Biologia Futura
https://doi.org/10.1007/s42977-023-00173-4

ORIGINAL PAPER

Sensory and affective aspects of the perception of respiratory resistance

Orsolya Drozdovszky[1,2] · **Tara Petzke**[3] · **Ferenc Köteles**[2,4]

Received: 15 February 2023 / Accepted: 7 July 2023

Abstract

Perception of airway resistance has a sensory and an affective aspect, i.e., perceived resistance and unpleasantness, respectively. The current study aimed to shed more light on the relationship of these aspects, as well as their malleability to trait-like aspects of body awareness. In a laboratory study, 71 young participants completed two respiratory resistive load discrimination tasks relying on sensory and affective evaluation, respectively, and filled out questionnaires assessing somatosensory amplification, anxiety sensitivity, somatic symptoms distress, and breath awareness. Frequentist and Bayesian statistical analysis revealed no differences in discrimination accuracy with respect to the sensory and affective aspect of perceived resistance. Psychological traits were not associated with accuracy scores. In conclusion, affective evaluation of respiratory load is as accurate as sensory evaluation. Neither sensory not affective accuracy is influenced by various aspects of body awareness.

Keywords Respiratory load · Discrimination · Affect · Displeasure

Breathing effort, i.e., the load of respiratory muscles needed to maintain normal ventilation, is primarily determined by the dimensions (diameter) of the respiratory tract (Urbankowski and Przybyłowski 2016). Higher levels of airway resistance necessitate more muscular effort during inhalation, which evokes the feeling of dyspnea (shortness of breath or breathlessness) (De Peuter et al. 2004; Parshall et al. 2012; Fukushi et al. 2021).

It is assumed that airway resistance is partly estimated by the brain via the muscular effort (motor command) needed to maintain the necessary flow of air (Bennett et al. 1962; Killian et al. 1980; Campbell et al. 1980; Gandevia et al. 1981). Discrepancy between actual muscle effort and expected ventilatory response indicates higher than normal airway resistance (Banzett et al. 1989). The contribution of other sensory processes, such as information from slowly adapting stretch receptors and upper-airway "flow" receptors, seems also probable (De Peuter et al. 2004; Parshall et al. 2012).

The term interoceptive accuracy refers to accuracy of perception of interoceptive signals in behavioral tasks (Garfinkel et al. 2015). Accuracy of perception of respiratory load is generally assessed by respiratory resistive load discrimination tasks (RRLDTs). In these tasks, participants are asked to compare two consecutively presented respiratory loads in terms of their sensory characteristics, most importantly intensity of the feeling (Parshall et al. 2012; Petersen et al. 2014; Zacharioudakis et al. 2020). This approach, similar to other measures of interoceptive accuracy, e.g., tests of cardioceptive and gastric accuracy, is based on the sensory-discriminative aspect of the perceived sensations (Köteles 2021a).

Beyond the sensory aspect (perceived resistance/effort), dyspnea is characterized by a marked affective-evaluative aspect (unpleasantness) (Parshall et al. 2012; Fukushi et al. 2021). It is generally assumed that pleasure and displeasure represent the "common currency" for the brain when a decision about priorities with respect to the maintenance of homeostasis should be made (Cabanac 1971; Cabanac et al. 2002). Displeasure associated with body sensations refers to an acute threat to homeostasis (Reiman 1997; Banzett et al. 2000; Barrett 2017), a warning signal that

---

✉ Tara Petzke
tpetzke@uni-mainz.de

[1] Institute of Health Promotion and Sport Sciences, ELTE Eötvös Loránd University, Budapest, Hungary

[2] Ádám György Psychophysiology Research Group, Budapest, Hungary

[3] Psychological Institute, Johannes Gutenberg University, Wallstraße 3, 55122 Mainz, Germany

[4] Károli Gáspár University of the Reformed Church in Hungary, Budapest, Hungary

often necessitates immediate steps in order to avoid harmful consequences (Whitehead and Drescher 1980; Ádám 1998). For example, displeasure accompanied with pain is able to catch and maintain attention in order to motivate the organism to behavioral steps through which the threat or damage can be reduced (Eccleston and Crombez 1999). Thus, from the viewpoint of homeostatic regulation, the affective aspect of body sensations appears more relevant that the sensory aspect (Dworkin et al. 1994; Ádám 1998; Köteles 2021a). In line with this idea, the terms homeostatic emotions (Craig 2003), interoceptive appraisal (Farb and Logie 2018), and interoceptive emotional evaluation (Herbert and Pollatos 2018) were proposed recently to emphasize the salience of affective-evaluative evaluation in interoception. An interesting question is whether the output of the affective process is able to provide the organism with more precise information about the magnitude of the threat than the pure sensory process. As the distinction between sensory and affective aspects of perceived airway resistance appears meaningful, these characteristics were assessed separately in previous studies (Petersen et al. 2014; Zacharioudakis et al. 2020); however, their respective values were not compared.

Perceived aspect of interoception, i.e., individuals' beliefs about their awareness of and attentiveness to body processes, is called body awareness or interoceptive awareness (Shields et al. 1989; Mehling et al. 2009); it is assessed with questionnaires. In certain cases, body awareness is associated with proneness to aversive affective mood states, called negative affectivity (Tihanyi et al. 2016). For example, somatosensory amplification refers to the tendency to perceive somatic sensations as intense, noxious, and disturbing (Barsky et al. 1990); it can be conceptualized as risk perception with respect to possible threats to the integrity of the body (Köteles and Witthöft 2017). Somatic symptom distress refers to the negative psychological consequences of the perception of multiple and/or severe symptoms (Witthöft et al. 2016). Finally, anxiety sensitivity is defined as the fear of anxiety-related body sensations, as it is assumed by the individual that such sensations can have serious somatic consequences (Taylor 1995). These constructs are not unrelated to each other; all of them refers to unpleasant body sensations that potentially refer to pathological processes. It is possible that higher levels of these trait-like characteristics are adaptive in cases when the threat is real, e.g., they enable the individual to detect possibly dangerous conditions earlier (Köteles 2021a). Another aspect of body awareness is more neutral (i.e., related to mindful attention), as it focuses on the sensory-discriminative rather than the affective-evaluative aspect of the construct. For example, the Breath Awareness Scale was designed to assess the nonjudgmental aspect of awareness of respiratory sensations (Daubenmier et al. 2013). As respiratory activity is clearly perceivable under healthy conditions, it can be assumed that higher levels of body-related attention are associated with higher respiratory accuracy.

The study presented here was designed to test three hypotheses related to affective evaluation of respiratory activity. First (H1), it was assumed that displeasure is a more sensitive indicator of airway resistance than perceived respiratory load. Second (H2), we expected that higher levels of trait-like psychological characteristics that are related to negative affectivity, such as somatosensory amplification, anxiety sensitivity, and somatic symptom distress, would be positively associated with the affective but not with the sensory aspect of perceived airway resistance. Third (H3), we assumed a positive association between perceived awareness of breathing-related sensations and the sensory but not the evaluative aspect of breathlessness.

Methods

Participants

In the lack of previous data usable for a priori sample size calculation, end point of data collection was set to $n = 70$. This sample size is large enough for the detection of a medium level correlation ($r = 0.3$, one-tailed $\alpha = 0.05$, $1 - \beta = 0.95$) or a difference in a paired-samples t-test (ES = 0.4, one-tailed $\alpha = 0.05$, $1 - \beta = 0.95$). Participants were undergraduate university students ($N = 71$; age: 20.6 ± 4.83 yrs.; 85.9% female). Participants were characterized by a mean resting heart rate (rHR) of 85.1 ± 12.25 bpm and a resting respiratory rate (rRR) of 16.6 ± 2.81 breaths/min). Exclusion criteria were any self-reported psychiatric or neurological disorders, and lack of acute and chronic respiratory disease. Data were collected between May and November 2022; students received partial course credit for their participation. All subjects signed an informed consent form before participating in the experiment. The study was approved by the Research Ethics Board of the Faculty of Education and Psychology, Eötvös Loránd University, Hungary.

Measurement

Questionnaires

To assess somatic symptom distress, the Patient Health Questionnaire Somatic Symptom Severity Scale (PHQ-15) (Kroenke et al. 2002), a 15-item scale that measures how disturbing the most common body symptoms (e.g., headache, heart pound) had been in the previous 4 weeks on a 3-point Likert scale was used. Higher scores indicate higher levels of somatic symptoms distress. Clinical cutoff points for low, moderate, and high symptom severity are scores of 5, 10, and 15, respectively (Kroenke et al. 2002). The

Hungarian version of the scale used in the study showed good psychometric properties (Stauder et al. 2021); internal consistency (McDonald's ω) was 0.744 in the current study.

The Somatosensory Amplification Scale (SSAS) (Barsky et al. 1990) was used to assess proneness to somatic sensations that were perceived as unpleasant and threatening. The scale consists of 10 items rated on a 5-point scale; higher scores indicate a higher amplification tendency. Internal consistency of the Hungarian version of the scale (Köteles et al. 2009) was 0.635 in the present study.

To assess the tendency to fear bodily sensations, we used the Anxiety Sensitivity Index (ASI) (Taylor et al. 2007). Sixteen items of the ASI are rated on a five-point Likert scale; higher scores refer to higher levels of anxiety sensitivity. The Hungarian version used in this study (Kerekes 2012) showed an internal consistency of 0.875.

The Breath Awareness Scale (BAS) (Daubenmier et al. 2013) assesses awareness of and attentiveness to respiratory activity with six items rated on a 7-point scale. Higher scores refer to higher levels of breath awareness. The Hungarian version of the scale was translated from the English version using the usual translation/back-translation procedure. Internal consistency in the present study was 0.873.

Physiological measurements

Heart rate and respiratory rate measurement The NeXus-10 Mark II, version 1.02, device and the BioTrace + software for NeXus-10 (V201581) (Mind Media BV, Herten, the Netherlands) were used to measure rHR and rRR. To assess cardiac activity, three disposable Ag/AgCl ECG electrodes were attached underneath the participants' clavicles and on the left lower ribs (modified Lead II configuration). Respiratory rate was assessed using a strain gauge attached to the participants' upper chest.

Maximal inspiratory pressure (MIP) The POWERbreathe K5 (POWERbreathe International Limited, Southam, UK), an inspiratory muscle trainer originally developed to improve physical performance of athletes, was used to create various levels of respiratory resistance. In the calibration phase, participants were asked to inhale swiftly with maximal force after a maximal exhalation. This procedure was repeated five times; the average of the five obtained values was used as MIP (cm H2O), a measure of the strength of the inspiratory muscles.

Respiratory resistive load discrimination task (RRLDT) In the present study, accuracy of respiratory perception was assessed separately for the sensory-discriminative and affective-evaluative aspect of body sensations. Participants performed the RRLDT while they were seated in a separated room in front of a computer at a desk. Wearing a nose clip, subjects breathed through the mouthpiece of the POWERbreathe device. We instructed participants to keep the mouthpiece in their mouth for the duration of inhalation only and to exhale without it in order to minimize the device plugging with saliva. RRLDTs were administered in two blocks, each consisting of 60 breathing cycles. We used the 30% of MIP as reference load. After presenting two base loads and two reference loads, from the fifth breathing cycle participants' task was to compare pairs of respiratory loads (overall 28 comparisons in 56 breathing cycles). In each pair, the first load was the reference load, and the second load was identical to the first (4 trials), or it was higher or lower (2–2 trials, respectively, for each difference) by 10, 20, 30, 40, 50, and 60% (2 × 2x6 = 24 trials). The presentation of trials was randomized. In the sensory block, participants were asked to compare pairs of loads on a sensory basis ("Easier", "Same", "Harder"), whereas in the affective block they had to make an affective evaluation ("Less comfortable", "Same", "More comfortable"). Accuracy of respiratory perception was characterized with two indices: index of sensitivity (i.e., number of correct choices/4) for each difference category and as index of specificity (i.e., number of correct choices/4) for the no-difference trials. In other words, sensitivity refers to the proportion of correctly identified difference trials, whereas specificity refers to the proportion of correctly identified no-difference trials. Finally, overall sensory and affective discrimination scores were calculated as ratio of sensory/affective hits in all trials, respectively.

Procedure

Questionnaires were completed online within 7 days before the scheduled appointment. Participants were measured individually in a separate room. Upon arrival, participants read and signed an informed consent form and a privacy statement. Then they were fitted with the ECG electrodes and the strain gauge, and asked to sit silently on a chair in a relaxed position for 10 min to assess their rHR and rRR. In the next step, subjects' MIP was measured, followed by the two RRLDT tasks (sensory-discriminative and affective-evaluative), administered in a randomized order.

Statistical analysis

Statistical analysis was conducted using the JASP version 0.16.4 software (JASP Team 2022). Specificity indices were compared with Student's t-test. The differences between sensitivity indices were estimated with two-way repeated measure (Evaluation(2) x Difference(6)) analysis of variance (ANOVA) with Greenhouse–Geisser correction. In post hoc analysis, Holm-corrected *p*-values were used. A Bayesian ANOVA with a similar design was also conducted. In this

ANOVA, the null model, including Difference, subject, and random slopes, was compared to the alternative model that included Evaluation too. Sensitivity and specificity indices' deviation from 0.33 (indicating random guessing) was checked with one-sample Wilcoxon signed-rank test with rank-biserial correlation as effect size indicator. Associations between questionnaire scores and sensory/affective accuracy were checked with frequentist and Bayesian correlation analysis (Pearson correlation). In the Bayesian analyses, Bayes factors (BF10) smaller than 0.33 were considered to support the null hypothesis, whereas BF10 larger than 3 were assumed to indicate the superiority of the alternative hypothesis (Jarosz and Wiley 2014).

Results

Differences between sensory-discriminative and affective-evaluative detection ability

Concerning Hypothesis 1, descriptive statistics of specificity and sensitivity indices for the no-difference and difference trials, respectively, are presented in Table 1. Paired samples t-test indicated no significant difference between specificity indices ($t(70) = -1.7345$, $p = 0.087$, $d = 0.177$). As for sensitivity indices, repeated measures ANOVA indicated a significant Difference main effect ($F(3.8637,270.4598) = 111.954$, $p < 0.001$, $\eta^2 = 0.424$) but no significant Evaluation main effect ($F(1,70) = 0.132$, $p = 0.717$, $\eta^2 = 0.0002$) and Difference x Evaluation interaction ($F(4.467,312.700) = 2.031$, $p = 0.082$, $\eta^2 = 0.0063$). Post hoc analysis indicated significant differences (pHolm < 0.05) between each pair of successive loads with the exception of the differences between 40, 50, and 60% ($p = 0.75$) (Fig. 1). According to the Bayesian repeated measures ANOVA, BF10 for Evaluation were 0.122, whereas BF10 for Difference x Evaluation interaction were 0.024. The latter results support the null hypothesis, i.e., the lack of difference between accuracy of sensory and affective evaluation.

Associations between the respective sensory and affective accuracy indices were nonsignificant for the no-difference trials and for differences ranging from 10 to 30%. Higher differences and total discrimination performance were characterized by moderate to strong correlations (Table 2).

According to Wilcoxon signed-rank tests, sensitivity indices for 10% difference did not significantly differ from random guessing (i.e., 0.33), whereas indices for 20% difference were significantly higher (Table 3). Specificity indices were also significantly higher than the reference value.

Table 1 Descriptive statistics of measures of respiratory accuracy, i.e., specificity (for no difference) and sensitivity indices in the different conditions, and total sensory and affective discrimination scores ($N = 71$)

Indicator of respiratory accuracy	Difference between the two stimuli	Type of evaluation	M	SD
Specificity	0%	Sensory	0.528	0.269
Specificity	0%	Affective	0.612	0.279
Sensitivity	10%	Sensory	0.363	0.256
Sensitivity	10%	Affective	0.285	0.233
Sensitivity	20%	Sensory	0.504	0.288
Sensitivity	20%	Affective	0.511	0.252
Sensitivity	30%	Sensory	0.669	0.234
Sensitivity	30%	Affective	0.659	0.284
Sensitivity	40%	Sensory	0.725	0.281
Sensitivity	40%	Affective	0.778	0.282
Sensitivity	50%	Sensory	0.799	0.252
Sensitivity	50%	Affective	0.828	0.256
Sensitivity	60%	Sensory	0.789	0.282
Sensitivity	60%	Affective	0.831	0.238
–	Total discrimination	Sensory	0.64	0.169
–		Affective	0.64	0.163

Associations between detection ability and questionnaire scores (H2 and H3)

Descriptive statistics for questionnaire scores are presented in Table 4. Overall, frequentist and Bayesian correlation analysis indicated the lack of association for the majority of tests for Hypothesis 2 and 3 (Table 5). Bayesian analysis was inconclusive with respect to the association between sensory discrimination performance and SSAS and BAS scores.

Discussion

In a laboratory experiment, no differences between accuracies of perception of respiratory load with respect to sensory and affective evaluation were found (H1). Contrary to our expectations, affective discrimination was not associated with indicators of negative aspects of body focus (anxiety sensitivity, somatic symptoms distress, and somatosensory amplification; H2), and sensory discrimination was not associated with a neutral measure of breath awareness (H3).

Participants' discrimination performance was not better than chance for 10% difference, whereas 20% difference was detected in both ways of evaluation. In the early study of Wiley and Zechman (1966), the threshold difference (also called just-noticeable difference) of discrimination of

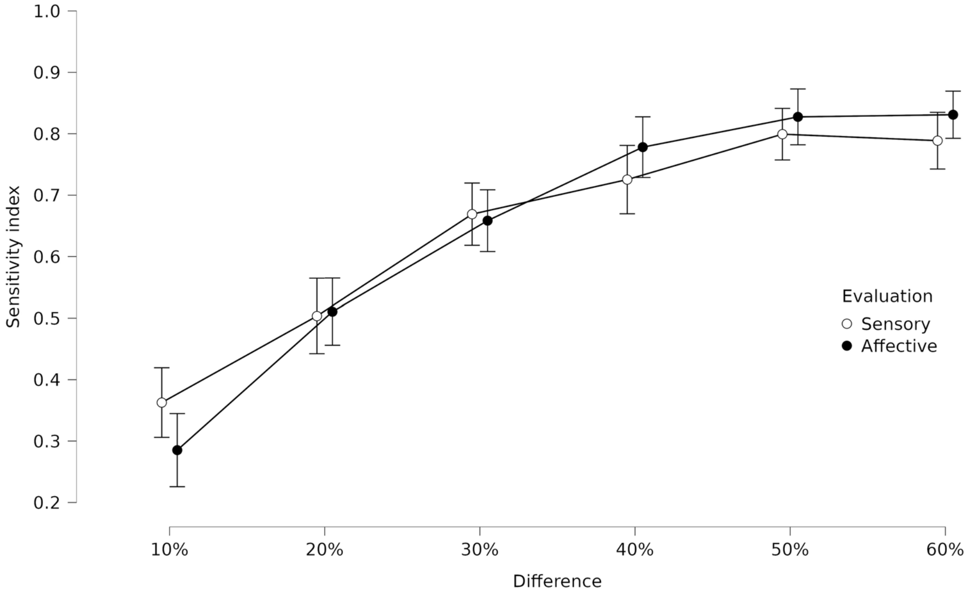

Fig. 1 Sensory and affective evaluation-based sensitivity indices for the various load differences. Error bars indicate 95% confidence intervals

Table 2 Associations between the respective sensory and affective accuracy indices (Pearson correlations)

N = 71	Specificity (no difference)	Sensitivity (10% difference)	Sensitivity (20% difference)	Sensitivity (30% difference)	Sensitivity (40% difference)	Sensitivity (50% difference)	Sensitivity (60% difference)	Total discrimination
r	− .10	.23	.10	.21	.40**	.49***	.56***	.51***

Table 3 Results of Wilcoxon tests comparing specificity/sensitivity values to 0.33 indicating random guessing

Index	*V*	*p*	Rank-biserial correlation
Specificity sensory	2213.0000	< 0.001	0.732
Specificity affective	2368.0000	< 0.001	0.853
Sensitivity 10% sensory	1521.0000	0.161	0.190
Sensitivity 10% affective	1011.0000	0.121	− 0.209
Sensitivity 20% sensory	2096.0000	< 0.001	0.640
Sensitivity 20% affective	2217.0000	< 0.001	0.735

Table 4 Descriptive statistics of self-reported instruments

N = 71	*M*	SD	Min	Max
ASI	38.96	10.676	19	67
PHQ-15	7.42	3.655	1	18
SSAS	29.68	5.437	19	46
BAS	22.9	7.554	6	39

ASI Anxiety Sensitivity Inventory, *PHQ-15* Patient Health Questionnaire Somatic Symptom Severity Scale, *SSAS* Somatosensory Amplification Scale, *BAS* Breath Awareness Scale

Table 5 Results of frequentist and Bayesian correlation analysis (Pearson correlations)

N = 71	Sensory discrimination		Affective discrimination	
	r	*p; BF10*	*r*	*p; BF10*
ASI	0.0217	0.858; 0.151	− 0.0339	0.779; 0.154
PHQ-15	− 0.030	0.803; 0.153	− 0.067	0.578; 0.173
SSAS	0.198	0.098; 0.566	0.039	0.748; 0.156
BAS	0.175	0.144; 0.422	0.060	0.618; 0.167

ASI Anxiety Sensitivity Inventory, *PHQ-15* Patient Health Questionnaire Somatic Symptom Severity Scale, *SSAS* Somatosensory Amplification Scale, *BAS* Breath Awareness Scale

respiratory resistance was about 25–30%. Dahme and colleagues (1996) calculated a mean Weber ratio of 0.25 from results of ten studies; our measurements indicate a somewhat lower threshold. This difference might be due to the different paradigms and devices. It is also worth noting that our value is comparable with values calculated in weight discrimination tests for light weights in normal subjects (Rosenbaum et al. 1965; Ritzler 1977; Leventhal et al. 1982). As effort of striated muscles plays a substantial role in the estimation of resistive load (Bennett et al. 1962; Killian et al. 1980; Gandevia et al. 1981), these similarities may reflect the common characteristics of muscle effort and motor control. Our results are in line with the idea that the basic laws of psychophysics might be valid for not just exteroceptive but also for interoceptive modalities (Ádám et al. 1999). Also, they can be helpful in the appropriate setting of respiratory load differences in future studies.

Contrary to our expectations (H1), accuracy of discrimination between respiratory loads was similar for the sensory and affective condition. It could be assumed that the two processes are so tightly associated in healthy individuals, as in the case of the perception of gastric distension and bitter sensitivity (Ferentzi et al. 2017, 2018a), that participants could not focus on one aspect only. However, associations between sensory and affective discrimination indices for small differences were very weak, whereas a moderate to strong association emerged for larger differences (above 30%). One possible explanation is related to the experiment leaders' observations that many participants were breathing more deeply and frequently than usual, in order to complete the task faster or perhaps for reasons of social desirability and demand characteristics. As respiratory changes impact both sensory and cognitive-affective processes (Heck et al. 2022), this may have made it even more difficult for some participants to focus on one aspect only when the difference was comparatively small.

Lack of difference between sensory and affective discrimination indicates that the latter is as accurate as the former, with the advantage of being able to catch and maintain attention under competing sensory cues (Dixon 1981). It has been proposed recently that negative affective bias leads to worse sensory accuracy via a so-called better safe than sorry processing strategy (Van den Bergh et al. 2021). In the light of our results and theoretical considerations, this idea should be refined. As stated by the better safe than sorry principle, dominance of negative expectations (priors) over sensory input characterizes sensory processing if negative affect is evoked by other processes, i.e., it is not part of the sensory process itself. However, for modalities that are inherently tied to affective evaluation, such as the distension of the urinary bladder, the rectum, and the stomach, and dyspnea (Paintal 1986), negative affect generated by displeasure can be considered a warning signal (Whitehead and Drescher 1980) that enables the brain to instant and precise processing of the sensory input (Köteles 2021a). In other words, it is an adaptive feature that helps the organism to prioritize the appropriate behavioral response over other alternatives (Ádám 1998). Thus, negative affect and displeasure generated by bottom-up and top-down sources can have a different impact on the processing of interoceptive signals.

Affective evaluation-based accuracy was not associated with trait-like characteristics that include both body focus and negative affectivity, i.e., somatosensory amplification, anxiety sensitivity, and somatic symptom distress (H2). Patient groups characterized by higher levels of these features, e.g., patients with panic disorder, typically show more intense reactions to various respiratory provocations than healthy controls (Griez et al. 1990; Gorman et al. 1994; Giardino et al. 2010). In the lack of such pathological conditions, as in the case of the volunteers participating in our study, these characteristics apparently do not intensify affective reactions to interoceptive cues. In a similar vein, perceived propensity to nonjudgmental awareness of breathing was not related to sensory evaluation-based accuracy (H3). The lack of expected associations can also be the consequence of discrepancy between actual and perceived internal events. Interoception-related psychological traits represent a generalization over time and modalities (Vig et al. 2022); thus, their dissociation from actual sensory accuracy is not surprising (Köteles 2021b). Empirical results show this dissociation primarily for visceral perception, typically cardioception (Ainley and Tsakiris 2013; Emanuelsen et al. 2015; Ferentzi et al. 2018b). Although respiratory as opposed to cardiac or gastrointestinal activity is partly accessible to conscious awareness, this apparently does not mean that higher level of perceived awareness of and attentiveness to breathing is accompanied with higher levels of perceptual accuracy.

A possible future research direction would be to replicate this experiment using nasal breathing instead of oral breathing. Recent studies have shown that low frequency cerebral cortical oscillations rely on nasal breathing and are disrupted with other modes of breathing (Fontanini et al. 2003). In behavioral experiments, Zelano et al. (2016) were able to show that fearful faces are recognized more quickly, and memory accuracy was higher at inhalation than at exhalation, and these effects dissipated when participants were asked to breathe orally. Currently, the relationship between respiration and cognitive-affective deficits is only poorly understood, but respiratory modulation of neural activity seems to a promising new causal mechanism (Heck et al. 2022). For this study, this could mean that using a nasal respiratory resistance setup may lead to better performance on the affective task because of the limbic oscillations entrained by nasal breathing (Zelano et al. 2016). Possible interactions between negative affect evoked by interoceptive (e.g., respiratory resistance) and exteroceptive (e.g., affective pictures; Bogaerts et al. 2010) and their impact on respiratory accuracy represent another promising idea for future research.

There are factors that limit the generalizability of the findings of the current study. Most importantly, participants represented a special group, i.e., they were not representative of the general population. Furthermore, it is known that inspiration and expiration differently impact slowly adapting pulmonary receptors (Davenport et al. 1981; Muza et al. 1984), which might impact discrimination ability. Finally, it is possible the focusing only on one aspect of the perception of airway resistance was difficult for participants. Low internal consistency of the SSAS can be regarded as another limitation of the study. It is worth mentioning, however, that values like this are typical for this scale (Köteles and Witthöft 2017).

It can be concluded that affective evaluation of respiratory load is as accurate as sensory evaluation. Accuracy of evaluation is not influenced by various aspects of body awareness.

Conclusion for future biology

Unpleasant body sensations evoked by interoceptive signals, such as breathlessness, cause suffering and often indicate an acute threat to homeostatic balance. Better understanding of the underlying psychophysiological mechanisms, including the correspondence between physiological disturbance and subjective sensation, may have serious practical implications.

Acknowledgements This research was supported by the Research Fund of the National Research, Development and Innovation Office (K 137724). This project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 956673 (for T.P.). This article reflects only the author's view, the agency is not responsible for any use that may be made of the information it contains.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

Ádám G (1998) Visceral perception: understanding Internal Cognition. Plenum Press, New York

Ádám G, Fent J, Kajtár M (1999) An attempt for the application of the basic law of psychophysics (Fechner-Stevens law) in the domain of visceral stimulus in humans. Acta Biol Hung 50:19–25

Ainley V, Tsakiris M (2013) Body conscious? Interoceptive awareness, measured by heartbeat perception, is negatively correlated with self-objectification. PLoS ONE 8:e55568. https://doi.org/10.1371/journal.pone.0055568

Banzett RB, Lansing RW, Reid MB et al (1989) “Air hunger” arising from increased PCO2 in mechanically ventilated quadriplegics. Respir Physiol 76:53–67. https://doi.org/10.1016/0034-5687(89)90017-0

Banzett RB, Mulnier HE, Murphy K et al (2000) Breathlessness in humans activates insular cortex. NeuroReport 11:2117–2120. https://doi.org/10.1097/00001756-200007140-00012

Barrett LF (2017) How Emotions Are Made: The Secret Life of the Brain, Illustrated edition. Mariner Books

Barsky AJ, Wyshak G, Klerman GL (1990) The somatosensory amplification scale and its relationship to hypochondriasis. J Psychiatr Res 24:323–334. https://doi.org/10.1016/0022-3956(90)90004-A

Bennett ED, Jayson MI, Campbell EJ (1962) The ability of man to detect added non-elastic loads to breathing. Clin Sci 23:155–162

Bogaerts K, Janssens T, De Peuter S et al (2010) Negative affective pictures can elicit physical symptoms in high habitual symptom reporters. Psychol Health 25:685–698. https://doi.org/10.1080/08870440902814639

Cabanac M (1971) Physiological role of pleasure. Science 173:1103–1107. https://doi.org/10.1126/science.173.4002.1103

Cabanac M, Guillaume J, Balasko M, Fleury A (2002) Pleasure in decision-making situations. BMC Psychiatry 2:7. https://doi.org/10.1186/1471-244X-2-7

Campbell EJ, Gandevia SC, Killian KJ et al (1980) Changes in the perception of inspiratory resistive loads during partial curarization. J Physiol 309:93–100

Craig AD (2003) A new view of pain as a homeostatic emotion. Trends Neurosci 26:303–307

Dahme B, Richter R, Mass R (1996) Interoception of respiratory resistance in asthmatic patients. Biol Psychol 42:215–229. https://doi.org/10.1016/0301-0511(95)05156-2

Daubenmier JJ, Sze J, Kerr CE et al (2013) Follow your breath: respiratory interoceptive accuracy in experienced meditators. Psychophysiology 50:777–789. https://doi.org/10.1111/psyp.12057

Davenport PW, Frazier DT, Zechman FW (1981) The effect of the resistive loading of inspiration and expiration on pulmonary stretch receptor discharge. Respir Physiol 43:299–314. https://doi.org/10.1016/0034-5687(81)90111-0

De Peuter S, Van Diest I, Lemaigre V et al (2004) Dyspnea: The role of psychological processes. Clin Psychol Rev 24:557–581. https://doi.org/10.1016/j.cpr.2004.05.001

Dixon NF (1981) Preconscious Processing. John Wiley Sons Australia Limited

Dworkin BR, Elbert T, Rau H et al (1994) Central effects of baroreceptor activation in humans: attenuation of skeletal reflexes and pain perception. Proc Natl Acad Sci U S A 91:6329–6333

Eccleston C, Crombez G (1999) Pain demands attention: a cognitive-affective model of the interruptive function of pain. Psychol Bull 125:356–366. https://doi.org/10.1037/0033-2909.125.3.356

Emanuelsen L, Drew R, Köteles F (2015) Interoceptive sensitivity, body image dissatisfaction, and body awareness in healthy individuals. Scand J Psychol 56:167–174. https://doi.org/10.1111/sjop.12183

Farb NA, Logie K (2018) Interoceptive appraisal and mental health. In: Tsakiris M, De Preester H (eds) The interoceptive mind. From homeostasis to awareness. Oxford University Press, Oxford, England, pp 227–241

Ferentzi E, Köteles F, Csala B et al (2017) What makes sense in our body? Personality and sensory correlates of body awareness and somatosensory amplification. Personal Individ Differ 104:75–81. https://doi.org/10.1016/j.paid.2016.07.034

Ferentzi E, Bogdány T, Szabolcs Z et al (2018a) Multichannel investigation of interoception: sensitivity is not a generalizable feature. Front Hum Neurosci 12:223. https://doi.org/10.3389/fnhum.2018.00223

Ferentzi E, Drew R, Tihanyi BT, Köteles F (2018b) Interoceptive accuracy and body awareness – temporal and longitudinal associations in a non-clinical sample. Physiol Behav 184:100–107. https://doi.org/10.1016/j.physbeh.2017.11.015

Fontanini A, Spano P, Bower JM (2003) Ketamine-Xylazine-Induced Slow (< 1.5 Hz) Oscillations in the Rat Piriform (Olfactory) Cortex Are Functionally Correlated with Respiration. J Neurosci 23:7993–8001. https://doi.org/10.1523/JNEUROSCI.23-22-07993.2003

Fukushi I, Pokorski M, Okada Y (2021) Mechanisms underlying the sensation of dyspnea. Respir Investig 59:66–80. https://doi.org/10.1016/j.resinv.2020.10.007

Gandevia SC, Killian KJ, Campbell EJ (1981) The effect of respiratory muscle fatigue on respiratory sensations. Clin Sci 60:463–466. https://doi.org/10.1042/cs0600463

Garfinkel SN, Seth AK, Barrett AB et al (2015) Knowing your own heart: distinguishing interoceptive accuracy from interoceptive awareness. Biol Psychol 104:65–74. https://doi.org/10.1016/j.biopsycho.2014.11.004

Giardino ND, Curtis JL, Abelson JL et al (2010) The impact of panic disorder on interoception and dyspnea reports in chronic obstructive pulmonary disease. Biol Psychol 84:142–146. https://doi.org/10.1016/j.biopsycho.2010.02.007

Gorman JM, Papp LA, Coplan JD et al (1994) Anxiogenic effects of CO2 and hyperventilation in patients with panic disorder. Am J Psychiatry 151:547–553. https://doi.org/10.1176/ajp.151.4.547

Griez E, de Loof C, Pols H et al (1990) Specific sensitivity of patients with panic attacks to carbon dioxide inhalation. Psychiatry Res 31:193–199. https://doi.org/10.1016/0165-1781(90)90121-k

Heck DH, Correia BL, Fox MB et al (2022) Recent insights into respiratory modulation of brain activity offer new perspectives on cognition and emotion. Biol Psychol 170:108316. https://doi.org/10.1016/j.biopsycho.2022.108316

Herbert BM, Pollatos O (2018) The relevance of interoception for eating behavior and eating disorders. In: Tsakiris M, De Preester H (eds) The interoceptive mind. From homeostasis to awareness. Oxford University Press, Oxford, England, pp 165–186

Jarosz A, Wiley J (2014) What are the odds? A practical guide to computing and reporting Bayes factors. J Probl Solving 7:2–9. https://doi.org/10.7771/1932-6246.1167

JASP Team (2022) JASP (Version 0.16.4) [Computer software]

Kerekes ZS (2012) A szorongás mint adaptív viselkedés. A szorongásérzékenység mérésének tapasztalatai különböző csoportoknál. PhD-disszertáció. Pécsi Tudományegyetem

Killian KJ, Mahutte CK, Campbell EJ (1980) Resistive load detection during passive ventilation. Clin Sci 59:493–495. https://doi.org/10.1042/cs0590493

Köteles F (2021a) What Can We Sense? Interoceptive Accuracy. In: Köteles F (ed) Body Sensations: The Conscious Aspects of Interoception. Springer International Publishing, Cham, pp 75–164

Köteles F (2021b) Can We Trust Our Body Feelings? The Discrepancy Between Actual and Perceived Events. In: Köteles F (ed) Body Sensations: The Conscious Aspects of Interoception. Springer International Publishing, Cham, pp 213–243

Köteles F, Witthöft M (2017) Somatosensory amplification – an old construct from a new perspective. J Psychosom Res 101:1–9. https://doi.org/10.1016/j.jpsychores.2017.07.011

Köteles F, Gémes H, Papp G et al (2009) A Szomatoszenzoros Amplifikáció Skála (SSAS) magyar változatának validálása. Mentálhig És Pszichoszomatika 10:321–335. https://doi.org/10.1556/Mental.10.2009.4.3

Kroenke K, Spitzer RL, Williams JBW (2002) The PHQ-15: validity of a new measure for evaluating the severity of somatic symptoms. Psychosom Med 64:258–266

Leventhal DB, Schuck JR, Clemons JT, Cox M (1982) Proprioception in schizophrenia. J Nerv Ment Dis 170:21–26

Mehling WE, Gopisetty V, Daubenmier J et al (2009) Body awareness: construct and self-report measures. PLoS ONE. https://doi.org/10.1371/journal.pone.0005614

Muza SR, Lee LY, Pan CP et al (1984) Respiratory volume-timing relationship during sustained elevation of functional residual capacity. Respir Physiol 58:77–86. https://doi.org/10.1016/0034-5687(84)90046-x

Paintal AS (1986) The visceral sensations — some basic mechanisms. In: Cervero F, Morrison JFB (eds) Visceral Sensation. Elsevier, Amsterdam, The Netherlands, pp 3–19

Parshall MB, Schwartzstein RM, Adams L et al (2012) An official American thoracic society statement: update on the mechanisms, assessment, and management of dyspnea. Am J Respir Crit Care Med 185:435–452. https://doi.org/10.1164/rccm.201111-2042ST

Petersen S, Schroijen M, Mölders C et al (2014) Categorical interoception: perceptual organization of sensations from inside. Psychol Sci 25:1059–1066. https://doi.org/10.1177/0956797613519110

Reiman EM (1997) The application of positron emission tomography to the study of normal and pathologic emotions. J Clin Psychiatry 58(Suppl 16):4–12

Ritzler B (1977) Proprioception and schizophrenia: a replication study with nonschizophrenic patient controls. J Abnorm Psychol 86:501–509. https://doi.org/10.1037/0021-843X.86.5.501

Rosenbaum G, Flenning F, Rosen H (1965) Effects of weight intensity on discrimination thresholds of normals and schizophrenics. J Abnorm Psychol 70:446–450

Shields SA, Mallory ME, Simon A (1989) The body awareness questionnaire: reliability and validity. J Pers Assess 53:802. https://doi.org/10.1207/s15327752jpa5304_16

Stauder A, Witthöft M, Köteles F (2021) Validation of the Hungarian PHQ-15. A latent variable approach. Ideggyógy SzemleClinical Neurosci 74:183–190. https://doi.org/10.18071/isz.74.0183

Taylor S (1995) Anxiety sensitivity: theoretical perspectives and recent findings. Behav Res Ther 33:243–258

Taylor S, Zvolensky MJ, Cox BJ et al (2007) Robust dimensions of anxiety sensitivity: development and initial validation of the Anxiety Sensitivity Index-3. Psychol Assess 19:176–188. https://doi.org/10.1037/1040-3590.19.2.176

Tihanyi BT, Sági A, Csala B et al (2016) Body awareness, mindfulness and affect: does the kind of physical activity make a difference? Eur J Ment Health 11:97–111. https://doi.org/10.5708/EJMH.11.2016.1-2.6

Urbankowski T, Przybyłowski T (2016) Methods of airway resistance assessment. Adv Respir Med 84:134–141. https://doi.org/10.5603/PiAP.2016.0014

Van den Bergh O, Brosschot J, Critchley H et al (2021) Better safe than sorry: a common signature of general vulnerability for psychopathology. Perspect Psychol Sci 16:225–246. https://doi.org/10.1177/1745691620950690

Vig L, Köteles F, Ferentzi E (2022) Questionnaires of interoception do not assess the same construct. PLoS ONE 17:e0273299. https://doi.org/10.1371/journal.pone.0273299

Whitehead WE, Drescher VM (1980) Perception of gastric contractions and self-control of gastric motility. Psychophysiology 17:552–558. https://doi.org/10.1111/j.1469-8986.1980.tb02296.x

Wiley RL, Zechman FW (1966) Perception of added airflow resistance in humans. Respir Physiol 2:73–87. https://doi.org/10.1016/0034-5687(66)90039-9

Witthöft M, Fischer S, Jasper F et al (2016) Clarifying the latent structure and correlates of somatic symptom distress: a bifactor model approach. Psychol Assess 28:109–115. https://doi.org/10.1037/pas0000150

Zacharioudakis N, Vlemincx E, Van den Bergh O (2020) Categorical interoception and the role of threat. Int J Psychophysiol off J Int Organ Psychophysiol 148:25–34. https://doi.org/10.1016/j.ijpsycho.2019.12.009

Zelano C, Jiang H, Zhou G et al (2016) Nasal respiration entrains human limbic oscillations and modulates cognitive function. J Neurosci 36:12448–12467. https://doi.org/10.1523/JNEUROSCI.2586-16.2016