After this period, participants were asked to sit for 5 min; HR measured in the final one-minute period was considered HR_{min}. Fourth, the first physical loading session of the three (in terms of HR (bpm): $HR_{threshold} - 30$, $HR_{threshold}$, $HR_{threshold} + 15$) started. Order of the three sessions was randomized. Participants were asked to step on the treadmill; speed was gradually increased until the target HR was reached. Under continuous monitoring, the target HR was kept relatively constant (within the range of ±7 bpm) for 3 min. The exact curve of the physiological response (e.g., HR) to increasing physical load is very hard to predict. Some people response to slight increases of load with marked elevations of HR, whereas the function is more or less linear for others. Therefore, it is impossible to keep the HR completely stable or within a very tight range under physical load. The ±7 bpm range was empirically determined for this experiment, taking also into consideration the parameters of the used treadmill (e.g., response time, setting options), in a pretest. It was found that almost all participants' HR could safely be kept within this range for 3 min. In concert with this, no participant was excluded from the experiment because of uncontrollable deviations from the predetermined HR range. The anaerobic load (T + 15) was calculated with this range kept in mind; the upper boundary of the threshold load was T + 7, whereas the lower boundary of the anaerobic load was T + 15–7 = T+8, thus, there was no overlap between the two. Considering the fact that the main goal of the study was the testing of hypotheses under different physical conditions, we think that the width of these ranges represents an acceptable compromise between theoretical

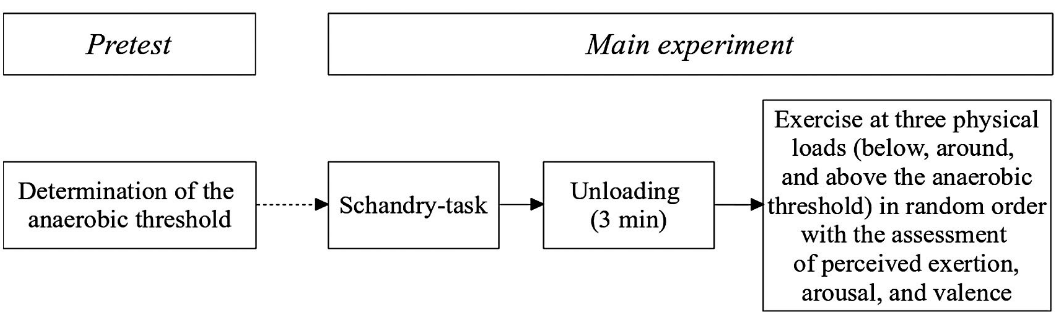

FIGURE 1 Design of the study

and practical constraints. The three scales (RPE, FAS, and FS) were verbally rated by participants at the end of the first, second, and third minute. Repetitions were included to increase internal consistency of the measurements. After finishing a session, participants were asked to sit and relax; the next session started when their HR reached 15% of their aerobic range (i.e., $HR_{min} + 0.15 * (HR_{threshold} - HR_{min})$).

2.4 | Statistical analysis

Statistical analysis was conducted using the JASP v0.11 Software (JASP Team, 2019). RPE, FAS, and FS values for each load were calculated as the average of the three values measured at the end of the first, second, and third minute. The three measurements were included to improve the reliability of the assessments. Cronbach's-alpha coefficients showed external internal consistency for each variable for each load ($HR_{threshold} - 30$, $HR_{threshold}$, and $HR_{threshold} + 15$): RPE: 0.926, 0.896, and 0.914; FAS: 0.917, 0.950, and 0.949; FS: 0.970, 0.973, and 0.975, respectively. As distribution of the IAc values showed a marked bimodal pattern with one peak around 0 and another around 0.7 (see Supporting Information, Part 2), data were transformed into binary form by median split (median = 0.5221; $N_{low} = 34$; $N_{high} = 33$). A repeated measures analysis of variance (ANOVA) was used to compare the three physical loadings. Hypotheses were tested using a mixed (2 × 3) ANOVA design with IAc as between-subject condition and physical loads as within-subject condition. Both frequentist and Bayesian methods were applied. In the frequentist approach, the Greenhouse–Geisser correction was used; in the post hoc analysis a Bonferroni-corrected $p < .05$ value was applied. In the Bayesian analysis, first the within-subject dimension was compared to a null model, then the between-subject dimension was compared to a null model including the within-subject dimension. BF_{10} values from 1 to 3 were considered indicating weak or anecdotal evidence in favor of the alternative hypothesis; values from 3 to 10 indicate substantial evidence, those between 10 and 100 strong evidence, where values above 100 are interpreted as decisive evidence (Jarosz & Wiley, 2014). This pattern of analysis was repeated after removing the Schandry values lower than 0.1 from the data set. This way, distribution of the Schandry score was normal thus it could be included in the analysis as covariant (for details, see Supporting Information, Part 3).

3 | RESULTS

Descriptive statistics are presented in Table 1. Concerning the three physical loads, repeated measures ANOVA indicated significant differences ($F(1.6,106.6) = 35,166.538$, $p < .001$, $\eta^2 = 0.695$); post hoc analysis showed significant differences between all loads (Bonferroni corrected $p < .05$).

Ratings for perceived exertion in the three physical loads differed significantly ($F(1.6,103.3) = 114.029$, $p < .001$, $\eta^2 = 0.346$) (Figure 2, left-hand side). Post hoc analysis revealed significant differences between each pairs (Bonferroni corrected $p < .05$). The main effect of cardioceptive accuracy (*Hypothesis 1*; $F(1,65) = 2.602$, $p = .112$, $\eta^2 = 0.038$) and the interaction between the two dimensions ($F(1.590,103.332) = 0.580$, $p = .524$, $\eta^2 = 0.002$) were not significant. Results of Bayesian analysis were in accordance with those of the frequentist analysis (Table 2). Findings of supplementary analysis with cardioceptive accuracy as covariant are in line with these results (see Supporting Information, part 3.1).

Concerning felt arousal, significant overall differences were found ($F(1.7,112.3) = 15.447$, $p < .001$, $\eta^2 = 0.059$) (Figure 2, central part). Bonferroni corrected post hoc analysis revealed significant differences between $Load_{threshold-30}$

TABLE 1 Descriptive statistics of the assessed variables

N = 67	*M* ± *SD*	Min–max
Cardioceptive accuracy (Schandry task)	0.46 ± 0.309	0.000–0.970
$HR_{threshold}$−30 (bpm)	123.01 ± 12.426	76.000–151.000
$HR_{threshold}$ (bpm)	152.86 ± 12.327	106.000–181.000
$HR_{threshold}$+15 (bpm)	167.71 ± 12.471	121.000–196.000
Perceived exertion at $Load_{threshold-30}$	8.81 ± 1.799	6.000–13.667
Perceived exertion at $Load_{threshold}$	10.82 ± 1.959	6.000–14.333
Perceived exertion at $Load_{threshold+15}$	12.46 ± 2.393	6.000–16.667
Felt arousal at $Load_{threshold-30}$	3.61 ± 1.072	1.000–6.000
Felt arousal at $Load_{threshold}$	4.09 ± 1.030	2.000–6.000
Felt arousal at $Load_{threshold+15}$	4.22 ± 1.034	1.667–6.000
Valence at $Load_{threshold-30}$	2.69 ± 1.471	−2.000–5.000
Valence at $Load_{threshold}$	2.49 ± 1.586	−1.000–5.000
Valence at $Load_{threshold+15}$	2.15 ± 1.914	−2.667–5.000

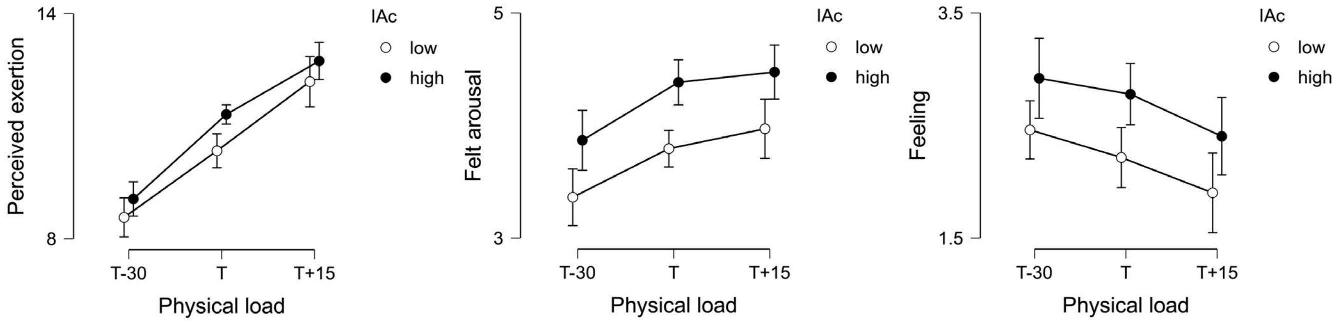

FIGURE 2 Average ratings for the three subjective variables (perceived exertion, arousal, and valence) during the three physical loads (error bars represent 95% confidence intervals). Statistical analysis indicated a significant effect on "Felt Arousal" of whether IAc was above or below median. Differences between these two IAc groups in "Perceived Exertion" or "Feeling" (Valence) were nonsignificant. Abbr: T − 30: anaerobic threshold—30 bpm; T: anaerobic threshold; T + 15: anaerobic threshold + 15 bpm; IAc: cardioceptive accuracy

TABLE 2 Results of Bayesian mixed ANOVAs (BF_{10} coefficients)

Dependent variable	Physical load main effect*	Cardioceptive accuracy (Schandry task)**
Perceived exertion	3.245e + 26	0.814
Felt arousal	18,198.067	3.768
Valence	12.580	0.717

*Model was compared to a null model including subjects only;

**Model was compared to a null model including subjects and physical load.

and $Load_{threshold}$, $Load_{threshold-30}$ and $Load_{threshold+15}$ but not between $Load_{threshold}$ and $Load_{threshold+15}$. Main effect of cardioceptive accuracy (*Hypothesis 2*; $F(1,65) = 6.411$, $p = .014$, $\eta^2 = 0.090$) was significant, whereas the interaction was not ($F(1.7,112.3) = 0.091$, $p = .888$, $\eta^2 = 0$). Higher heartbeat perception scores were associated with higher arousal ratings. Again, Bayesian results supported these findings (Table 2). Findings of supplementary analysis with cardioceptive accuracy showed a different pattern. Cardioceptive accuracy as covariant was marginally significant, whereas the load main effect became insignificant. However, Bayesian analysis showed the superiority of the null model (including the within-subject dimension) compared to the alternative model, including the covariant (see Supporting Information, part 3.2).

Finally, significant overall differences in valence were found ($F(1.8,119.8) = 6.335$, $p = .003$, $\eta^2 = 0.018$) (Figure 2, right-hand side). According to the results of post hoc analysis, differences were not significant between $Load_{threshold-30}$ and $Load_{threshold}$, marginally significant between $Load_{threshold}$ and $Load_{threshold+15}$, and significant between $Load_{threshold-30}$ and $Load_{threshold+15}$. Neither cardioceptive accuracy (*Hypothesis 3*; $F(1,65) = 1.929$, $p = .170$, $\eta^2 = 0.029$) nor the interaction term ($F(1.8,119.8) = 0.058$, $p = .932$, $\eta^2 = 0$) was significant. Bayesian results were in line with frequentist results (Table 2). Findings of supplementary analysis with cardioceptive accuracy as covariant indicated neither significant main effects nor interaction; Bayesian analysis showed a within-subject main effect and the superiority of the null model compared to the alternative model with cardioceptive accuracy as covariant (see Supporting Information, part 3.3).

4 | DISCUSSION

In an experiment with sport-oriented undergraduate students, the increase of physical load on the treadmill from below to above the anaerobic threshold led to a monotonic increase of perceived exertion and felt arousal, and a decrease of valence above the anaerobic threshold. Cardioceptive accuracy, as measured with the Schandry task, was associated with felt arousal but not with perceived exertion and valence.

Ratings of perceived exertion showed a monotonic, close to linear upward trend with relatively small confidence intervals (Figure 1), which supports the idea that the RPE scale appropriately assesses the actual level of physical exertion (Borg, 1982, 1998; Lox et al., 2010). Contrary to *Hypothesis 1*, cardioceptive accuracy was not associated with participants' exertion ratings. This can be explained in two ways. First, as perceived exertion relies on a number of tightly associated stimuli (cardiovascular, respiratory, and muscle level changes go hand in hand during physical activity) (Borg, 1970, 1974, 1982), better or worse performance with respect to one single modality does not substantially change the overall accuracy of the estimation. According to the findings of Jameson and Ring (2000), respiratory and muscle-related sensations influence perceived exertion more than HR. Second, it is also possible that the accuracy of heartbeat perception at rest cannot be generalized to physical exercise (Köteles et al., 2020). Although cardiac output increases with increased sympathetic activation under physical load, which theoretically makes detection of individual heartbeats easier (Schandry & Bestler, 1995; Schandry, Bestler, & Montoya, 1993), the internal noise (due to rhythmic movements, breathing, etc.) also increases (Köteles et al., 2020). In consequence, whereas the Schandry task requires the sensation of a weak internal signal, stronger signals should be identified in the presence of considerable internal noise during physical activity. These might represent different conditions, requiring different perceptual abilities.

Intensity of the experienced affective state (i.e., the arousal component of affect) also showed a monotonic increasing trend. The shape of this trend is different from that of perceived exertion, which suggests that the two constructs differ from each other. Moreover, in contrast to perceived exertion, arousal ratings were associated with the accuracy of heartbeat perception (*Hypothesis 2*); those with higher Schandry scores were characterized by higher levels of perceived arousal during load. The main effect of cardioceptive accuracy was still present (although only as a tendency) in the supplementary analysis involving the subsample with normally distributed Schandry scores. A positive association between cardioceptive accuracy and the intensity of emotions under physically inactive conditions was reported in a number of studies (Barrett et al., 2004; Herbert et al., 2010; Herbert, Pollatos, et al., 2007; Pollatos, Herbert, Matthias, et al., 2007; Pollatos, Kirsch, & Schandry, 2005a; Pollatos, Traut-Mattausch, Traut-Mattausch, Schroeder, & Schandry, 2007; Wiens et al., 2000). The present study extends this finding to the domain of physical activity. It is important to note, however, that direction of causality is not clear here. For example, cardiovascular reactivity may represent a third variable that explains causality. Performance in the Schandry task was positively associated with cardiovascular reactivity and anxiety in previous studies (Herbert et al., 2010; Pollatos, Herbert, Kaufmann, Herbert, Kaufmann, Auer, & Schandry, 2007). Thus, those with higher cardiovascular reactivity might show better heartbeat tracking performance as well as experience generally more arousal in cognitively or physically demanding situations.

Average valence ratings in the aerobic domain and around the anaerobic threshold showed no difference, whereas a marked decrease occurred in the anaerobic domain. This neatly replicates previous findings (for a recent review, see Ekkekakis et al., 2011). Further, the existence of marked individual differences, indicated by the relatively broad confidence intervals, is also described in the literature. These differences might partly rely on acquired and hereditary differences in cardiovascular fitness, previous experiences with physical activity, and cognitive factors, such as physical self-efficacy and self-presentational concerns (Ekkekakis, 2003; Ekkekakis & Acevedo, 2006; Ekkekakis et al., 2011). The fact that cardioceptive accuracy did not influence valence ratings *(Hypothesis 3)* is again in accordance with previous findings obtained under physically inactive conditions (Herbert et al., 2010; Pollatos, Herbert, Matthias, et al., 2007; Pollatos et al., 2005a; Pollatos, Schandry, Schandry, Auer, & Kaufmann, 2007; Pollatos, Traut-Mattausch, et al., 2007; Wiens et al., 2000).

The majority of conscious body sensations, such as pain, itch, the urge to urinate and defecate, or distension of the stomach are associated with negative affect, which is explained by their homeostatic function (Ádám, 1967, 1998). An intrinsically positive affective state characterizes only a few interoceptive modalities, such as affective (sensual) touch and sexual excitement (Björnsdotter, Morrison, & Olausson, 2010; Chivers, Seto, Lalumière, Laan, & Grimbos, 2010; Laan & Janssen, 2007; Olausson et al., 2002). The sensation of heartbeats appears to be neutral from this point of view as it can be associated with anxiety-related conditions (Domschke et al., 2010; Van der Does, Antony, Ehlers, & Barsky, 2000), as well as with positive emotions, such as happiness and joy (Kreibig, 2010). According to the findings of the present study, more accurate perception of heartbeats is associated with more intense emotional states during physical activity, regardless of their valence. In the framework of affective neuroscience, primary emotional systems with positive valence are seeking (exploration), play, care, and lust; the former two are tightly associated with (moderate) physical activity (Panksepp, 1982, 1991, 1998). The activation of these systems or physical exercise in the aerobic domain generate pleasure, which can counterbalance negative emotional states, such as anger or fear (Panksepp & Biven, 2012). On the one hand, as the ability to accurately sense heartbeats can intensify (already present) pleasure, it may play an adaptive role in the maintenance of regular physical activity. On the other hand, physical activity is often unpleasant for those with low levels of physical fitness and/or a sedentary lifestyle. When these individuals attempt to change their lifestyle, their first experiences with physical activity are often negative; high cardioceptive accuracy makes this unpleasantness even more intense. In summary, more accurate perception of heartbeats can act as a double-edged sword in the context of physical activity.

In the study of Herbert and colleagues (Herbert, Ulbrich, et al., 2007), those with better cardioceptive accuracy showed lower physical performance under experimental conditions; however, potential mediating factors were not assessed. Taking into consideration the findings of the present study, this association might have been mediated by perceived arousal, but not by perceived exertion or valence.

The present study is not without limitations. Because of the experimental conditions, aspects of the affective state were measured with single items; despite the repetitions, these assessments may be less reliable than multi-item scales (Ekkekakis et al., 2011). The mental tracking paradigm by Schandry has received criticism since its development, as measured performance is an amalgam of accuracy and bias. For example, an overestimation tendency and knowledge of actual HR might contribute to higher scores (Desmedt, Luminet, & Corneille, 2018; Ehlers & Breuer, 1996; Ring & Brener, 1996, 2018; Ring, Brener, Knapp, & Mailloux, 2015). To reduce overestimation tendency, we applied a stricter than usual instruction, explicitly mentioning to participants that estimation should be avoided and zero counted heartbeats can also be reported. This instruction, however, resulted in a bimodal distribution of the Schandry scores. Beyond the statistical challenges posed by this distribution, it shows that the reported number of felt heartbeats may rely on different decision strategies. A proportion of participants may have applied a very strict criterion, thus counted no or only very few heartbeats, whereas others were more liberal. It is also possible that the applied decision strategy interacts with detection ability, for example, those with poor detection ability are more prone to use the strict criterion than good detectors. Participants of the current study were engaged in regular physical activity and were characterized by above-average (although not elite level) cardiovascular fitness. Moreover, their knowledge of their own HR values at rest and under load might have been above that of physically less active individuals thus might have impacted the findings of the study. Finally, participants of the study had a marked positive attitude toward sports and physical activity; this further limits the generalizability of the findings.

5 | CONCLUSION

Cardioceptive accuracy is positively associated with perceived intensity (arousal) of the affective state during physical activity but not with valence and perceived exertion.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Supplementary Material

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