Research paper

Sleep and the heart: Interoceptive differences linked to poor experiential sleep quality in anxiety and depression

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Donna L. Ewing[a,b,1,*], Miranda Manassei[a], Cassandra Gould van Praag[a,b], Andrew O. Philippides[c], Hugo D. Critchley[a,b,d], Sarah N. Garfinkel[a,b]

[a] Psychiatry, Department of Neuroscience, Brighton and Sussex Medical School, Universities of Brighton and Sussex, United Kingdom
[b] Sackler Centre for Consciousness Science, University of Sussex, United Kingdom
[c] Department of Informatics, University of Sussex, United Kingdom
[d] Sussex Partnership NHS Foundation Trust, Sussex Education Centre, Millview Hospital, Hove BN3 7HY, United Kingdom

ABSTRACT

Interoception is the sense through which internal bodily changes are signalled and perceived. Individual differences in interoception are linked to emotional style and vulnerability to affective disorders. Here we test how experiential sleep quality relates to dimensions of interoceptive ability. 180 adults (42 'non-clinical' individuals, 138 patients accessing mental health services) rated their quality of sleep before performing tests of cardiac interoception. Poor sleep quality was associated with lower measures of interoceptive performance accuracy, and higher self-report measures of interoceptive sensibility in individuals with diagnoses of depression and/or anxiety. Additionally, poor sleep quality was associated with impaired metacognitive interoceptive awareness in patients with diagnoses of depression (alone or with anxiety). Thus, poor sleep quality, a common early expression of psychological disorder, impacts cardiac interoceptive ability and experience across diagnoses. Sleep disruption can contribute to the expression of affective psychopathology through effects on perceptual and interpretative dimensions of bodily awareness.

1. Introduction

Interoception refers to the sensing of visceral signals from the inner body and contrasts with exteroceptive senses (including touch, vision, hearing, smell) and with proprioceptive signals about the spatial location of body parts from joints, tendons and muscles (Cameron, 2001; Craig, 2002; Sherrington, 1948). The measurement of interoception has focused on quantifying individual differences in interoceptive sensitivity, most frequently assessed using tests of how well a person can perceive their heart beating at rest, perhaps as heartbeats are discrete and easily measurable (Wiens, Mezzacappa, & Katkin, 2000). Two tests dominate: the 'heartbeat tracking' task in which participants report the number of heartbeats they feel over a predetermined time interval (accuracy reflects how close this reported number is to actual recorded number of heartbeats; Schandry, 1981), and of 'heartbeat discrimination' in which participants judge whether external signals (for example, auditory tones) are cued to be synchronous or asynchronous to their own heartbeat (Brener & Kluvitse, 1988; Katkin, Reed, & Deroo, 1983; Whitehead, Drescher, Heiman, & Blackwell, 1977).

Self-report indices of interoception ('interoceptive sensibility') include questionnaires probing subjective sensitivity to specific bodily changes, and confidence ratings of interoceptive task performance. Such experiential measures frequently diverge from the objective measures of interoceptive accuracy. Recently, a dimensional model, supported by empirical data, was proposed for the conceptualization of psychological aspects of interoception along dimensions of interoceptive accuracy, interoceptive sensibility, and interoceptive awareness (Garfinkel et al., 2015Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Here, interoceptive awareness describes the metacognitive correspondence between self-report and performance measures: i.e. how well interoceptive sensibility matches interoceptive accuracy (Garfinkel & Critchley, 2013; Garfinkel et al., 2015). Importantly, dissociation between these interoceptive dimensions demonstrate that individuals do not necessarily have good insight into their interoceptive ability, and is very relevant to understanding anxiety in terms of interoceptive prediction error (Garfinkel et al., 2016, 2015; Paulus & Stein, 2006).

Interoception is influenced by the dynamic state of physiological

arousal (we become aware of heartbeats when running or scared) or hunger (Herbert et al., 2012), and by attention-dependent processes including self-observation (Ainley, Maister, Brokfeld, Farmer, & Tsakiris, 2013; Ainley, Tajadura-Jiménez, Fotopoulou, & Tsakiris, 2012). Here, we explore the proposition that poor experiential sleep quality may be associated with poor interoception, impairing interoceptive accuracy. Interoceptive information contributes to the regulation of sleep-wake cycles: Sleep arises from the interaction between a homeostatic process dependent on sleep propensity and a sleep-independent circadian process (Borbély, 1982). Correspondingly, poor quality sleep may perturb the processing of viscerosensory information, including cardiovascular signals. Normal sleep is accompanied by predictable changes in bodily physiology: a decrease in blood pressure and heart rate is observed when an individual progresses from wakefulness to non-rapid eye movement (NREM) sleep. Increases in blood pressure and heart rate periodically occur during NREM sleep. During REM sleep, blood pressure and heart rate are comparable to wakefulness (Calandra-Buonaura, Provini, Guaraldi, Plazzi, & Cortelli, 2016). Additionally, sleepiness reduces physiological arousal, including heart rate (Bonnet & Arand, 2005Corcoran, 1964), particularly in the absence of a requirement for effort to remain awake (Corcoran, 1964).

Sleep problems are an early indicator of psychological disorder and they are bi-directionally associated with depression and anxiety (Gregory et al., 2005, 2011; Harshaw, 2015; Jansson-Frojmark & Lindblom, 2008; Shanahan, Copeland, Angold, Bondy, & Costello, 2014). Poor sleep quality can have distinct effects on interoception for individuals with different mental health diagnoses. Reduced interoceptive accuracy is reported in individuals with depression (Furman, Waugh, Bhattacharjee, Thompson, & Gotlib, 2013) and suicidality (Forrest, Smith, White, & Joiner, 2015), while enhanced interoceptive accuracy is often linked to the expression of panic disorder, panic attacks, and other anxiety disorders (Ehlers & Breuer, 1992; Richards, Cooper, & Winkelman, 2003; Van Der Does, Antony, Ehlers, & Barsky, 2000). There may be a vicious cycle where, for example in depression, interoceptive dysfunction causes errors in the interpretation of somatic signals necessary for normal sleep, thereby contributing to sleep disturbance and further interoceptive deficits (Harshaw, 2015).

Poor sleep is linked to specific deficits in cognitive functioning and emotional information processing (Fulda & Schulz, 2001; Gobin, Banks, Fins, & Tartar, 2015; Soffer-Dudek, Sadeh, Dahl, & Rosenblat-Stein, 2011), yet there is currently no published research that explores whether experiential sleep quality is associated with disturbances in interoception. In addition, there is no published research that explores differential effects of sleep quality on interoception for individuals with different mental health diagnoses. The current study aimed to explore associations between experiential sleep quality and distinct dimensions of interoception, measured as performance accuracy, self-report sensibility or as metacognitive awareness in people with and without mental health diagnoses. Interoception is influenced by physiological states, such as hunger (Herbert et al., 2012). We therefore hypothesised that experiential sleep quality would similarly predict interoceptive accuracy, sensibility and metacognitive awareness. Given the reported alteration of performance on interoceptive tasks in clinical populations (Forrest et al., 2015; Furman et al., 2013), and associations between sleep problems and mental health difficulties (Harshaw, 2015; Shanahan et al., 2014), we further hypothesised that the presence of specific clinical diagnoses would enhance the impact of poor sleep in interoception. Specifically, our hypotheses were that (1) perceived poor sleep quality would predict impaired interoceptive accuracy (that is, impaired performance on behavioural tests of interoception), with this negative effect enhanced for individuals with mental health diagnoses, (2) perceived poor sleep quality would predict elevated interoceptive sensibility (that is, self-report ratings about their interoceptive performance), particularly for individuals with mental health diagnoses, and (3) perceived poor sleep quality would predict reduced interoceptive

awareness (that is, a reduced correspondence between interoceptive accuracy and confidence ratings), with a greater discrepancy between accuracy and confidence for individuals with mental health diagnoses.

2. Method

2.1. Participants

A total of 180 participants were recruited to the study. Participants with no mental health diagnosis were recruited through advertisements placed around the university, inviting healthy volunteers to take part in the study. Forty-two participants with no history of mental health diagnoses were recruited to the study, including 8 males (19%) and 34 females (81%), with a mean age of 28.2 years (range 18–65). Thirty participants (71%) had received either an undergraduate or postgraduate degree.

Participants with current or previous mental health diagnoses ($n = 138$) were referred to the study by psychiatrists and clinical psychologists from the Assessment and Treatment Services (secondary care), or were self-referred to the study and recruited through advertisements placed within primary care and community settings. The study team were informed of participant diagnoses at the time of referral, and the Electronic Care Plan Approach (eCPA) patient notes were referred to for a subset of participants to verify their diagnosis. eCPA notes are systematically updated by the clinical care team, and are an electronic record of the patient's care notes, including details such as patient diagnosis, care plan, assessments, and any associated documents, notes or letters for that patient. Where there was a discrepancy between patient self-report and clinical notes, the diagnosis as detailed in the clinical notes was used. This diagnosis was based on either International Classification of Diseases (ICD) or Diagnostic and Statistical Manual (DSM) criteria, depending on the preference of the psychiatrist. The sample of clinical participants included 43 males (31.2%), 92 females (66.7%), 1 other (0.7%), and 2 undisclosed (1.4%), with a mean age of 34.21 (range 18–64), and with 53 participants (38.9%) educated at either undergraduate or postgraduate degree level. Primary diagnoses included: major depression $n = 44$ (33%), anxiety $n = 24$ (25%), mixed anxiety and depressive disorder $n = 18$ (13%), psychosis $n = 11$ (8%), bipolar disorder $n = 10$ (7%), personality disorder $n = 8$ (6%), obsessive compulsive disorder $n = 7$ (5%), eating disorder $n = 5$ (4%), posttraumatic stress disorder $n = 3$ (2%), autistic spectrum disorder $n = 2$ (1%), attention deficit hyperactivity disorder $n = 1$ (1%), and dissociative disorder $n = 2$ (1%). Due to low numbers of participants with some diagnoses, diagnosis groups with less than 15 participants were excluded for the interoception analyses. As such, 133 participants remained for the interoception analyses, including healthy controls, and participants with depression, anxiety, and mixed anxiety and depressive disorder. However, analyses that did not require groupings by diagnosis (including the principal component analysis) used the full sample of participants. Participants with a significant history of cognitive impairment or an additional neurological condition, and participants with alcohol intake on the day of testing, were excluded from the study.

2.2. Measures

Demographic questionnaire. Background information was collected from participants, including age, gender, BMI, education level, working status, medication use, and exercise uptake.

PiBTsburgh Sleep Quality Index (Buysse et al., 1989Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). The Pittsburgh Sleep Quality Index (PSQI) is a 19-item self-rated measure of sleep quality and disturbances, with subscales of experiential sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. Each subscale was scored from 0 to 3, with higher scores indicating poorer sleep quality.

The PSQI has good test-retest reliability, with correlations of 0.85 for the global score, and ranging between 0.65 and 0.84 for the subscales, across two testing sessions (Buysse et al., 1989).

Porges Body Perception Questionnaire (Porges, 1993). The Porges Body Perception Questionnaire (BPQ) is a 45-item self-rated scale of interoceptive sensibility (participants' awareness of bodily sensations, such as stomach and gut pains), rated on a five-point scale with ratings of 'never', 'occasionally', 'sometimes', 'usually', and 'always' (range: 1–5). The BPQ contains five sub-tests ('awareness', 'stress response', 'autonomic nervous system reactivity', 'stress style', and 'health history inventory'). For the purpose of the current study, only the 'awareness' sub-test was used. For the current sample, the BPQ had high internal consistency (α = 0.92).

Heartbeat Tracking (Schandry, 1981). For the heartbeat tracking task participants were instructed: '*Without manually checking, can you silently count each heartbeat you feel in your body from the time you hear "start" to when you hear "stop"*'. Participants completed six trials, across randomised time-windows of 25, 30, 35, 40, 45 and 50 s. The number of heartbeats counted was recorded after each trial.

Heartbeat Discrimination (Brener & Kluvitse, 1988Katkin et al., 1983; Whitehead et al., 1977). For the heartbeat discrimination task, participants judged whether a series of ten auditory tones were synchronous or asynchronous with their own heartbeat. They were instructed: '*You will hear ten tones. Please tell me if the tones are in sync or out of sync with your own heartbeat*'. Each participant completed twenty trials, consisting of ten tones (triggered by the participant's own heartbeat) presented at 440 Hz for 100 ms. Synchronous tones were presented at the beginning of the rising edge of the pulse pressure wave. Asynchronous tones were presented after a delay of 300 ms, adjusting for the average delay (~250 ms) between the R-wave and the arrival of the pressure wave at the finger (Payne, Symeonides, Webb, & Maxwell, 2006). The participants then reported whether the ten tones were synchronous or asynchronous with his/her heartbeat on each trial.

Confidence judgements. After each trial for both the heartbeat tracking (N = 6) and heartbeat discrimination (N = 20) tasks, the participant immediately rated his/her confidence in their perceived interoceptive ability. These confidence values were then averaged to yield a measure of interoceptive sensibility (i.e. self-perceived proficiency) for these two tasks (Garfinkel et al., 2015). The participant marked this on a 10 cm continuous visual analogue scale (VAS) to indicate confidence. The VAS was labelled with 'total guess/no heartbeat awareness' at 0 cm, and 'complete confidence/full perception of heartbeat' at 10 cm.

2.3. Procedure

Ethical approval was received from the university research ethics committee and from the National Research Ethics Committee (NRES). The study was explained to each participant, who gave written consent to take part. Participants completed the questionnaires before performing the tasks of cardiac interoception: a heartbeat tracking task, and a heartbeat discrimination task. Heartbeat measures were derived from finger pulse oximetry (Nonin 8600 with a 'soft' sensor fitting to reduce exteroceptive feedback) from the index finger of the non-dominant hand. After each trial for both tasks, the participant rated confidence in the accuracy of his/her response using the VAS. The average accuracy score was used as an index of interoceptive accuracy, and the average confidence rating was used as an index of interoceptive sensibility for these tasks. As the heartbeat discrimination task may guide participants about the speed and rhythm of their heartbeat, this task was always completed after the heartbeat tracking task.

2.4. Data analysis

The PSQI consists of seven subscales to assess sleep quality. However, it was likely that some of these variables were measuring the same construct and would be highly correlated, which would warrant some of these subscales redundant. Therefore, exploratory principal components analysis (PCA) with direct oblimin rotation was conducted on the seven subscales of the PSQI to determine the factor structure of this questionnaire for the current sample. Missing data (n = 2) was excluded from analysis. Iterative analyses were conducted, and PSQI subscales with factor loadings < 0.30 were excluded. The PCA model was based on 178 participants and met the standards for sampling adequacy and assumptions of sphericity (KMO statistic = 0.76, and individual KMO values from the diagonals of the anti-image correlation matrix > 0.64; Bartlett's Test χ^2 = 223.97, $p < 0.001$).

To assess the role of sleep and diagnosis on dimensions of interoception, hierarchical regression analyses were conducted using participants from diagnosis groups where $n > 15$, which included participants with no diagnosis, major depression, anxiety disorder, and mixed anxiety and depressive disorder. These analyses were, therefore, based on a sample size of 133 participants. Dummy variables were calculated for diagnoses, with healthy controls used as the baseline group, against which all other diagnoses were compared.

Interoceptive accuracy, interoceptive sensibility and interoceptive awareness were entered into the regression as dependent variables. For the heartbeat tracking task, interoceptive accuracy was calculated for each trial (Garfinkel et al., 2015; Hart, McGowan, Minati, & Critchley, 2013): $1 - (|nbeats_{real} - nbeats_{reported}|)/((nbeats_{real} + nbeats_{reported})/2)$. The average of these scores was taken to give an overall accuracy score. For the heartbeat discrimination task, accuracy was determined using signal detection analyses. The sensitivity measure d' was calculated based on the difference between z-transformed hit rates and z-transformed false-alarm rates (Schaefer, Egloff, & Witthöft, 2012). Interoceptive sensibility values included VAS confidence ratings for both interoception tasks, and BPQ scores.

Interoceptive awareness is a metacognitive measure that represents the extent that confidence during the interoception tasks (as rated on the VAS) predicts interoceptive accuracy. For the heartbeat discrimination task (which uses binary variables of correct/incorrect responses to the synchrony of tones), receiver operator characteristic (ROC) curve analysis was conducted to determine the strength of correspondence between confidence and accuracy ratings for each trial. The area under the ROC curve was used as an index of interoceptive awareness (Garfinkel et al., 2015). For the continuous variable of accuracy during the heartbeat tracking task (number of heartbeats counted), Pearson's r was used to consider the association between accuracy and confidence for each trial.

Hierarchical regression analyses were conducted with gender and age entered into the first model, the dummy variables for diagnosis entered into the second model, sleep quality entered into the third model, and the interaction between diagnosis (dummy variables) and sleep quality entered into the fourth model. Interoceptive accuracy, interoceptive sensibility, and interoceptive awareness were respectively entered into the regression analyses as dependent variables.

3. Results

3.1. Principal components analysis on the PSQI

A 2-factor model of the PSQI was identified, with eigenvalues > 1 for each factor and the 2-factor model accounting for 54.4% of the total variance. Final component loadings (pattern matrix) after direct oblimin rotation are shown in Table 1. Factor 1 (Sleep Effectiveness) accounts for 38.7% total variance, and Factor 2 (Sleep Difficulties) accounts for 15.78% total variance (Table 2).

3.2. Interoceptive accuracy

3.2.1. Heartbeat tracking accuracy

A diagnosis of anxiety significantly predicted a reduction in

Table 1
Demographics information and means (SD) for questionnaire measures and interoception tasks.

	Healthy Controls	Major Depression	Anxiety	Mixed Anxiety and Depressive Disorder
Gender				
Male	19% ($n = 8$)	29.5% ($n = 13$)	16.7% ($n = 4$)	16.7% ($n = 3$)
Female	81% ($n = 34$)	68.2% ($n = 30$)	83.3% ($n = 20$)	83.3% ($n = 15$)
Other	0% ($n = 0$)	2.3% ($n = 1$)	0% ($n = 0$)	0% ($n = 0$)
Age				
Mean (SD)	28.19 (9.8)	34.27 (14.25)	24.88 (8.54)	34.50 (14.84)
Sleep Effectiveness				
Mean (SD)	−0.40 (0.60)	0.07 (0.91)	0.02 (0.74)	0.77 (1.29)
Sleep difficulties				
Mean (SD)	−0.56 (0.62)	- 0.10 (0.99)	0.02 (1.11)	0.06 (0.87)
BPQ				
Mean (SD)	97.24 (19.78)	107.24 (27.47)	116.04 (26.84)	118.81 (32.29)
Heartbeat Tracking Accuracy				
Mean (SD)	0.64 (0.28)	0.55 (0.28)	0.46 (0.32)	0.51 (0.38)
Heartbeat Tracking Confidence				
Mean (SD)	3.97 (2.27)	3.83 (2.65)	4.39 (2.32)	3.55 (2.01)
Heartbeat Tracking Sensibility				
Mean (SD)	0.20 (0.54)	0.17 (0.42)	0.11 (0.49)	0.09 (0.64)
Heartbeat Discrimination Accuracy				
Mean (SD)	0.57 (0.14)	0.53 (0.13)	0.50 (0.32)	0.50 (0.08)
Heartbeat Discrimination Confidence				
Mean (SD)	4.23 (2.67)	4.43 (2.37)	4.66 (2.10)	4.49 (2.70)
Heartbeat Discrimination Sensibility				
Mean (SD)	0.55 (0.17)	0.51 (0.14)	0.53 (0.18)	0.51 (0.11)

Table 2
Factor component loadings (pattern matrix) after direct oblimin rotation for the exploratory PCA.

PSQI Subscale	Component 1: Sleep Effectiveness	Component 2: Sleep Difficulties
Sleep Efficiency	0.85	
Sleep Duration	0.84	
Sleep Quality	0.55	0.34
Daytime Dysfunction	0.35	0.35
Sleep Medicine		0.82
Sleep Disturbance		0.71
Sleep Latency	0.37	0.48

Table 3
Regression analysis for interoceptive accuracy on the heartbeat tracking and heartbeat discrimination tasks.

	Heartbeat Tracking			Heartbeat Discrimination		
	B	SE B	β	B	SE B	β
Step 1						
Constant	0.51	0.07		0.29	0.18	
Gender	0.14	0.06	0.22*	0.29	0.15	0.18
Age	0.00	0.00	0.02	−0.01	0.01	−0.08
Step 2						
Constant	0.59	0.08		0.50	0.20	
Gender	0.14	0.06	0.22*	0.28	0.15	0.17
Age	0.00	0.00	0.03	−0.01	0.01	−0.09
Depression (dummy)	−0.11	0.07	−0.17	−0.15	0.17	−0.09
Anxiety (dummy)	−0.18	0.08	−0.22*	−0.49	0.20	−0.24*
Mixed (dummy)	−0.13	0.09	−0.14	−0.31	0.22	−0.14
Step 3						
Constant	0.52	0.08		0.53	0.22	
Gender	0.13	0.06	0.19*	0.29	0.16	0.18
Age	0.00	0.00	0.08	−0.01	0.01	−0.10
Depression (dummy)	−0.08	0.07	−0.12	−0.16	0.18	−0.10
Anxiety (dummy)	−0.13	0.08	−0.16	−0.51	0.21	−0.25*
Mixed (dummy)	−0.06	0.09	−0.07	−0.33	0.24	−0.15
Sleep Effectiveness	−0.03	0.03	−0.10	0.00	0.09	0.00
Sleep Difficulty	−0.05	0.03	−0.16	−0.03	0.08	−0.04
Step 4						
Constant	0.55	0.09		0.71	0.24	
Gender	0.13	0.06	0.21*	0.31	0.15	0.19*
Age	0.00	0.00	0.06	−0.00	0.01	−0.07
Depression (dummy)	−0.10	0.08	−0.15	−0.41	0.21	−0.25
Anxiety (dummy)	−0.15	0.09	−0.19	−0.73	0.23	−0.36**
Mixed (dummy)	−0.19	0.11	−0.22	−0.60	0.28	−0.27*
Sleep Effectiveness	−0.05	0.08	−0.15	−0.18	0.20	−0.21
Sleep Difficulty	0.00	0.07	−0.00	0.57	0.20	0.66**
Depression X Sleep Effectiveness	0.02	0.09	0.03	0.19	0.24	0.13
Anxiety X Sleep Effectiveness	−0.15	0.11	−0.15	0.33	0.30	0.13
Mixed X Sleep Effectiveness	0.17	0.10	0.31	0.23	0.27	0.16
Depression X Sleep Difficulty	−0.04	0.09	−0.08	−0.68	0.23	−0.49**
Anxiety X Sleep Difficulty	−0.03	0.09	−0.05	−0.63	0.25	−0.38*
Mixed X Sleep Difficulty	−0.30	0.12	−0.32*	−0.63	0.34	−0.25

Note: Heartbeat Tracking $R^2 = 0.05$ for Step 1 ($p = 0.038$); $\Delta R^2 = 0.05$ for Step 2 ($p = 0.105$); $\Delta R^2 = 0.04$ for Step 3 ($p = 0.084$); $\Delta R^2 = 0.09$ for Step 4 ($p = 0.056$); Heartbeat Discrimination $R^2 = 0.03$ for Step 1 ($p = 0.157$); $\Delta R^2 = 0.05$ for Step 2 ($p = 0.092$); $\Delta R^2 = 0.00$ for Step 3 ($p = 0.924$); $\Delta R^2 = 0.07$ for Step 4 ($p = 0.149$).
* $p < 0.05$.
** $p < 0.01$.

interoceptive accuracy for the heartbeat tracking task ($\beta = −0.22$, $p = 0.024$). After controlling for sleep effectiveness and sleep difficulty (step 3), anxiety was no longer a predictor of interoceptive accuracy for heartbeat tracking (Table 3).

The interaction between sleep difficulty and mixed anxiety and depressive disorder was a significant predictor of interoceptive accuracy on the heartbeat tracking task ($\beta = −0.30$, $p = 0.015$), with increased sleep difficulties predicting a greater reduction in interoceptive accuracy for individuals with mixed anxiety and depressive disorder compared to those without this disorder (Fig. 1).

3.2.2. Heartbeat discrimination accuracy

After controlling for gender, age, sleep quality, and the interaction between sleep quality and diagnosis, reduced interoceptive accuracy was predicted by a diagnosis of anxiety ($\beta = −0.36$, $p = 0.002$) and a diagnosis of mixed anxiety and depressive disorder ($\beta = -0.27$,

$p = 0.035$; Table 3).

Increased sleep difficulties predicted increased interoceptive accuracy on the heartbeat discrimination task ($\beta = 0.66$, $p = 0.005$). However, reduced interoceptive accuracy was predicted by the interaction between sleep difficulties and depression ($\beta = −0.49$, $p = 0.005$), and the interaction between sleep difficulties and anxiety ($\beta = −0.38$, $p = 0.012$), with increased sleep difficulties predicting a greater reduction in interoceptive accuracy for individuals with these diagnoses compared to those without these diagnoses (Fig. 2).

3.3. Interoceptive sensibility

3.3.1. Heartbeat tracking confidence

After controlling for gender and age, diagnosis and the interaction between diagnosis and sleep quality, sleep difficulties was a significant
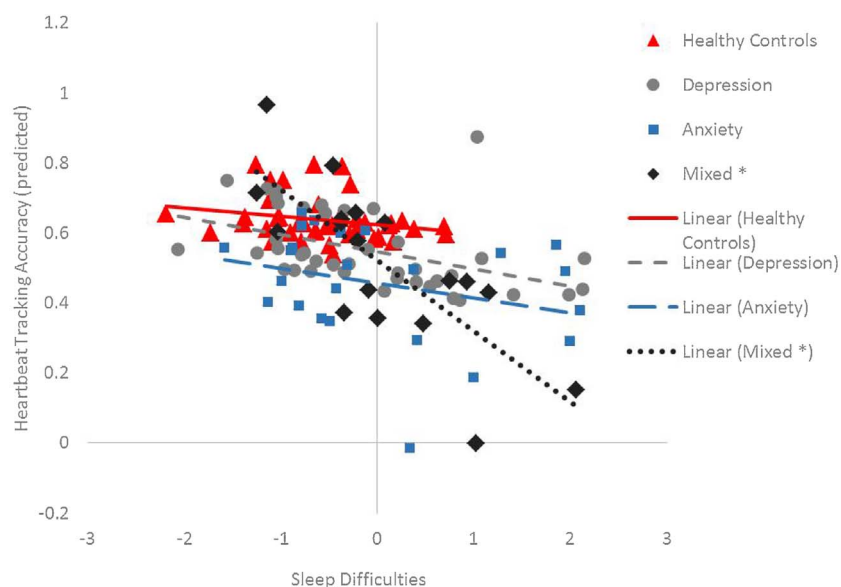
predictor of confidence ratings on the heartbeat tracking task (β = 0.50, p = 0.040), with more sleep difficulties predictive of reduced confidence in performance. No other variable significantly predicted confidence during the heartbeat tracking task (Table 4).

3.3.2. Heartbeat discrimination confidence

After controlling for gender and age, diagnosis and the interaction between diagnosis and sleep quality, greater sleep difficulties was a significant predictor of reduced confidence ratings during the heartbeat discrimination task (β = −0.69, p = 0.004). Interactions between diagnosis and sleep difficulties significantly predicted an increase in confidence ratings during the heartbeat discrimination task (depression X sleep difficulties β = 0.52, p = 0.003; anxiety X sleep difficulties β = 0.47, p = 0.002; Mixed X sleep difficulties β = 0.29, p = 0.031). That is, compared to participants without the diagnosis, participants with greater sleep difficulties and diagnoses of depression, anxiety and mixed anxiety and depressive disorder showed greater confidence in their performance during the heartbeat discrimination task (Fig. 3).

3.3.3. BPQ

After controlling for gender and age, increased interoceptive sensibility according to BPQ scores was predicted by a diagnosis of depression (β = 0.22, p = 0.030), anxiety (β = 0.26, p = 0.008) and mixed

anxiety and depression disorder (β = 0.28, p = 0.004). However, these diagnoses no longer predicted interoceptive sensibility according to BPQ scores after controlling for sleep quality and the interaction between sleep quality and diagnosis. Sleep difficulties predicted increased interoceptive sensibility according to BPQ scores, after controlling for gender, diagnosis, and the interaction between sleep quality and diagnosis (β = 0.45, p = 0.045).

3.4. Interoceptive awareness

3.4.1. Heartbeat tracking

After controlling for gender, age, sleep quality and the interaction between diagnosis and sleep quality, mixed anxiety and depressive disorder predicted reduced interoceptive awareness (β = −0.33, p = 0.010). The interaction between sleep effectiveness and mixed anxiety and depressive disorder predicted increased interoceptive awareness (β = 0.45, p = 0.018); that is greater interoceptive awareness was predicted by greater sleep effectiveness for individuals with mixed anxiety and depressive disorder compared with those without this disorder (Fig. 4).

Reduced interoceptive awareness on the heartbeat tracking task was predicted by the interaction between depression and sleep difficulties (β = −0.36, p = 0.036), and the interaction between mixed anxiety

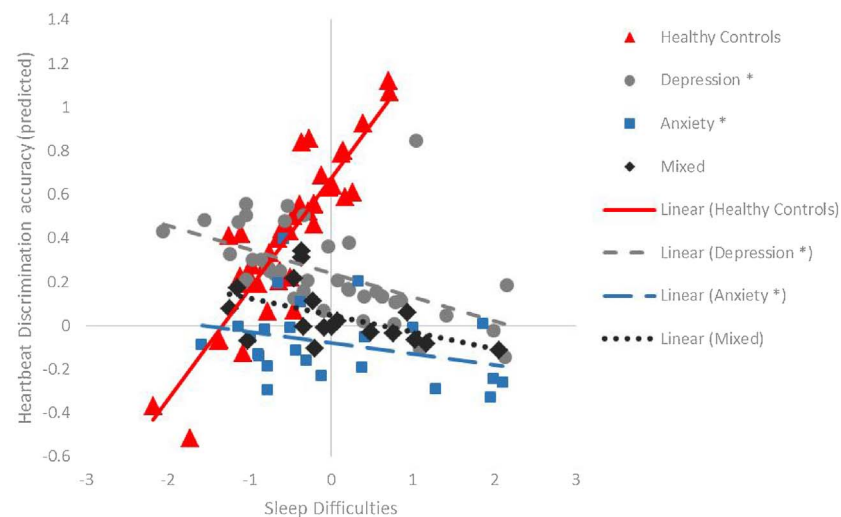**Table 4**

Regression analysis for interoceptive sensibility according to the heartbeat tracking task, heartbeat discrimination task, and the BPQ.

	Heartbeat Tracking			Heartbeat Discrimination			BPQ		
	B	SE B	β	B	SE B	β	B	SE B	β
Step 1									
Constant	3.52	0.56		4.55	0.58		115.00	6.343	
Gender	0.62	0.46	0.13	0.55	0.48	0.11	−8.00	5.21	−0.14
Age	0.01	0.02	0.05	−0.01	0.02	−0.04	−0.21	0.20	−0.10
Step 2									
Constant	3.37	0.62		4.37	0.65		105.80	6.77	
Gender	0.62	0.47	0.13	0.56	0.49	0.11	−7.56	5.06	−0.12
Age	0.02	0.02	0.09	−0.01	0.02	−0.04	−0.25	0.20	−0.12
Depression (dummy)	−0.31	0.53	−0.06	0.16	0.55	0.03	12.43	5.65	0.22*
Anxiety (dummy)	0.50	0.61	0.08	0.41	0.64	0.07	17.90	6.61	0.26**
Mixed (dummy)	−0.51	0.68	−0.08	0.32	0.71	0.05	22.22	7.53	0.28**
Step 3									
Constant	3.03	0.68		4.63	0.72		116.41	7.16	
Gender	0.53	0.46	0.11	0.63	0.50	0.12	−5.40	4.89	−0.10
Age	0.02	0.02	0.12	−0.01	0.02	−0.07	−0.44	0.20	−0.20*
Depression (dummy)	−0.15	0.55	−0.03	0.03	0.57	0.01	7.55	5.60	0.14
Anxiety (dummy)	0.72	0.64	−0.12	0.25	0.67	0.04	11.94	6.56	0.17
Mixed (dummy)	−0.22	0.74	−0.03	0.01	0.77	0.00	13.52	7.75	0.17
Sleep Effectiveness	−0.15	0.27	−0.06	0.28	0.28	0.11	4.84	2.74	0.17
Sleep Difficulty	−0.25	0.25	−0.10	0.04	0.27	0.01	6.69	2.62	0.23*
Step 4									
Constant	2.92	0.86		4.07	0.78		120.80	7.90	
Gender	0.53	0.48	0.11	0.51	0.49	0.10	−4.28	4.93	−0.08
Age	0.02	0.02	0.09	−0.02	0.02	−0.09	−0.48	0.21	−0.22*
Depression (dummy)	0.21	0.66	0.04	0.83	0.67	0.16	4.41	6.75	0.08
Anxiety (dummy)	1.00	0.73	0.17	0.93	0.74	0.15	8.17	7.50	0.12
Mixed (dummy)	−0.10	0.87	−0.01	0.92	0.89	0.13	5.69	8.96	0.07
Sleep Effectiveness	0.55	0.64	0.21	1.17	0.65	0.44	5.42	6.50	0.19
Sleep Difficulty	−1.28	0.62	−0.50*	−1.86	0.63	−0.69**	12.50	6.27	0.43*
Depression X Sleep Effectiveness	−0.97	0.77	−0.21	−1.18	0.78	−0.25	−4.89	7.76	−0.10
Anxiety X Sleep Effectiveness	−1.30	0.94	−0.17	−0.74	0.95	−0.10	−5.03	9.76	−0.06
Mixed X Sleep Effectiveness	−0.43	0.83	−0.10	−1.16	0.85	−0.26	5.51	8.63	0.11
Depression X Sleep Difficulty	1.23	0.73	0.30	2.23	0.74	0.52**	−6.86	7.46	−0.15
Anxiety X Sleep Difficulty	1.33	0.76	0.27	2.344	0.78	0.47**	−9.43	7.84	−0.17
Mixed X Sleep Difficulty	1.04	1.01	0.14	2.26	1.04	0.29*	−2.22	10.54	−0.03

Note: Heartbeat Tracking $R^2 = 0.02$ for Step 1 ($p = 0.252$); $\Delta R^2 = 0.02$ for Step 2 ($p = 0.525$); $\Delta R^2 = 0.01$ for Step 3 ($p = 0.442$); $\Delta R^2 = 0.04$ for Step 4 ($p = 0.500$); Heartbeat Discrimination $R^2 = 0.01$ for Step 1 ($p = 0.514$); $\Delta R^2 = 0.00$ for Step 2 ($p = 0.922$); $\Delta R^2 = 0.01$ for Step 3 ($p = 0.558$); $\Delta R^2 = 0.10$ for Step 4 ($p = 0.060$); BPQ $R^2 = 0.04$ for Step 1 ($p = 0.106$); $\Delta R^2 = 0.10$ for Step 2 ($p = 0.007$); $\Delta R^2 = 0.08$ for Step 3 ($p = 0.003$); $\Delta R^2 = 0.04$ for Step 4 ($p = 0.433$).
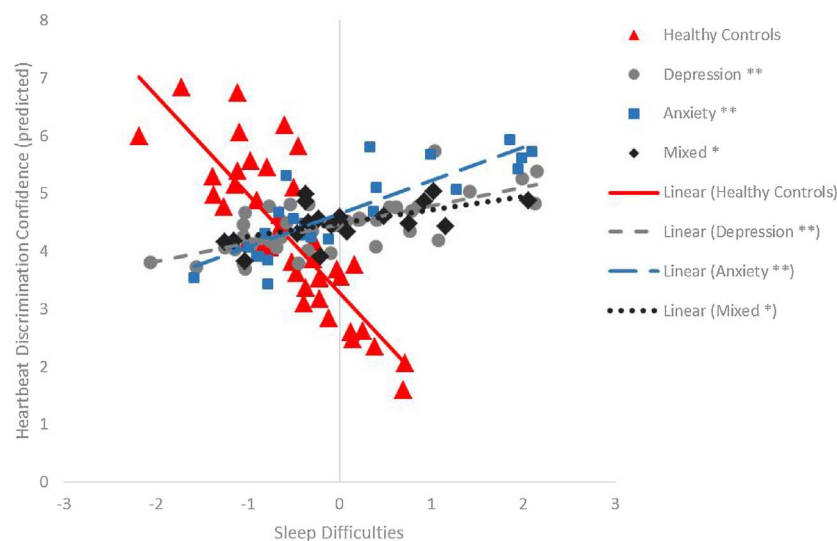
* $p < 0.05$.
** $p < 0.01$.

Fig. 3. Interaction between sleep difficulties and diagnosis on interoceptive sensibility for the heartbeat discrimination task.
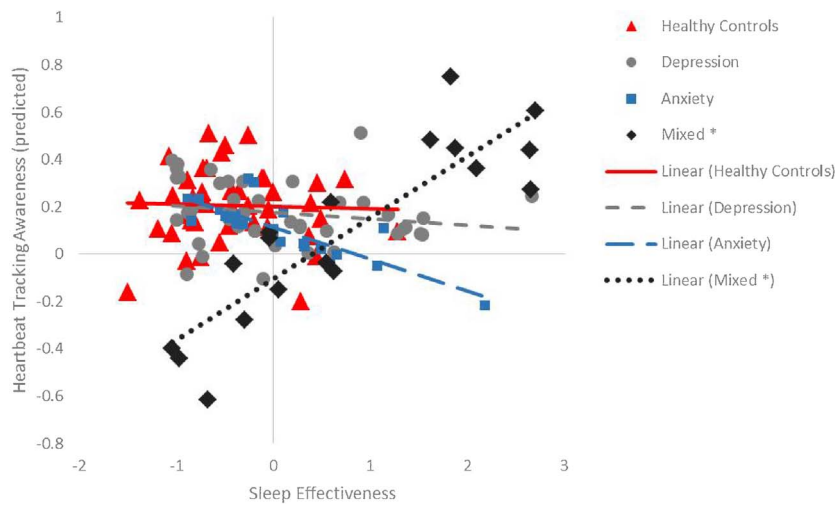
Fig. 4. Interaction between sleep effectiveness and diagnosis on interoceptive awareness for the heartbeat tracking task.
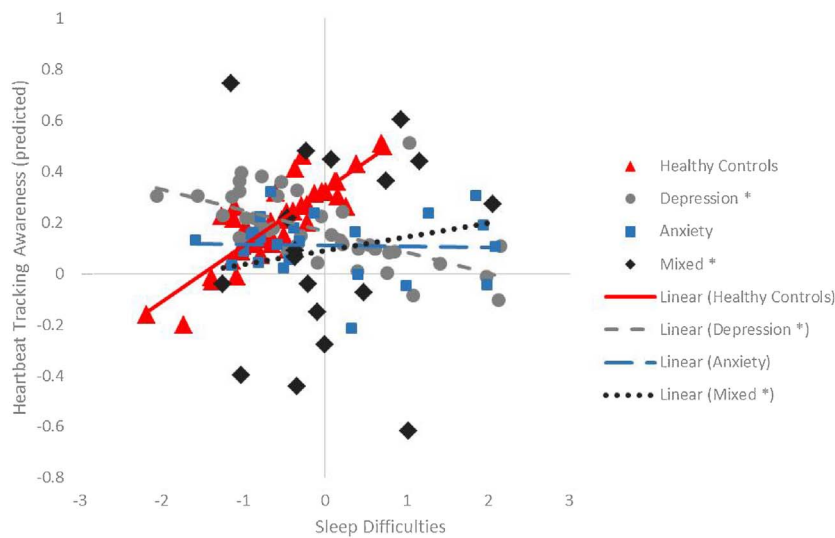

Fig. 5. Interaction between sleep difficulties and diagnosis on interoceptive awareness for the heartbeat tracking task.

and depressive disorder and sleep difficulties ($\beta = -0.29$, $p = 0.032$); that is, reduced interoceptive awareness was predicted by greater sleep difficulties for individuals with a diagnosis of depression and for those with a diagnosis of mixed anxiety and depressive disorder, compared to those without these diagnoses (Fig. 5).

3.4.2. Heartbeat discrimination awareness

Interoceptive awareness for the heartbeat discrimination task was not predicted by gender, age, diagnosis, sleep quality, or the interaction between diagnosis and sleep quality (Table 5).

4. Discussion

We tested how self-reported sleep quality relates to measures of cardiac interoception in patients accessing secondary mental health services and control participants. The relationship between distinct dimensions of interoception and sleep quality, specifically in regard to sleep difficulties and sleep effectiveness, was explored in patients with distinct affective disorders (anxiety disorder, major depression, mixed anxiety and depressive disorder), and in healthy controls. Our results suggest that self-reported sleep quality (namely, sleep effectiveness and sleep difficulties) differentially impacts distinct dimensions of interoception: Here, poor sleep quality was associated with a detrimental effect on objective interoceptive accuracy for patients with depression and/or anxiety, and on interoceptive awareness for patients with depression with or without anxiety, yet engendered (across patients) an

amplification of subjective interoceptive sensibility. While the direction of causation cannot be established from this cross-sectional study, and it is indeed plausible that poorer interoceptive accuracy may induce poorer sleep quality, our data suggest that the perceived quality of sleep directly influences interoceptive processing. This influence may, in part, be explained by the unfavourable effect of sleep on attentional and cognitive processes (e.g. Fulda & Schulz, 2001), where poor experiential sleep quality may similarly lead to suboptimal performance in interoception tasks.

Participants with greater sleep difficulties and a diagnosis of mixed anxiety and depressive disorder showed lower measures of interoceptive performance accuracy during the heartbeat tracking task, and participants with greater sleep difficulties and a diagnosis of depression or anxiety showed lower interoceptive accuracy during the heartbeat discrimination task. On the other hand, healthy control participants with greater sleep difficulties showed enhanced interoceptive accuracy during the heartbeat discrimination task. This finding, based on healthy controls, complements research evidence for enhanced objective interoceptive accuracy amongst individuals with insomnia (Wei et al., 2016). However, Wei et al. (2016) excluded participants with clinical diagnoses of depression or anxiety. The results from the current study suggest that, unlike for healthy controls, poorer interoceptive accuracy is predicted by increased sleep difficulties for individuals with a diagnosis of depression and/or anxiety. Sleep effectiveness did not predict interoceptive accuracy.

Interoceptive sensibility was predicted by sleep quality, with

Table 5
Regression analysis for interoceptive awareness according to the heartbeat tracking task and heartbeat discrimination task.

	Heartbeat Tracking			Heartbeat Discrimination		
	B	SE B	β	B	SE B	β
Step 1						
Constant	0.17	0.12		0.57	0.04	
Gender	0.15	0.10	0.14	0.00	0.03	−0.00
Age	−0.00	0.00	−0.04	−0.00	0.00	−0.11
Step 2						
Constant	0.22	0.13		0.59	0.04	
Gender	0.14	0.10	0.14	0.01	0.03	0.00
Age	−0.00	0.00	−0.04	−0.00	0.00	−0.10
Depression (dummy)	−0.05	0.11	−0.04	−0.04	0.04	−0.12
Anxiety (dummy)	−0.09	0.13	−0.07	−0.03	0.04	−0.06
Mixed (dummy)	−0.10	0.15	−0.07	−0.03	0.05	−0.08
Step 3						
Constant	0.27	0.15		0.58	0.05	
Gender	0.16	0.10	0.15	0.00	0.03	−0.00
Age	−0.00	0.00	−0.06	−0.00	0.00	−0.09
Depression (dummy)	−0.07	0.12	−0.07	−0.04	0.04	−0.11
Anxiety (dummy)	−0.12	0.14	−0.10	−0.02	0.04	−0.06
Mixed (dummy)	−0.17	0.16	−0.12	−0.03	0.05	−0.08
Sleep Effectiveness	0.06	0.06	0.11	0.00	0.02	0.03
Sleep Difficulty	0.00	0.06	−0.00	−0.01	0.02	−0.05
Step 4						
Constant	0.38	0.16		0.59	0.05	
Gender	0.19	0.010	0.18	0.00	0.03	0.00
Age	−0.00	0.00	−0.08	−0.00	0.00	−0.08
Depression (dummy)	−0.17	0.14	−0.16	−0.05	0.04	−0.16
Anxiety (dummy)	−0.22	0.15	−0.17	−0.03	0.05	−0.09
Mixed (dummy)	−0.47	0.18	−0.33**	−0.03	0.06	−0.06
Sleep Effectiveness	−0.05	0.13	−0.09	−0.02	0.04	−0.09
Sleep Difficulty	0.25	0.13	0.45	0.03	0.04	0.17
Depression X Sleep Effectiveness	0.06	0.16	0.06	0.03	0.05	0.11
Anxiety X Sleep Effectiveness	−0.10	0.19	−0.07	0.04	0.06	0.09
Mixed X Sleep Effectiveness	0.41	0.17	−0.45*	−0.01	0.06	−0.05
Depression X Sleep Difficulty	−0.32	0.15	−0.36*	−0.05	0.05	−0.20
Anxiety X Sleep Difficulty	−0.23	0.16	−0.22	−0.05	0.05	−0.16
Mixed X Sleep Difficulty	−0.46	0.21	−0.29*	0.01	0.07	0.03

Note: Heartbeat Tracking $R^2 = 0.02$ for Step 1 ($p = 0.331$); $\Delta R^2 = 0.01$ for Step 2 ($p = 0.864$); $\Delta R^2 = 0.01$ for Step 3 ($p = 0.535$); $\Delta R^2 = 0.12$ for Step 4 ($p = 0.023$); Heartbeat Discrimination $R^2 = 0.01$ for Step 1 ($p = 0.443$); $\Delta R^2 = 0.01$ for Step 2 ($p = 0.725$); $\Delta R^2 = 0.00$ for Step 3 ($p = 0.870$); $\Delta R^2 = 0.03$ for Step 4 ($p = 0.820$).

  * $p < 0.05$.
  ** $p < 0.01$.

reduced confidence ratings for both the heartbeat tracking and heartbeat discrimination tasks predicted by greater sleep difficulties. This contrasts with an opposite effect, where diagnoses of depression, anxiety or mixed anxiety and depressive disorder predicted increased confidence in interoceptive accuracy for the heartbeat discrimination task if they had greater sleep difficulties. Thus, poorer perceptions of sleep quality (specifically in regard to greater sleep difficulties) may falsely exacerbate depressed and anxious patients' beliefs about their interoceptive performance.

The reduced self-reported interoceptive sensibility ratings for participants with greater sleep difficulties complements previous findings regarding the capacity of individuals to maintain insight about their performance despite sleep difficulties: Sleep-deprived participants engaged in tests of cognitive ability are able to accurately assess their performance in these tasks (Baranski, 2007). Similarly, junior doctors'

were successful in appropriately monitoring their work performance following a period of sleep deprivation (Lewis, Blagrove, & Ebden, 2002). However, results from our current study suggest that participants with depression, anxiety or mixed anxiety and depressive disorders are more negatively affected by increased sleep difficulties, while showing inflated confidence in their performance during interoceptive tasks.

Anxiety and depression often present with comorbid sleep problems (e.g. Gregory et al., 2011; Jansson-Frojmark & Lindblom, 2008; Neckelmann, Mykletun, & Dahl, 2007; Spoormaker & van den Bout, 2005; Taylor, Lichstein, Durrence, Riedel, & Bush, 2005), and our results suggest that poor sleep quality may exacerbate the misinterpretation of bodily signals often found within these disorders (e.g. Yoris et al., 2015). It is possible that this may reflect the greater amount of sleep disturbance within individuals with anxiety and/or depression compared to that of healthy controls. Additionally, other symptoms that arise as a result of poor sleep quality, such as fatigue, may have led to further interoceptive cues that interfered with the individual's ability to focus on the interoception tasks of the current study. Given the small sample sizes available for other mental health diagnoses in the current study, future research is required to explore the effect of sleep quality on interoceptive accuracy and sensibility within other mental health diagnoses, in which anxiety symptoms are very common, including personality disorder, psychosis and autistic spectrum disorder. High functioning adults with autistic spectrum disorder have an impaired ability to detect accurately signals from the heart, along with exaggerated interoceptive sensibility (Garfinkel et al., 2016). However, the role of sleep quality on these dimensions of interoception is yet to be characterised in individuals with autistic spectrum disorder.

The results of the current study are also consistent with interoceptive training literature that suggests that interoception is not a stable trait (Parkin et al., 2014). Instead, interoceptive accuracy and interoceptive sensibility may be altered according to physiological and psychological states of the individual, in this case, sleep quality and mental health diagnosis. This finding is consistent with research evidence of the effect of hunger states on interoceptive accuracy (Herbert et al., 2012). A range of physiological states, not least cardiovascular arousal and psychological states (e.g. anxiety and depression), can affect accuracy and confidence in heartbeat detection.

Previous research suggests that there is often a discrepancy between how interoceptively aware individuals are, and how interoceptively aware individuals *think* that they are (Vaitl, 1996). In particular, significant correlations between confidence and accuracy can be observed only in those with high interoceptive accuracy, and a greater discrepancy seen between interoceptive accuracy and interoceptive sensibility for those with low interoceptive accuracy (Garfinkel et al., 2015). With mounting evidence supporting the dimensional disassociation between interoceptive confidence and accuracy, it is important to independently consider objective, subjective and metacognitive facets of interoception (Garfinkel and Critchley, 2016; Garfinkel & Critchley, 2016). This is the first study to address these distinctions in relation to the role of perceived sleep quality across mental health diagnoses. Findings from the current study suggest that participants with mixed anxiety and depressive disorder with greater sleep effectiveness show greater metacognitive awareness about their interoceptive performance during the heartbeat tracking task. On the other hand, participants with depression, anxiety and mixed anxiety and depressive disorder with greater sleep difficulties show reduced metacognitive awareness about their interoceptive ability during this task. This finding is in contrast with research that has found that sleep deprivation within non-clinical populations does not reduce awareness about performance, with poorer driving simulation performance associated with experiential ratings of reduced performance (Fairclough & Graham, 1999Vakulin et al., 2007). This discrepancy in findings can be explained by the focus on a clinical sample in the current study, with results suggesting that it is the interaction between

poor sleep quality and diagnosis that is of importance, rather than sleep quality alone.

Although the current study explores a novel research area, namely the effect of sleep quality on interoception, there were some limitations to the study. Some key findings pertaining to sleep were based on the heartbeat tracking task, while others were related to the heartbeat discrimination task. The heartbeat tracking task is a purer test of interoception, although it is also susceptible to inflated performance driven by higher order knowledge of heart rate (Ring, Brener, Knapp, & Mailloux, 2015). The heartbeat discrimination task is an internal – external integration task and although dependent on interoceptive accuracy, also requires additional processing. While performance on these tasks tends to be correlated (e.g. Garfinkel et al., 2015), there is not a one-to-one mapping, correlations are not always observed and different factors, such as stress, differentially affect these two measures of interoceptive accuracy (Schulz, Lass-Hennemann, Sütterlin, Schächinger, & Vögele, 2013). Different brain regions subserve these two tasks (Schulz, 2016) and together, these differences could contribute to their separate correspondence to key sleep results. Future studies and precise mechanistic research are needed to further delineate mapping of interoceptive processing to sleep measures in affective disorders. The current study also relied on self-reported sleep quality measures, and did not objectively assess participants' sleep quality through the use of actigraphy or polysomnography, or use a sample of individuals with sleep disorder diagnoses. Experiential reports of sleep quality are moderately correlated with objective measures of sleep (Cespedes et al., 2016; Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008). However, experiential sleep quality may represent distinct sleep parameters from those measured objectively, and it is valuable to consider both experiential and objective sleep quality (Werner, Griffin, & Galovski, 2016). Future research could explore associations between interoception and sleep quality by utilising such objective measures of sleep quality, and also explore interoception within a sample of individuals who present with sleep disorders. Such research has the potential to provide insight into the embodied mechanisms underlying affect regulation, and to provide integrative understanding into how interactions between interoception and sleep disturbance may underscore phenomena such as dissociation, or switching from episodes of depression to mania or hypomania.

4.1. Conclusion

This study adopts a multi-faceted approach to consider clinical diagnosis and experiential sleep quality as predictors of interoceptive sensitivity across dimensions of interoceptive accuracy, interoceptive sensibility, and metacognitive interoceptive awareness. Poor sleep quality, including perceptions about both sleep difficulties and sleep effectiveness, appears to adversely affect interoceptive accuracy, while (falsely) increasing confidence in perceived interoceptive proficiency, for participants with depression, anxiety and mixed anxiety and depressive disorder. These findings suggest that interoceptive ability is intimately tied to physiological and psychological states, such as sleep quality and mental health. Moreover, greater sleep difficulties and less sleep effectiveness may lead to a greater misinterpretation of bodily signals for individuals with mental health diagnoses such as anxiety and depression.

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