Contingent biofeedback outperforms other methods to enhance the accuracy of cardiac interoception: A comparison of short interventions

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ABSTRACT

Background and objectives: Deviations in interoception might contribute to the development and maintenance of mental disorders. The improvement of interoceptive accuracy (IA) is desirable but assessment and training methods remain controversial. For instance, it was assumed that performance increases in heartbeat counting paradigms after cardiac feedback were due to an improvement of knowledge with regard to heart rate rather than due to an actual improvement in IA.

Methods: Here, we examined effects of contingent cardiac feedback training, non-contingent cardiac feedback, mindfulness practice, and a waiting period with external attentional focus on IA. 100 healthy participants underwent a mental tracking paradigm before and after 20 min of training or waiting.

Results: Results revealed a significant increase of IA in the contingent feedback condition ($d = 1.21$, $p \leq .001$) and no significant changes after non-contingent feedback, mindfulness practice or waiting ($d \leq 0.37$; $p \geq .06$). Furthermore, IA increase was significantly higher after the contingent feedback training compared to all other conditions, including non-contingent feedback.

Limitations: Future studies need to replicate these findings in clinical samples and examine time dependent effects.

Conclusions: The results provide evidence for the trainability of heartbeat perception. IA improvements may reduce the symptom burden in people suffering from mental disorders and psychophysiological conditions that have been linked to lower interoceptive accuracy such as depression, somatic symptom disorder, chronic pain, and functional somatic syndromes. Consequently, exploration of biofeedback training procedures shall be continued with the aim of identifying relevant mediators of beneficial effects and future implementation in clinical practice.

1. Introduction

The processing of internal bodily signals - interoception - is a multifaceted construct, including the accurate detection of body sensations (interoceptive accuracy: IA), as well as the interpretation and integration of these (Khalsa et al., 2018). Assessment of IA needs objective quantification of body signals (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). To accomplish this is quite challenging, because few interoceptive signals are readily observable (Khalsa et al., 2018). Since heartbeat is easily recorded and is a robust physiological signal (Phillips, Jones, Rieger, & Snell, 1999), IA is most often assessed in the cardiac domain (IA$_{cd}$ J. Brener & Ring, 2016). In the widely-used mental tracking task by Schandry (1981), participants are asked to count their heartbeats in varying time intervals. In other mental tracking tasks, participants tap their heartbeat (McFarland, 1975) or adjust frequencies of external stimuli until these match their heartbeat (Carroll & Whellock, 1980). In addition to mental tracking, HBP is often assessed in discrimination tasks. Here, participants are asked to decide if a given external signal accurately represents the heartbeat or not (Brener & Ring, 2016).

Dysfunctional IA is related to different mental disorders conceptually (Khalsa et al., 2018), whereby empirical evidence is strongest for anxiety disorders (for a review on enhanced IA in pathological anxiety see Domschke, Stevens, Pfleiderer, & Gerlach, 2010). Next to deviant IA, cognitively biased processing of interoceptive signals, changes in the tendency of engagement by body sensations, or a poor metacognitive evaluation of IA (not knowing when one makes good or bad interoceptive decisions) are supposed to contribute to the

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maintenance of different mental disorders (Khalsa et al., 2018). Biased processing of interoceptive or ambiguous tactile signals was shown for somatic symptom and illness anxiety disorders in analogue (Brown, Brunt, Poliakoff, & Lloyd, 2010; Krautwurst, Gerlach, Gomille, Hiller, & Witthöft, 2014; Petersen, Van Staeyen, Vogele, von Leupoldt, & Van den Bergh, 2015) and clinical samples (Katzer, Oberfeld, Hiller, Gerlach, & Witthöft, 2012; Katzer, Oberfeld, Hiller, & Witthöft, 2011; Krautwurst, Gerlach, & Witthöft, 2016). Here, higher impairment is associated with liberalization of responses, indicating a 'better safe than sorry' approach of participants (Petersen et al., 2015). An improved detection of body sensations would not only address deviant IA, but also biased processing and the way of engaging with bodily signals. Following the rational of signal detection theory, response bias is a measure for the tendency to assume a signal in case of uncertainty. Thus, high accuracy would be accompanied by a reduction of uncertainty and therefore a reduced response bias (Macmillan & Creelman, 2004). Therefore, improvement of IA might be a promising approach for the treatment of some mental disorders but methods to assess and train IA are under debate.

To the best of our knowledge, two methods have been considered to improve IA_{cd}: mindfulness training and biofeedback. Mindfulness is being described as a state, in which a person focuses his/her attention to experiences of the present moment with an attitude of curiosity and acceptance (Bishop et al., 2004). During mindfulness trainings, people are often specifically guided to bring their attention to bodily sensations. It has been argued that this interoceptive attention focus enhances the accuracy to perceive bodily signals (Khalsa et al., 2008). One commonly used example of mindfulness practice with body focus is the so called "body scan" (Williams, 2010). During a body scan intervention participants are guided to use their breath as an anchor for internal attention and bring different body parts one after another into the focus of attention. An increase of self-reported interoceptive awareness following mindfulness training was shown by several studies (e.g. Khalsa et al., 2008; Parkin et al., 2014). Furthermore, after a brief period of body scan training, near threshold tactile signals were detected more sensitively and tactile misperceptions decreased in a task, in which tactile signals were conceptualized as laboratory analogues of somato-form symptoms (Mirams, Poliakoff, Brown, & Lloyd, 2013). This lead to the assumption that body scan training might foster a more accurate perception of bodily signals (Mirams et al., 2013). Contrary to this finding, HBP did not improve after body scan training (study one and two Parkin et al., 2014). In line with this, no significant differences in HBP were found, when performance of experienced mediators was compared to non-mediators (Khalsa et al., 2008; Melloni et al., 2013).

In contrast to mindfulness practice, cardiac biofeedback is a more promising approach to increase IA_{cd} (e.g. Schandry & Weitkunat, 1990; Weitkunat, Schandry, Sparrer, & Beck, 1987). During cardiac biofeedback, patients receive a visual, acoustic or tactile feedback on their heart activity. Through this, they are supposed to learn to perceive and in some cases influence bodily processes more accurately. In an early study, participants underwent a discrimination task before and after a series of acoustic heartbeat feedback training blocks. The training blocks included three different sequences of 1 min each, whereby acoustic feedback was presented 130 ms after the R-wave constantly, fading out or in no trial. Participants were to tap after every sensed heartbeat. Correct responses were rewarded by a specific acoustic signal. Performance in the second discrimination task increased, even when feedback was faded out after one third of each training block (Schandry & Weitkunat, 1990). Also, a heartbeat discrimination task, in which participants were presented with auditory tones in rhythm of their heartbeats improved performance in a heartbeat tapping task (Weisz, Balazs, & Adam, 1988). Schaefer, Egloff, Gerlach, and Witthöft (2014) adapted the training of Schandry et al. (1990). However, they used visual cardiac biofeedback instead of an acoustic signal. Their training was separated into five blocks, each separated into two phases (with and without visual feedback). Participants were to press a button

after each 2nd to 4th consecutive heartbeat (amount of heartbeats to count was indicated before each trial). A feedback of (in)correctness of response was presented after each trial to maximize learning effects. Not having to tap every single heartbeat and phases without visual feedback allowed participants to better focus on their body without having to split their attention. Importantly, this training did not only improve IA_{cd}, but also reduced state symptom distress in patients suffering from somatic symptom disorder (Schaefer et al., 2014).

However, mental tracking paradigms and the results of cardiac biofeedback studies have been put into question (Phillips et al., 1999; Ring, Brener, Knapp, & Mailloux, 2015). Based on studies that demonstrated an influence of beliefs about heart rate on mental tracking (e.g. Ring & Brener, 1996), it was assumed that people improved in IA_{cd} not because of a better detection of actual heartbeats but rather because their knowledge about their heart rate became more accurate (Phillips et al., 1999; Ring et al., 2015). In line with this, heartbeat tapping performance increased after exposure to an auditory sample of one's own heartbeats that was not synchronized with the R-wave of the actual heartbeat (Ludwick-Rosenthal & Neufeld, 1985). A better performance in the Schandry task was shown after false feedback that was faster than the actual heart-rate of participants, while accuracy was lower after false feedback that was slower compared to no biofeedback (Phillips et al., 1999). It was assumed that this effect was due to the underestimation of one's own heart rate by most people. In a direct comparison of contingent and non-contingent cardiac feedback, mental tracking performance improved similarly, while there was no improvement, when participants underwent no feedback training (Ring et al., 2015).

The studies that showed increased performance after cardiac feedback that was not synchronized with actual heartbeats therefore underlined that mental tracking tasks were solved superiorly, when people had accurate beliefs on their heart rate. However, so far, no study coupled the false feedback with the actual heart activity of each participant. Consequently, timing of feedback and heartbeat sensation remained unclear. For example Ring et al. (2015) provided participants with feedback triggered by heartbeats recorded five beats before the actual heartbeat. Therefore, at least some of the feedback signals might have been contingent to the actual heart rate. Furthermore, the feedback training was relatively short (6 min). Although beliefs about heart rate might be updated fast, learning to better detect one's heartbeat possibly needs a longer training.

Here, we aimed at comparing the different methods thought to improve IA_{cd} and consider methodological criticism concerning cardiovascular feedback training. For this purpose, HBP before and after four different interventions was assessed: a HBP training with contingent cardiac (true) biofeedback and with non-contingent (false) cardiac feedback, mindfulness practice ("body scan") and a film condition (external focus of attention). We expected that HBP training with true biofeedback would have the highest impact on IA_{cd}. Although our false biofeedback was non-contingent, it may have updated beliefs on heart rate in our participants. Therefore, we assumed an increase of IA_{cd} after false feedback, too. We hypothesized no influence of mindfulness practice or film watching on IA_{cd}.

2. Methods

2.1. Participants

104 participants were recruited from Cologne University and surroundings using electronic message boards. In accordance with the declaration of Helsinki all participants were informed about the procedure beforehand and gave written informed consent concerning the study protocol. Due to technical errors during recording of biodata, 4 participants had to be excluded from further analyses. The final sample consisted of 74 women and 26 men aged between 17 and 44 years (M = 25.28; SD = 5.67). Most participants were unmarried (94%),

named German as mother tongue (90%) and were currently studying (94%).

2.2. Procedure and experimental manipulations

First, all participants were pseudo-randomly assigned to one of the four experimental groups. Group allocation was randomized in blocks. A randomization block contained four participants and each of the four experimental groups to secure similar sample sizes in the experimental groups (final sample sizes: contingent feedback: $N = 26$, non-contingent feedback $N = 25$, mindfulness practice $N = 25$, waiting group $N = 24$). Then, three Ag-AgCl electrodes were applied to participants' lower left rib cage, to the right mid-clavicle and to the left mid-clavicle (ground electrode) to acquire the electrocardiogram. After assessing baseline heart rate, participants performed the mental tracking task (Time 1), received the respective experimental manipulation (one of the trainings or film) and underwent the mental tracking task again (Time 2). Biodata were recorded and analyzed (sampled at 512 Hz) with the help of a Variport system (Becker Meditec, Germany). Before receiving monetary compensation or class credit, participants completed several questionnaires. The entire procedure lasted approximately 60 min.

2.2.1. Mental tracking task

IA was assessed with the Schandry task (Schandry, 1981). Participants were instructed to silently count their heartbeats in three time intervals by paying attention to body sensations that could be related to their heart activity. They were not allowed to feel their pulse or check their watch. The time intervals of 25, 35 and 45 s were presented in randomized order (Uvariotest; Gerhard Mutz). A tone signaled the beginning and end of each interval. The duration of the intervals and if their answers were correct was unknown to the participants. IA was calculated by comparing measured and counted heartbeats. Detection of R-waves and computation of the mean heart rate were conducted by a custom-built software (Uvariotest; Gerhard Mutz). The scores of three time intervals were averaged. The HBP score was calculated as follows:

HBP score = $1-1/3 \Sigma$ ((|recorded heartbeats – counted heartbeats|) / recorded heartbeats)

A perfect correspondence between the recorded and counted heartbeats resulted in a value of 1. In the present sample, Cronbachs α for the mental tracking task based on the HBP scores of the three intervals was $\alpha = 0.88$ for Time 1 and $\alpha = 0.92$ for Time 2. The retest reliability was $r = 0.59$.

2.2.2. Experimental manipulation

The experimental manipulation lasted for approximately 20 min and consisted of either HBP training with true or false biofeedback, mindfulness training or a waiting period during which a film was presented.

2.2.2.1. HBP training with contingent (true) cardiac feedback.

The HBP training was based on the training of Schaefer et al. (2014) and presented by Uvariotest (Gerhard Mutz). Participants underwent three training blocks, which were divided into two phases each. 48 trials were presented in each trainings block (24 per phase). In the first phase, biofeedback was presented, while in the second phase no biofeedback was given. Other than in the original training, only three instead of five training blocks were implemented to equal the length of all four experimental manipulations.

In biofeedback trials (phase 1 of each block) a visually presented animated heart symbol presented 200 ms after R-wave detection. The delay of 200 ms was selected, because most people sense their heartbeat at this time point (Jasper Brener, Ring, & Liu, 1994). During both phases, participants were asked to press a button after a specified number of heartbeats (2, 3 or 4 heartbeats). They were instructed

before each trial how many heartbeats they had to count before the button press (e.g. "3 beats until button press"). A reaction was classified as correct, if the participant pressed the button within 450 ms (reaction time) after the last heartbeat that had to be counted. Participants received feedback about their performance in form of a green check mark or a red "X" after each trial. Moreover, participants received feedback on the percentage of correct responses after each phase. The intertrial interval varied between 1 and 4 heartbeats. The number of heartbeats until button press and the length of the intertrial interval were pseudo-randomized. A pause of 15 s was implemented between the two phases. Prior to the actual HBP training, 12 practice trials were completed to familiarize participants with the procedure and assure compliance with the task.

2.2.2.2. HBP training with non-contingent (false) cardiac feedback.

The false feedback training was similar to the true feedback, but presented information slightly varied from true feedback condition. Here, feedback was not coupled to the R-wave and actual heart rate was reduced by 20%. Using the small number of events to be counted (2–4 heartbeats) results in approximately the same number of beats within each trial for both true and false feedback. This procedure ensured that general knowledge about the individual heartbeat was improved (because false feedback was linked to one's individual heartbeat), whereas the reaction expected of the participant was not to be presented at a time at which the participants were likely feeling their actual heartbeats. The participants did not know about the reduction but were debriefed after the experiment.

2.2.2.3. Mindfulness training.

A 20 min audio-recording of the body scan training as adapted from Michalak, Heidenreich, Williams, and Meibert (2012) was conducted via loudspeaker. Most adaptations pertained to the introduction, because participants performed the training in sitting position. During the body scan participants were guided to focus on specific body parts with a non-judgemental acceptance of the arising sensations, thoughts and feelings. They were guided to direct their attention to different body parts consecutively: body parts in contact to the chair, the breath felt in the abdomen, the left leg and foot, the right leg and foot, hip and pelvis, back and shoulder blade, lower and upper abdomen, breast, shoulders and neck, head and face and last the whole body. Participants were instructed to support the perception of their body by breathing consciously. In order to enhance the comparability of the four groups, participants in the mindfulness group listened to the body scan recording in a sitting position.

2.2.2.4. Waiting condition.

Participants allocated to this experimental manipulation watched the first 20 min of a documentary on the Etosha desert without any instruction (Wilde Paradiese – Etosha: In der Glut der Savanne, WVG Medien, 2000). This manipulation was designed to control for time and learning effects of the repeated Schandry task while at the same time, encouraging the participants to focus their attention externally.

2.2.3. Self-report data

Participants completed questionnaires on psychopathological symptoms, mindfulness and interoceptive awareness to check for baseline differences in variables potentially related with IA between the four experimental groups. Additionally, they were asked how often they currently practiced mindfulness techniques per month.

Depressive and somatoform symptoms were assessed using the Patient Health Questionnaire-D (PHQ-D Spitzer, 1999). The burden of 13 physical symptoms, sleep problems (one item) and fatigue (one item) during the last four weeks were rated on a 3-point Likert scale (0–2) to assess somatic symptom distress. Depressiveness was assessed with the help of nine items (4-point Likert scale ranging from 0 to 3). Sum scores were calculated for each participant for the two subscales

Table 1

Test statistics and effect sizes of χ^2-tests and MANOVA on initial differences between the experimental groups.

variable/scale	M_{con} (SD)	M_{noncon} (SD)	M_{mind} (SD)	M_{wait} (SD)	test statistic	df	p	effect size
demographic variables								
age	25.81 (5.08)	24.68 (5.54)	25.24 (6.05)	25.38 (6.26)	$F = 0.17$	3,16	.92	$\eta_p^2 = .01$
sex					$\chi^2 = 1.54$	3	.67	$V = .12$
marital status					$\chi^2 = 3.75$	6	.71	$V = .07$
mother tongue					$\chi^2 = 0.46$	3	.93	$V = .11$
level of education					$\chi^2 = 7.69$	6	.26	$V = .23$
job					$\chi^2 = 8.83$	9	.45	$V = .10$
physiological variables								
basic heart rate	74.77 (15.00)	73.77 (10.65)	74.23 (9.38)	78.02 (8.96)	$F = 0.72$	3, 273	.55	$\eta_p^2 = .02$
heartbeat perception T1 (Schandry)	0.61 (0.16)	0.70 (0.16)	0.66 (0.18)	0.63 (0.18)	$F = 1.22$	3,95	.48	$\eta_p^2 = .04$
questionnaires								
FFA: trait-mindfulness	34.32 (5.56)	36.68 (6.25)	34.68 (5.64)	35.54 (6.41)	$F = 0.77$	3,95	.51	$\eta_p^2 = .02$
STAI-T: trait-anxiety	44.40 (11.98)	37.32 (9.62)	41.80 (12.96)	41.75 (8.68)	$F = 1.79$	3,95	.15	$\eta_p^2 = .05$
PHQ-D: psychopathology								
somatic symptom distress	7.56 (4.76)	6.57 (3.57)	8.00 (4.70)	6.17 (2.79)	$F = 1.08$	3,95	.36	$\eta_p^2 = .03$
depression	7.32 (5.36)	5.16 (3.29)	6.88 (4.31)	5.67 (3.45)	$F = 1.45$	3,95	.23	$\eta_p^2 = .04$
MAIA: interoceptive awareness								
noticing	3.13 (0.79)	3.22 (0.82)	3.03 (0.82)	3.06 (1.05)	$F = 0.23$	3,95	.88	$\eta_p^2 = .01$
not-distracting**	1.83 (0.69)	1.73 (0.75)	2.04 (0.88)	2.42 (1.04)	$F = 3.11*$	3,95	.03*	$\eta_p^2 = .09$
not-worrying	2.81 (0.95)	2.44 (1.20)	2.39 (1.02)	2.49 (1.25)	$F = 0.75$	3,95	.52	$\eta_p^2 = .02$
attention-regulation	2.47 (0.83)	2.70 (0.94)	2.53 (0.77)	2.77 (1.08)	$F = 0.60$	3,95	.62	$\eta_p^2 = .02$
emotional awareness	3.46 (0.93)	3.47 (0.79)	3.67 (0.83)	3.59 (0.85)	$F = 0.36$	3,95	.78	$\eta_p^2 = .01$
self-regulation	2.43 (1.17)	2.51 (1.19)	2.45 (0.99)	2.47 (1.26)	$F = 0.05$	3,95	.98	$\eta_p^2 < .01$
body listening	2.19 (1.17)	2.43 (1.04)	2.11 (1.02)	2.24 (1.40)	$F = 0.34$	3,95	.80	$\eta_p^2 = .01$
trusting	3.20 (1.29)	3.53 (0.90)	2.96 (1.28)	3.46 (1.01)	$F = 1.32$	3,95	.27	$\eta_p^2 = .04$

Note: mind = mindfulness training, wait = waiting condition, con = HBP training with cardiac contingent feedback, non-con = HBP training with cardiac non-contingent feedback, level of education: categorical variable with categories: no degree, high school degree, college degree; job: employee, self-employed, student; PHQ-D = Patient Health Questionnaire (German version); FFA = Freiburg Mindfulness Questionnaire ("Freiburger Fragebogen zur Achtsamkeit"); STAI-T = State-Trait-Anxiety-Inventory (Trait-Version); MAIA = Multidimensional Assessment of Interoceptive Awareness; * $p < .05$; **$N = 99$.

somatic symptom distress and depressiveness.

Trait-anxiety was assessed using the State-Trait-Anxiety Inventory (STAI-T; Spielberger, 1970; 1983). Participants rated 20 items on their individual disposition to react anxiously (from 1 'almost never' to 4 'almost every time'). A sum score was calculated across all items (ranging from 20: low trait anxiety to 80: high trait anxiety).

Mindfulness was estimated using the short version of the Freiburger mindfulness questionnaire (Freiburger Fragebogen zur Achtsamkeit, FFA-14; Buchheld, 2001). Participants answered 14 items concerning their trait mindfulness on a 4-point-Likert scale (ranging from 1 'seldom' to 4 'almost every time'). A sum score was calculated across all items (range between 14 and 54).

Interoceptive awareness was measured with the Multidimensional Assessment of Interoceptive Awareness (MAIA; Mehling, 2012). Participants rated 32 statements on their disposition to focus on bodily signals on a 6-point Likert scale (ranging from 0 'never' to 5 'always'). Means are calculated for the following eight subscales: 'Noticing' (be aware of body sensations in general), 'Not Distracting' (not ignore unpleasant body sensations), 'Not Worrying' (not worry about body sensations or feel distressed by them), 'Attention Regulation' (be able to regulate attention towards body sensations and sustain it), 'Emotional Awareness' (be aware of the connection of emotions and body sensations), 'Self-Regulation' (to be able to downregulate distress via attention to the body), 'Body Listening' (disposition to focus on the body to gain insight) and 'Trusting' (to experience the body as trustworthy).

Cronbachs alpha indicated internal consistencies of $\alpha = 0.82$ for depressive symptoms, $\alpha = 0.70$ for somatic symptoms, $\alpha = 0.93$ for anxiety symptoms, $\alpha = 0.79$ for self-reported mindfulness in the current sample. The internal consistency of the MAIA subscales was good (all $\alpha > 0.77$), except for the subscales "Noticing" ($\alpha = 0.67$) and "Not-Distracting" ($\alpha = 0.57$).

2.3. Data analysis

To test for group differences in variables possibly linked with IA, a MANOVA was calculated with experimental manipulations as independent variables and sociodemographic and psychopathological variables, mindfulness, interoceptive awareness and basic heart rate as dependent variables.

A 4 (experimental manipulation: correct biofeedback training, incorrect biofeedback training, mindfulness training, film watching) x 2 (time: time 1, time 2) ANOVA was calculated with HBP scores (mental tracking task) as dependent variable. We expected a significant group $\times$ time interaction, indicating that HBP would improve after the two biofeedback trainings, but would not improve after mindfulness training and film watching.

Furthermore, a direct comparison of difference scores of HBP (Time 2 – Time 1) was calculated. An ANOVA with experimental manipulation as independent and the difference score as dependent variable was calculated. A main effect of experimental manipulation was expected, indicating that improvement of HBP in the correct biofeedback group was higher than in all other groups.

To test to which extent improvement of HBP in the experimental groups depended on initial HBP ability of participants, HBP scores of the first mental tracking task were correlated with the HBP difference scores (Time 2 – Time 1) for all four conditions. These correlations were then compared according to Cohen, Cohen, West, and Aiken (2003). We expected higher improvement of HBP in participants with low initial HBP scores. This relation was expected to be weaker in the contingent feedback group, because we assumed that participants with more accurate beliefs on their heart rate would rather benefit from contingent but not from non-contingent feedback training. We assumed a weaker relation for the mindfulness and the waiting group, too, since we did not expect improvement after experimental manipulation.

To further analyze the improvement of HBP in both feedback groups, we compared the percentage of correct responses in the three training blocks in a 3 (training block) x 2 (feedback phase/no feedback phase) x 2 (contingent/non-contingent feedback group) repeated measures ANOVA. A main effect of phase and a block by group interaction effect was expected, indicating that performance was higher in phases

with visual feedback, and that percent correct responses improved from block 1 to block 3 with a stronger improvement in the contingent feedback group.

3. Results

3.1. Sociodemography and psychopathology

Average scores on the Patient Health Questionnaire, German version (PHQ-D) were low and corresponded to a mild degree of symptoms (Kroencke, Spitzer, & Williams, 2001). Trait anxiety as assessed with the German version of the State-Trait Anxiety Inventory, trait version (STAI-T) was also within the typical range of non-clinical populations (means of student norming samples for the trait measure range from 40.29 to 41.68 Laux, 1981) (compare Table 1 for means and standard deviations of the current sample).

The four groups did not differ concerning sociodemographic and psychopathologic variables, as well as mindfulness and interoceptive awareness (with the exception of the subscale "Not-Distracting") and basic heart rate (see Table 1 for details).

As the amount of mindfulness training sessions per month was not normally distributed (kurtosis and skewness) in all groups, Man and Whitney U-Tests were calculated. There were no group differences (all $p \geq .16$) except for the comparison of film ($Mdn = 0$, $IQR = 2$) and contingent feedback group ($Mdn = 0$, $IQR = 0$) ($U = 234.50$, $z = -1.36$, $r = -0.19$, $p = .02$). More participants of the film group reported to practice mindfulness ($N = 7$ vs. $N = 1$).

3.2. Comparison of the biofeedback, mindfulness and control group on HBP

The comparison of the HBP scores revealed a significant main effect of time, $F(1, 96) = 23.51$, $p < .001$, $\eta_p^2 = 0.20$, indicating that performance increased from time 1 ($M = 0.65$, $SD = 0.02$) to time 2 ($M = 0.72$, $SD = 0.02$). There was also a significant time x experimental group interaction effect, $F(3, 96) = 9.89$, $p < .001$, $\eta_p^2 = 0.24$, indicating that performance changes differed between experimental groups. Post-hoc tests showed that HBP increased significantly in the true biofeedback training group, $F(1, 96) = 50.42$, $p < .001$, $d = 1.21$. In the false biofeedback group, there was only a trend towards significance, with a much smaller effect size, $F(1, 96) = 3.72$, $p = .06$, $d = 0.37$. However, there was no improvement in the mindfulness training group, $F(1, 96) = 0.12$, $p = .74$, $d = 0.05$ or waiting group, $F(1, 96) = 0.21$, $p = .65$, $d = 0.07$.

Fig. 1 Heartbeat perception accuracy before and after experimental manipulation.

The comparison of the difference scores demonstrated a significant main effect of experimental group, $F(1, 96) = 9.89$, $p < .001$, $\eta_p^2 = 0.24$. Post-hoc comparisons using the Tukey-HSD test showed that the difference score of the true cardiac feedback group was significantly higher than of the other three experimental groups: the false cardiac feedback group ($p = .003$), the mindfulness group ($p < .001$) and the waiting group ($p < .001$). The difference score of the false biofeedback group was not significantly higher than that of the mindfulness group ($p = .68$) or the waiting group ($p = .74$). Also mindfulness and waiting group did not differ significantly ($p > .99$).

Effect size d_{ppc3} was calculated for pre-post group comparisons to display the increase of treatment response after true cardiac feedback in comparison to all other experimental manipulations (Morris, 2008). We found an effect of $d_{ppc3} = 0.18/d_{ppc3} = 0.19$ when treatment response after true feedback was compared with waiting/mindfulness group and an effect of $d_{ppc3} = 0.17$ for the comparison of true feedback and false feedback group.

The improvement on the HBP score was negatively correlated to the initial HBP score in the contingent (true) feedback group, $r(26) = -0.54$, $p = .004$, as well as in the non-contingent (false) feedback group, $r(25) = -0.68$, $p < .001$. A significant correlation was also found for

the mindfulness group $r(25) = -0.42$, $p = .04$ but not for the waiting group, $r(24) = -0.27$, $p = .2$. The correlation for the true feedback group did not differ significantly from all other groups (comparison with false feedback: $Z = 0.73$, $p = .47$; with the mindfulness group: $Z = -0.52$, $p = .6$ and with the waiting group: $Z = -1.08$, $p = .28$). Note that the sample size for the comparison of correlations was rather low.

3.3. Comparison of the blocks of the HBP training

Comparison of the percent correct responses in the training blocks of both feedback groups showed a significant main effects of block, $F(2, 98) = 6.96$, $p = .001$, $\eta_p^2 = 0.12$, of phase, $F(1, 49) = 138.1$, $p < .001$, $\eta_p^2 = 0.74$, and of group, $F(1, 49) = 5.97$, $p = .02$, $\eta_p^2 = 0.11$. There were no significant interaction terms of block by group, $F(2, 98) = 0.001$, $p = 1$, $\eta_p^2 < 0.001$, phase by group, $F(1, 49) = 0.80$, $p = .38$, $\eta_p^2 = 0.02$, block by phase, $F(2, 98) = 0.26$, $p = .78$, $\eta_p^2 = 0.01$, or block by phase by group $F(2, 98) = 0.32$, $p = .73$, $\eta_p^2 = 0.01$. Bonferroni corrected pairwise comparisons indicated that the percentage of correct reactions improved significantly from block 1 to block 2 ($p = .04$) and 3 ($p = .002$), but not from block 2 to block 3 ($p = .76$). There were relatively more correct reactions in the phases with visual feedback ($M = 72.41\%$, $SD = 22.8$) than without ($M = 40.80\%$, $SD = 14.01$). Participants in the true feedback group showed more correct reactions across both training phases and all three blocks ($M = 61.80\%$, $SD = 13.48$) than participants in the non-contingent feedback group ($M = 51.16\%$, $SD = 17.43$).

Fig. 2 Performance during biofeedback training for phases with and without biofeedback.

3.4. Relation of training and HBP improvement

To examine the relation of improvement during training and improvement in the Schandry task for both biofeedback groups, a contingency table was created (see Table 2).

Compared to the non-contingent group more participants of the contingent group that profited in the training, also improved in the Schandry task ($X^2(1) = 4.76$, $p = .03$, $V = -0.27$). Therefore, the relation of improvement in the training with improvement in the Schandry task was closer in the contingent -, compared to the non-contingent feedback group.

4. Discussion

Interoception is important for maintaining body integrity as well as for physical and emotional well-being (e.g. Ainley, Apps, Fotopoulou, & Tsakiris, 2016; Critchley & Garfinkel, 2017; Seth, Suzuki, & Critchley, 2011). Lower IA has been linked to a number of mental disorders and psychophysiological conditions (e.g. Ainley et al., 2016; Khalsa et al., 2018). Thus, methods for improving IA represent promising therapeutic interventions in case of lower or biased IA in the future (Ainley et al., 2016; Farb et al., 2015). In the present study, we tested an innovative interoceptive training that was able to reliably increase IA_{cd}. We found a significant impact of true biofeedback training on IA_{cd} and a marginally significant impact of false biofeedback on IA_{cd}. Arguably, this improvement was not simply due to the repetition of the Schandry task as waiting with an external attention focus (film) did not result in score changes. In line with the study of Ring et al. (2015), improved knowledge about one's own heartbeat (provided by both biofeedback conditions) enhanced the performance of participants. However, contrary to the results of Ring and colleagues, improvement of IA_{cd} was significantly higher after cardiac contingent (i.e. true) feedback.

To our mind, two differences between the current study and the study of Ring and colleagues (Ring et al., 2015) might be of importance: the training length and the training phases without feedback cues. We implemented a training approximately three times longer than Ring
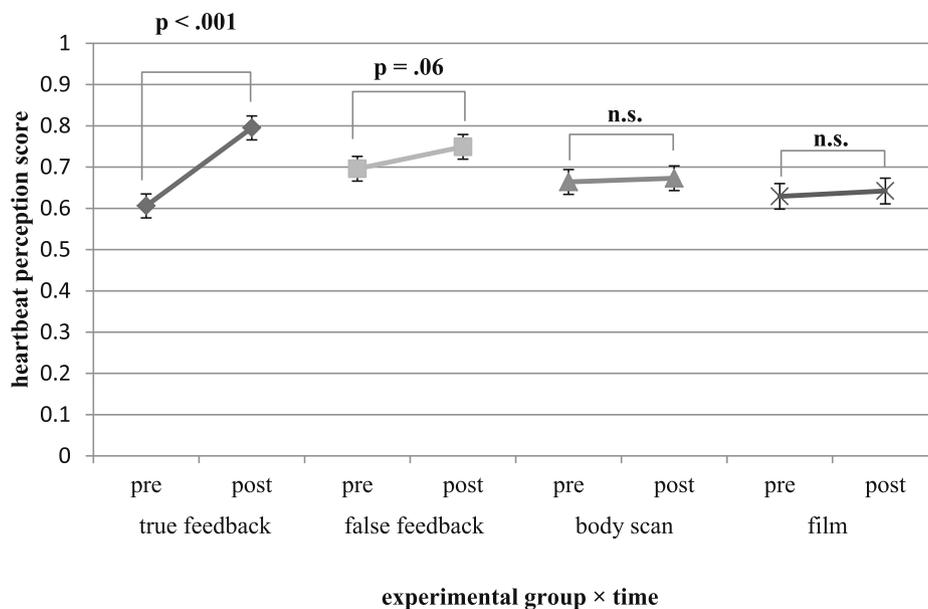
experimental group × time

Fig. 1. Averaged heartbeat perception scores from the Schandry task and standard error of the four experimental groups before and after experimental manipulation.

et al. (2015). Arguably, performance differences between true and false cardiac feedback will only be effective if training is sufficient to learn this relatively difficult ability. Indeed, we found performance increase in the mental tracking paradigm. However, somewhat contradicting our original notion, a detailed analysis of block by block performance changes during training revealed a significant performance increase only from the first to the second but not from the second to the third block. Using the same contingent feedback protocol, Schaefer et al. (2014) reported a nearly linear increase of percent correct responses from the first to the fourth block in the feedback phase. Percent correct responses in the phase without feedback increased until third block, decreased from third to fourth block and increased again from fourth to fifth block. Therefore, the non-significant difference concerning the comparison of the second and third block in our study has to be interpreted tentatively and the best training length will have to be determined by future studies. Besides training length, the integration of a phase without feedback might have been important. In this phase, participants had the chance to concentrate on their heartbeat sensations

without splitting their attention between competing internal bodily and external (visual) biofeedback cues, which possibly facilitates interoceptive learning.

Conforming to the results of other studies, heartbeat perception did not simply improve after mindfulness practice (Khalsa et al., 2008; Melloni et al., 2013; Nielsen & Kaszniak, 2006; Parkin et al., 2014). This task is nonetheless interesting because it allows us to conclude that simply focusing internally does not by itself lead to a better perception of cardiac activity. A number of factors possibly explaining the lack of impact of mindfulness practice on heartbeat perception are currently debated in the literature. For example, meditation as operationalized in the body scan exercise was assumed to be too unspecific to impact cardiac perception as attention is directed to diverse body sensations (Khalsa et al., 2008; Melloni et al., 2013) and often attention focus is guided towards breathing (Khalsa et al., 2008). Indeed, respiratory IA was reported to improve by mindfulness practice (Daubenmier, Sze, Kerr, Kemeny, & Mehling, 2013). In addition to specificity of mindfulness practice, the length of training practice was debated. It was
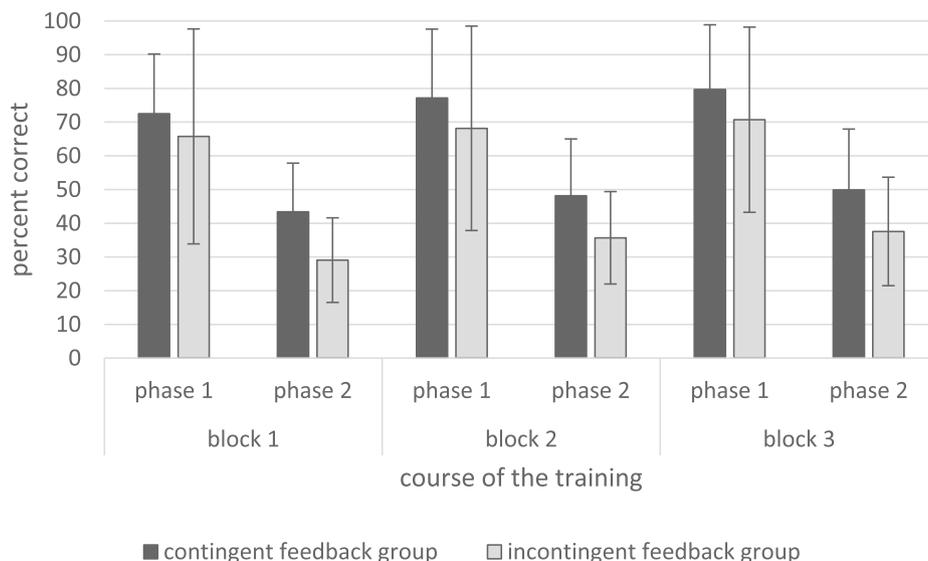

Fig. 2. Percent correct responses and standard deviation for the three blocks of heartbeat feedback trainings (contingent/non-contingent) in phases with (phase 1) and without (phase 2) feedback.

Table 2
Contingency table with the dimensions 'improvement during biofeedback training' and 'improvement in the Schandry task' for the contingent – and the non-contingent biofeedback group.

		Improvement in the Schandry task			
		YES		NO	
		contingent	non-contingent	contingent	non-contingent
Improvement during Training	YES	13	8	2	8
	NO	11	9	0	0

Note: Frequencies for the differences scores are presented. Concerning the training dimension, the percent correct score of the first block (phase 2/without feedback) was subtracted from the percent correct score of the third block (phase 2). Concerning the Schandry task, the HBP score at Time 1 was subtracted from the HBP score at Time 2. Improvement was coded as YES, if the difference score was bigger than zero and as NO if the difference score was equal to or lower than zero.

assumed that the implemented mindfulness trainings were too short to impact IA_{cd} effectively (Bornemann, Herbert, Mehling, & Singer, 2015). Findings concerning longer training protocols or meditation experience are heterogeneous and inconclusive up to now. While a moderate but non-significant effect of an eight week training on IA_{cd} was found in one study (Parkin et al., 2014), a similar training procedure had no effect of on cardiac perception (Melloni et al., 2013). Recently, it was shown that IA_{cd} increased steadily during contemplative practice until the end of a nine month lasting training procedure. A significant change was reported after sixth month of practicing (Bornemann et al., 2015). In contrast, meditators with a long experience of mindfulness practice did not perceive their heartbeat more accurate than laymen in other studies (Khalsa et al., 2008; Melloni et al., 2013; Nielsen & Kaszniak, 2006). This was explained by the diversity of the background of meditators and unclear amounts of body focus of their contemplative practice (Bornemann et al., 2015). But, nearly all meditation traditions integrate at least some attention to body sensations (Khalsa et al., 2008) and one study examined experienced meditators, who practiced a tradition with clear body focus, did not find increased IA_{cd} (Melloni et al., 2013). Furthermore, Bornemann et al. (2015) did not find significant differences between training modules with different amount of body focus.

Lastly, when assessing the current results it is important to notice that there is a recurrent debate on advantages and disadvantages of tasks on IA_{cd}. Mental tracking tasks are influenced by (implicit) knowledge about heart rate and may classify too many people as good perceivers (Brener, Knapp, & Ring, 1995; Luoto et al., 1996; Phillips et al., 1999). Furthermore, mental tracking might be prone to ceiling effects (Bornemann et al., 2015). On the other hand, discrimination based methods involve multisensory integration, which withdraw cognitive and attentional resources from bodily signals (e.g. Bornemann et al., 2015; Domschke et al., 2010; Khalsa, Rudrauf, Sandesara, Olshansky, & Tranel, 2009). While the knowledge on the heart rate was accurate in the contingent feedback group of our study, information was biased in the non-contingent feedback group. Consequently, we cannot rule out that enhanced knowledge about heart rate in the contingent feedback group accounts for the additional increase of the performance in the Schandry task. In a previous study, Phillips et al. (1999) compared the influence of receiving no, 5 min of slowed or fastened cardiac biofeedback on performance in the Schandry - and in a discrimination task (Whitehead). While performance in the Whitehead task was not influenced by biofeedback, Schandry performance was worse, in the slow -, compared to no feedback group (effect of $d = 0.38$, when Schandry task was performed first). Fastened feedback did not lead to an overestimation of heartbeats in the Schandry task. Note, however that Philips et al. (1999) instructed their participants to count heartbeats, or if beats were not clear, to count in the way they thought

their heart was beating. In the present study, participants were exclusively instructed to count heartbeats. Arguably, this instruction makes it more unlikely that Schandry Task performance is influenced by improved knowledge about heart rhythm. Furthermore, task order (Schandry or Whitehead task first) had a surprising impact on Schandry performance in the Philips et al. (1999) study (participants that performed the Schandry task before the Whitehead task were better than participants that performed the Whitehead task first, $d = 1.88$ in the slow feedback condition and $d = 0.63$ in the no feedback condition). Effects possibly can be explained by other variables that were not controlled for (i.e. body mass index). In the present study, IA_{cd} training effect sizes of the contingent – compared to the non-contingent feedback group differ quite largely (T1-T2-difference $d = 1.21$ vs $d = 0.37$). In summary, it is therefore unlikely that this difference can be explained by increased knowledge on heart rate only.

5. Limitations and conclusion

Here, we showed increased mental tracking performance after biofeedback training. Most importantly, greatest improvement was found after cardiac contingent feedback providing evidence that participants did not only improve in their (implicit) knowledge about their own heart activity but actually got better in sensing their heartbeat. We examined healthy participants, which limits the generalizability of our results.

As a similar heartbeat perception training was effective in patients with somatic symptom disorders (Schaefer et al., 2014), future studies are encouraged to continue work on cardiac biofeedback trainings for somatic symptom disorders. First, the findings have to be replicated in studies with clinical samples assessing effects on somatic symptom burden or illness anxiety. As we cannot examine to which extend beliefs on heart rate impacted our findings, presenting the accurate heart rate decoupled from R-wave might be a reasonable control condition in future studies. However, coupling feedback to the R-wave in our study ensured that non-contingent feedback was presented at a time, when most participants do not sense their heartbeat. Decoupling feedback from the R-wave would have the disadvantage that feedback signals would be contingent to the actual heart rate in some trials by chance. Furthermore, an assessment of beliefs on the own heart rate and changes after biofeedback is appreciated for future research.

The appropriate training duration (trials per training and amount of training sessions) and the most efficient proportion of trials with and without biofeedback have to be identified. Second, studies will have to replicate symptom reduction after training and demonstrate this is not only statistically significant but also clinically relevant according to established criteria (Jacobson & Truax, 1991). Finally, long-term effects have to be tested. In this study, we focused on heartbeat, because most research on IA assessed the cardiovascular domain and cardiovascular biofeedback can be easily and economically implemented. However, other interoceptive cues such as muscle tension and skin conductance are clearly also interesting targets in somatic symptom disorders (Nanke & Rief, 2003) and other specific disorders such as bruxism (Ilovar, Zogler, Castrillon, Car, & Huckvale, 2014).

Arguably, our implementation of mindfulness practice was too short to influence IA_{cd}. Indeed, in a study implementing a much longer training episode of 8 weeks mindfulness practice was found to improve heartbeat perception in comparison to listening to an audio book (Fischer, Messner, & Pollatos, 2017). However, true cardiac biofeedback may be especially economical to improve IA_{cd}.

Conflicts of interest

Any commercial or financial involvements that might cause a conflict of interest regarding this article do not exist.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbtep.2018.12.002.

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