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Heightened Interoception in Adults with Fibromyalgia

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Abstract

Previous research suggests that the processing of internal body sensations (interoception) affects how we experience pain. Some evidence suggests that people with fibromyalgia syndrome (FMS) – a condition characterised by chronic pain and fatigue – may have altered interoceptive processing. However, extant findings are inconclusive, and some tasks previously used to measure interoception are of questionable validity. Here, we used an alternative measure – the Phase Adjustment Task (PAT) – to examine cardiac interoceptive accuracy in adults with FMS. We examined: (i) the tolerability of the PAT in an FMS sample ($N = 154$); (ii) if there are differences in facets of interoception (PAT performance, PAT-related confidence, and scores on the Private Body Consciousness Scale) between an FMS sample and an age- and gender-matched pain-free sample ($N = 94$); and (iii) if subgroups of participants with FMS are identifiable according to interoceptive accuracy levels. We found the PAT was tolerable in the FMS sample, with additional task breaks and a recommended hand posture. The FMS sample were more likely to be classified as 'interoceptive' on the PAT, and had significantly higher self-reported interoception compared to the pain-free sample. Within the FMS sample, we identified a subgroup who demonstrated very strong evidence of being interoceptive, and concurrently had lower fibromyalgia symptom impact (although the effect size was small). Conversely, self-reported interoception was positively correlated with FMS symptom severity and impact. Overall, interoception may be an important factor to consider in understanding and managing FMS symptoms. We recommend future longitudinal work to better understand associations between fluctuating FMS symptoms and interoception.

Keywords: Interoception; Phase Adjustment Task; Cardioception; Fibromyalgia; Chronic Pain; Task Tolerability

1. Introduction

Interoception refers to the nervous system's processing of internal physiological signals, such as heart beats and gut signals (Khalsa et al., 2018). It is a process by which the nervous system detects, interprets, integrates, and regulates information from the internal body (Chen, 2021). Interoceptive processing is multidimensional, and several different theoretical frameworks – with differing nomenclature – exist (e.g., Garfinkel et al., 2015; Khalsa et al., 2018; Murphy et al., 2019; Suksasilp & Garfinkel, 2022). The most commonly examined aspects of interoceptive processing include *interoceptive accuracy* (i.e., accurate and precise monitoring of internal bodily signals), and *self-reported interoception/interoceptive beliefs* (i.e., subjectively reported experiences and interpretations of interoceptive sensations, including task-related confidence judgements; Khalsa et al., 2018; Suksasilp & Garfinkel, 2022).

Dysfunction of interoception is an important component of numerous physical and mental health conditions (e.g., Khalsa et al., 2018). As such, it is relevant to examine its potential implications for conditions such as fibromyalgia syndrome (FMS), a poorly understood condition which is challenging to diagnose and treat. The primary symptoms of FMS are chronic widespread pain, fatigue (physical and mental), and sleep disturbances (Sarzi-Puttini et al., 2020). Other common features include mental health symptoms, cognitive symptoms, autonomic disturbances, regional pain syndromes, and hypersensitivity to external stimuli (Sarzi-Puttini et al., 2020).

The aetiopathogenesis of FMS remains unclear, but several interacting factors have been proposed (Pinto, Luís, et al., 2023; Sarzi-Puttini et al., 2020), many of which are linked to interoception. For example, studies with FMS samples have consistently shown increased activation in pain-related areas of the brain, and changes in the microstructures of certain regions associated with interoceptive processing (Dehghan et al., 2016; Lutz et al., 2008). In particular, abnormal insula activity has been consistently described in FMS, and it has been argued that this may explain most FMS symptoms (De Paepe et al., 2020). In addition, maladaptive cognitive processes such as pain-related fear, negative expectations and attributions, and catastrophising may affect the intensity of subjective pain, and increase activation of pain-related areas in the brain (e.g., Gracely et al., 2004). These processes may also be central to pain chronification, by fuelling interoceptive hypervigilance and avoidance behaviour (Pinto, Greenen et al., 2023; Pinto, Luís, et al., 2023).

In accordance with these theorised interoceptive mechanisms, previous research suggests that FMS is associated with altered interoceptive processing. Specifically, several studies have found differences in self-reported interoception and interoceptive beliefs between people with FMS and healthy matched participants. For example, FMS participants tend to report significantly higher noticing or attention to internal bodily sensations (Bogaerts et al., 2022; Martínez et al., 2018; Schmitz et al., 2021; Valenzuela-Moguillansky et al., 2017), but significantly lower levels of trust in bodily signals compared to healthy control groups (Borg et al., 2018; Valenzuela-Moguillansky et al., 2017; Schmitz et al., 2021; for a review, see Horsburgh et al., 2024). The increased tendency to notice internal bodily sensations is consistent with the bodily hypervigilance hypothesis in FMS.

Regarding interoceptive accuracy, two studies have found that people with FMS demonstrate lower cardiac accuracy (measured using the heartbeat counting task) compared to matched healthy participants (Di Lernia et al., 2020; Duschek et al., 2015). However, other studies have failed to demonstrate this group difference (Borg et al., 2018; Rost et al., 2017; Valenzuela-Moguillansky et al., 2017). A negative association between FMS symptom severity and heartbeat counting task scores has also been identified in one study (Duschek et al., 2017), and another study found a negative association between interoceptive insight (confidence-accuracy correspondence) and pain symptoms in FMS (Borg et al., 2018).

To summarise, previous research suggests that FMS might be associated with altered interoceptive processing, but there has been limited research on the topic, and findings have not been consistently replicated. Moreover, the validity of existing cardiac accuracy data from the heartbeat counting/tracking task and the Whitehead/heartbeat discrimination task has been widely challenged, with evidence indicating that these measures are susceptible to physiological and psychological confounds (e.g., Desmedt et al., 2020; Murphy et al., 2018; Ring et al., 2015; Zamariola et al., 2018). Of crucial importance is the fact that that heartbeat counting/tracking task is susceptible to false positives, and the Whitehead/heartbeat discrimination task to false negatives. To address these issues, we sought to examine cardiac interoceptive accuracy in adults with FMS using a recently developed method: the Phase Adjustment Task (PAT; Plans, Ponzo et al., 2021). The PAT appears to be free from the confounds of other cardiac measures in healthy adults (Plans, Ponzo et al., 2021), is not susceptible to false positives (within standard statistical tolerances), and can be completed at home using a smartphone app, making it far more accessible than traditional heartbeat perception tasks, particularly for an FMS sample. Specifically, to be judged as interoceptive on the PAT, one cannot use knowledge of one's heart rate (a limitation of the heartbeat

counting task). Furthermore, individual differences in the time at which the heartbeat is perceived with respect to the heart's R-wave cannot produce false negatives (a limitation of the 2FAC heartbeat discrimination task).

1.1. The Present Study

We first examined if the PAT is tolerable for participants with FMS. The original PAT required participants to sustain their attention to the task continuously for approximately15-20 minutes, and to maintain a relatively still hand posture while holding their phone and completing the task. However, people with FMS have chronic pain which could be exacerbated by maintaining a fixed hand posture, fatigue, and difficulties sustaining attention and concentration. Based upon feedback from a pilot study and subsequent modifications to the task (see section 2.1.1.), we expected the PAT would be rated as tolerable by participants with FMS, and that participants would have acceptable task completion rates (i.e., ≥ 80% trials completed).

Next, we examined whether there are differences in interoceptive accuracy (as measured by the PAT) and self-reported interoception between an FMS sample and a matched pain-free control group. To assist with *a priori* power calculations and hypothesis generation, we compared mean PAT scores from our FMS dataset and the community sample reported by Plans, Ponzo and colleagues (2021). Based on this, we expected to find a difference between our FMS sample and a new sample of matched pain-free control participants, with the FMS sample expected to evidence higher PAT scores. Furthermore, we expected a significantly larger proportion of participants in the FMS group would be classified as interoceptive in comparison to the pain-free matched control sample. Regarding the self-reported indices/interoceptive beliefs, we predicted that the FMS group would have significantly higher PBCS scores, but significantly lower PAT-related confidence scores, in comparison to the pain-free control sample. These expectations were based upon previous research indicating that participants with FMS evidence higher self-reported interoception (e.g., Schmitz et al., 2021; Valenzuela-Moguillansky et al., 2017), and high trait prediction error (Sharp et al., 2021).

Finally, we examined whether subgroups of people with FMS could be identified according to interoceptive accuracy levels (i.e., FMS with/without poor interoceptive accuracy), and explored if these groups differed in FMS symptomology. Some previous studies have found that FMS is associated with lower levels of interoceptive accuracy (albeit with likely invalid tasks, Di Lernia et al., 2020; Duschek et al., 2017), and other studies have found negative correlations between pain or general symptom severity and interoception

(Borg et al., 2018; Ciaramella et al., 2022; Duschek et al., 2017). Accordingly, we predicted that participants with the strongest evidence of being interoceptive on the PAT would have lower levels of FMS symptom severity and impact compared to non-interoceptive participants.

2. Method

2.1. Measures

2.1.1. Interoceptive accuracy. Interoceptive accuracy was assessed using the PAT (Plans, Ponzo, et al., 2021). For a full overview of the smartphone application that was utilised for the PAT in the present study, and the procedures for data acquisition and scoring of the data, see Plans, Ponzo and colleagues (2021). Briefly, during the task, participants place their finger over their smartphone camera and flash, and their heartbeats are detected at the finger. HR/HRV was assessed using a camera-driven photoplethysmogram sensor that detects heartbeats when participants place their finger over their phone's camera and flash. This method has been previously validated (for details and validation see Cropley et al., 2017; Morelli et al., 2018), and overcomes issues with previous methods (e.g., a white light rather than the older-style red/green was used for illumination, which means issues with skin tone are not encountered; Dasari et al., 2021). HR/HRV was assessed from the 180 second baseline recording period at the beginning of the task and data were analysed using the RHRV package for *R*.

During the task, participants are presented with a series of tones that are delivered at the same frequency as their heartbeat, but out of phase. Participants are asked to rotate a virtual dial on their smartphone to advance or delay the tones until they perceive the tones to be synchronous with their heartbeats. For each trial, the starting asynchrony between the heartbeats and tones is randomly determined. 'Interoceptive' participants are identified by a high consistency in their selected delay between heartbeats and the tones across all trials. 'Non-interoceptive participants' are identified by low consistency in their selected delay between heartbeats and tones. 'Unclassified' participants are identified by a lack of sufficient evidence to classify a participant as either interoceptive or not (see Section 3.2.1. for further details).

Consistent with Plans, Ponzo and colleagues (2021) participants rated their confidence in their ability to synchronise the tones to their heart rate after each completed trial on a 10-point visual analogue scale (1 = *Not at all confident,* 10 = *Extremely confident*). After each set of 5 trials, participants also selected the bodily location from which they had

felt their heartbeat using a body map. In total, the task takes approximately 15−20 minutes, without breaks.

Prior to the main study, a pilot study was conducted with 11 participants (one man) aged between 24 and 54 years of age (M = 40.45, SD = 10.20), who had all been previously diagnosed with FMS and experienced symptoms for at least one year. In the pilot, the key problems identified were difficulties concentrating for the length of the task (70% of participants), and pain associated with the task (30% of participants). Following participant feedback, several modifications were made to optimise the PAT for an FMS sample, including: a recommended relaxed open hand posture developed with the pilot participants; the use of a cushion or armchair to support the forearm throughout the task; and, the incorporation of task breaks after each set of five trials. During the break, participants were encouraged to remain seated and relaxed, and to rest their arm and/or hand if necessary. The pain-free control sample completed the task with the same modifications, to ensure comparability across the two groups.

2.1.2. Self-reported interoception/interoceptive beliefs. The Private Body Consciousness Subscale of the Body Consciousness Questionnaire (PBCS; Miller et al., 1981) is a 5-item measure which examines the tendency to focus on internal bodily sensations (sample item: "I can often feel my heart beating"). All items are responded to on a 5-point Likert scale, ranging from 0 (*extremely uncharacteristic*) to 4 (*extremely characteristic*). Scores are computed by summing all items, and higher scores represent a greater tendency to focus on internal bodily sensations. The measure has good patterns of reliability and validity in clinical samples (Mehling et al., 2009), and good levels of test-rest reliability over a two-month period (Miller et al., 1981). In the present study, internal consistency was acceptable for PCBS scores, as McDonald's ω was .73 (95% CI = .63, .80) in the FMS sample and .75 (95% CI = .65, .82) in the pain-free sample.

2.1.3. FMS diagnostic criteria and symptom severity. The Fibromyalgia Severity Scale is a self-report questionnaire version of the 2016 American College of Rheumatology (ACR) FMS criteria (Wolfe et al., 2016) that was designed for clinical and epidemiological research (Wolfe et al., 2010, 2011). The measure comprises a Widespread Pain Index (WPI), where patients indicate whether they experienced pain in the preceding 7 days across 19 different body locations (each indicated body area scores 1 point; maximum WPI score = 19). In the present study, the widespread pain index was assessed using the Michigan Body Map (Brummett et al., 2016). The measure also comprises the Symptom Severity Index (SSI), which assesses the presence and severity of fatigue, waking unrefreshed, and cognitive

symptoms in the preceding 7 days (scored from 0 = *no problem',* to 3 = s*evere: pervasive, continuous, life-disturbing problem*s) in addition to the presence of headaches, pain or cramps in the lower abdomen, and depression in the last 6 months (scored dichotomously: 0 = *no*, 1 = *yes*; maximum SSI score = 12). The WPI and SSI are summed for a total severity score (ranging from 0–31).

Scores from the Fibromyalgia Severity Scale can be used dichotomously to confirm whether a participant meets the ACR 2016 diagnostic criteria for FMS. For a confirmed diagnosis, participants must: indicate generalised pain (i.e., pain in at least 4 of 5 bodily regions on the WPI); indicate that symptoms have been present at a similar level for at least 3 months; and have a WPI score ≥ 7 and SSI score ≥ 5 OR WPI of 4–6 and SSI score ≥ 9 (Wolfe et al., 2016). Fibromyalgia Severity Scale scores can also be used on a continuous basis to measure the magnitude and severity of FMS symptoms across participants who satisfy and do not satisfy the full ACR diagnostic criteria (Wolfe et al., 2016).

2.1.4. FMS impact. The Revised Fibromyalgia Impact Questionnaire (FIQR; Bennett et al., 2009) is a 21-item self-report questionnaire measure that was designed to assess the overall impact of the range of problems associated with FMS. The measure is divided into three domains: function (9 items, sample item: "How much did your fibromyalgia make it difficult to walk continuously for 20 minutes over the past 7 days?"), overall impact (2 items, sample item: "Fibromyalgia prevented me from accomplishing my goals for the week"), and symptoms (10 items, sample item: "What was the intensity of your level of pain over the past 7 days?"). All items are responded to on an 11-point numeric rating scale, ranging from 0–10. To score the FIQR, the summed score for function (range 0 to 90) is divided by 3, the summed score for overall impact (range 0 to 20) is not changed, and the summed score for symptoms (range 0 to 100) is divided by 2. The total FIQR is the sum of the three modified domain scores (total maximal score = 100). In previous research, FIQR scores have demonstrated good patterns of convergent and discriminant validity and good internal consistency. In the present study, internal consistency was good for FIQR total item scores in the FMS sample, as McDonald's ω was .92 (95% CI = .90, .94), and good for domain scores (Function: ω = .91, 95% CI = .88, .94; Symptoms: ω = .79, 95% CI = .73, .83). The pain-free sample did not complete this measure.

2.1.5. Task-related feedback items. To examine the acceptability of the PAT in the FMS sample, participants were asked to complete a 5-item feedback questionnaire, which asked participants to rate the clarity of task instructions, and to rate how happy they would be to complete the task again in the future. These items were both presented on 5-point Likert

scales, ranging from 1 = *extremely unclear/unhappy* to 5 = *extremely clear/happy.* Participants were also asked to state whether they encountered any problems with the app and/or task (including technical/functional problems when downloading or using the app, difficulties concentrating for the length of the task, pain related to the task, and any other problems), and to provide any other comments they wanted to share about the app and/or task.

2.1.6. Additional items. Participants were asked to complete a demographic questionnaire, which included items related to gender identity, age, self-reported height and weight, ethnicity, educational attainment, and employment status. The self-reported height and weight measurements were used to compute BMI as kg/m^2. These details were used for descriptive purposes. Participants were also asked to report their medication, nicotine, alcohol, and caffeine consumption over the past 24 hours.

2.2. Procedure

Prior to data collection, institutional ethics approval was obtained from Anglia Ruskin University (approval code: PSY-S19-023). The study was completed remotely, with data for the FMS sample collected between May and September 2021, and data for the pain-free sample collected in August 2022. The FMS sample was recruited via online advertisements with relevant UK pain charities, and the pain-free sample was recruited via the Prolific website, a crowdsourcing internet marketplace that allows individuals to complete surveys for monetary compensation. Participants first completed an online screening questionnaire to ascertain whether they met the inclusion and exclusion criteria for the study. Participants were recruited according to the following criteria:

(1) For both groups, general inclusion criteria were ability to provide informed consent, owning a compatible smartphone, and willingness to download the free application to complete the PAT. General exclusion criteria were the presence of significant hearing loss (or registered deaf) that prevents response to auditory stimuli, presence of a diagnosed cardiac condition, and pregnancy.

(2) For the FMS sample, additional inclusion criteria were UK adults aged ≥ 18 and ≤ 70, a previous diagnosis of FMS by a clinician such as a rheumatologist, and presence of symptoms for ≥ 1 year duration. Diagnosis and symptom duration was confirmed by asking participants to report the year that they were diagnosed, and the year that they first started experiencing symptoms.

(3) For the pain-free sample, additional inclusion criteria were UK women aged ≥ 29 and ≤ 65, to match the gender and age range of the final FMS sample used in the group-

comparison analyses (see section 3.1.). Exclusion criteria were previous diagnosis of a pain condition, or presence of chronic pain symptoms in the last three months. We confirmed that participants in this group did not meet the 2016 ACR FMS diagnostic criteria, as evidenced by scores from the Wolfe (2016) self-report survey.

Eligible participants were then invited to complete an online survey, which included the participant information sheet, consent form (participants provided digital informed consent by clicking a box), and the self-report measures detailed in Section 2.1. Participants were then directed to complete the PAT via a smartphone application, which was downloaded via a private link. Once they had completed the PAT, FMS participants were directed to complete a final online questionnaire, which included the task-related feedback items. All participants were then directed to an online debriefing information sheet. Participants were offered a retail voucher worth £8, or equivalent payment via Prolific as remuneration for their time.

2.3. Statistical Analyses.

Analyses were computed using RStudio (Version 2022.12.0+353; Boston, MA) and JASP (Version 0.10.2.0, Amsterdam, NL.

Participants were classified as more likely to be interoceptive or not interoceptive, with Bayes Factors (BF) reflecting the strength of evidence in favour of a classification. BFs were calculated as the ratio of the probability of belonging to one of the two distributions (interoceptive and non-interoceptive) over the probability of belonging to the other distribution. Thresholds were applied to BFs, so that participants can be classified as interoceptive, not interoceptive, or unclassified (i.e., where there is insufficient evidence to classify a participant as either interoceptive or not). By convention, BFs > 3 provide moderate evidence that a participant is interoceptive or not interoceptive, BFs >10 provide strong evidence, and BFs > 30 provide very strong evidence.

To ascertain whether participants were responding in a random way or in a stratified manner (i.e., choosing responses based on a pattern or strategy associated with one's own heartbeat), FMS participant responses ($N = 154$) were compared against a randomly generated distribution (5000 iterations) using a Wilcoxon test.

The assumptions of normal distribution (Shapiro-Wilks ps < .05) and homogeneity of variances (Levine's ps <.05) were both violated, therefore Kruskal-Wallis tests were used to examine group differences in resting heart rate, heart rate variability components (SDNN, pNN50, RMSSD), BMI, age, mean task-related confidence ratings and PCBS scores between participants who were classified as interoceptive, non-interoceptive, and unclassified under

BF >3 and BF >10. Mann-Whitney U tests were used to examine group differences under the BF >30 group classification because there were only two groups.

Chi-squared tests were used to examine between-group differences in the distribution of ACR women (n = 108) and pain-free participants (n = 94) who were classified as interoceptive, non-interoceptive and unclassified. In addition, a one-way independent samples t-test was also used to determine whether there was a statistically significant difference in PAT scores when treated as continuous data between the ACR women (n = 108) and the matched pain-free sample (n = 94), and we examined whether there was a group difference in PAT scores after controlling for resting heartrate and BMI using an ANCOVA. Finally, the PBCS scores and PAT-related confidence scores were not normally distributed (Shapiro-Wilks ps < .05), therefore Mann-Whitney U tests were employed to compare the self-report interoceptive indices across the ACR women (n = 108) and pain-free participants (n = 94.

3. Results

3.1. Participants

For the FMS sample, 154 participants (women n = 144, men n = 8, non-binary n = 2) provided useable datasets for the PAT (see Table 1). Participants self-reported that they had been living with FMS symptoms for between 1 and 40 years (M = 10.72 years, ± 8.34 years), and had been diagnosed between 0 and 26 years ago (M = 4.97 years, ± 4.84). While all participants indicated that they had been formally diagnosed with FMS by a general practitioner or rheumatologist, 38 participants did not meet the revised ACR FMS diagnostic criteria (Wolfe et al., 2016; see Section 2.1.3.), leaving a sample of 116 participants with a confirmed diagnosis at the point of research commencement (see Figure 1 and Table 1). Of the participants who did not meet the criteria, the majority (n = 34) were placed in this group because they did not meet the generalised pain criterion (i.e., pain in at least 4 of 5 bodily regions on the WPI). We elected to compute the analyses for our second research question (i.e., whether subgroups of people with FMS could be identified according to interoceptive accuracy levels, and to explore the factors of FMS symptomology that might characterise these groups) using both the total sample and the subsample of participants who met the ACR criteria.

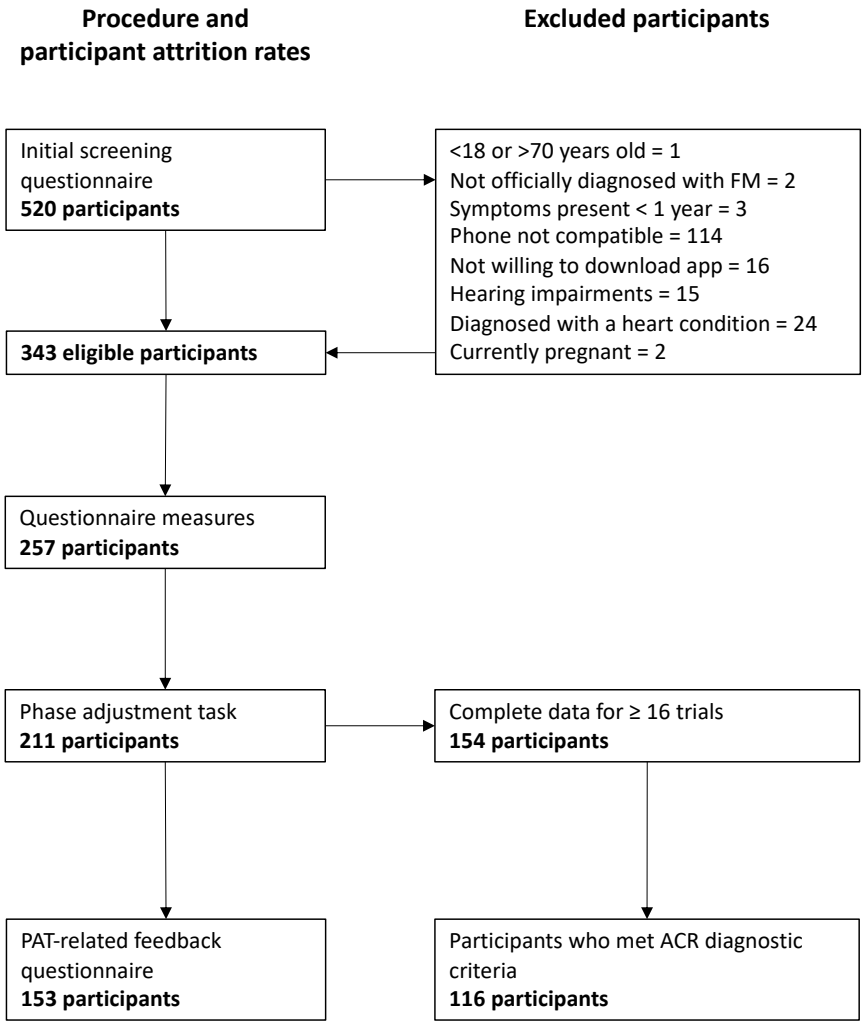

Figure 1. Flow chart depicting the study procedure, participant attrition rates, and participant exclusions.

For the pain-free sample, 110 participants were recruited, however only 94 provided complete data and were subsequently included in the analyses. For the between-group comparison analyses, we further pruned the subsample of FMS participants who met the ACR diagnostic criteria so that it was only comprised of women (n = 108). This was to facilitate a better match across the FMS and pain-free samples due to the limited number of male (n = 6) and non-binary (n = 2) participants in the ACR sample. These samples (i.e., ACR women n = 108 vs pain-free n = 94) did not statistically differ in age, or in the distribution of ethnic groups (see Table 1). However, consistent with previous literature (e.g., D'Onghia et al., 2021; Guymer et al., 2016; Liedberg et al., 2002; Rakovski et al., 2012; Riva et al., 2012), the pain-free sample had lower BMIs and resting heart rates (ps <.001), however, there were no group differences in heart rate variability (RMSSD; p = .473). The

372 pain-free sample also were less likely to be unemployed and had a higher level of educational
373 attainment (*p*s <.001; see Table 1).

Table 1
Participants' Self-Reported Demographic Characteristics, and Scores on the Fibromyalgia Severity Scale

		FMS participant distribution		Samples for between group comparison		Between-group differences
		FMS total sample	ACR criteria met	ACR women	Pain-free women	
N		154	116	108	94	
Age (*M*)		42.13 ± 12.00	42.10 ± 12.43	42.19 ± 12.27	40.09 ± 8.21	$t(194) = 1.40$, $p = .164$, $d = 0.20$
BMI (*M*)		31.99, ± 7.94	31.84 ± 7.72	31.69 ± 7.82	27.89 ± 7.46	$t(197) = 3.50$, $p < .001$, $d = 0.50$
Ethnicity (*n*)	British White	138	105	97	88	$\chi^2(4) = 5.45$, $p = .244$
	Asian or Asian British	0	0	0	3	
	Black African, Caribbean or Black British	1	1	1	2	
	Mixed or multiple ethnic groups	3	3	3	1	
	Other ethnic group	2	1	1	0	
Education (*n*)	GCSEs or equivalent	32	23	21	9	$\chi^2(4) = 30.51$, $p < .001$
	A-levels or equivalent	38	33	31	20	
	Undergraduate degree	33	21	20	49	
	Postgraduate degree	33	25	23	15	
	Other	18	14	13	1	
Employment (*n*)	Employed full time	43	29	27	51	$\chi^2(6) = 28.79$, $p < .001$
	Employed part-time	34	26	26	22	
	Self-employed full time	2	1	0	3	

	Self-employed part-time	8	7	7	3	
	Student	4	3	2	1	
	Unemployed	61	48	44	13	
	Prefer not to say	1	1	1	1	
ACR diagnostic criteria (*Mdn*)	Widespread pain index	10.00	12.00	12.00	0.00	$U = 10151.50$, $p < .001$, $r_B = 1.00$
	Symptom severity index	9.00	9.00	9.00	2.00	$U = 10102.50$, $p < .001$, $r_B = 0.99$
	Fibromyalgia symptom severity	19.00	20.50	20.00	3.00	$U = 10152.00$, $p < .001$, $r_B = 1.00$

3.2. Task Reliability and Tolerability in the FMS Sample (*n* = 154)

3.2.1. Completion rates and Bayes factor classifications. For the PAT, 211 individuals provided data, but 154 participants had usable data for 16 or more trials. Of the 154 participants, 60% completed all 20 trials (see Figure 2). When the data were analysed using only the first 18 trials (excluding trials 19 and 20, usable data for *n* = 146), 58 (39.7%) of participants were classified as interoceptive at a BF threshold of >3. However, when the data were analysed up to trial 16 (excluding trials 17-20, usable data for *n* = 154), 112 (72.7%) of participants were classified as interoceptive (see Figure 3, and Table 2). These findings suggest a reduction in task performance from trial 17 onwards, which aligns with findings from our pilot study, where 70% of participants reported difficulties concentrating for the length of the task. Furthermore, there were significant small correlations between similarity scores and time spent on trials and number of dial movements (see Table 3), which suggests that the ability to engage with the task was associated with a higher similarity score, for data up to both trial 16 and trial 18. For these reasons, we used the data up to trial 16 (excluding trials 17–20 in all further analyses)[1].

3.2.2. Comparison against random responding. A Wilcoxon test (Z = -10.993, p <.001) indicated that the distribution of participants' responses was different to the randomly generated distribution (r = - 0.153, see Figure 4), suggesting that participants were not responding randomly.

[1] In previous analyses, simulated data were used to assess the impact of the number of trials on expected similarity. 20 trials was considered an acceptable balance in terms of expected similarity and participant burden, with 15 trials considered the minimum cut-off. If fewer than 15 trials are used, there is a risk of erroneously classifying some interoceptive users as 'unclassified'. See Supplementary Figure 1.

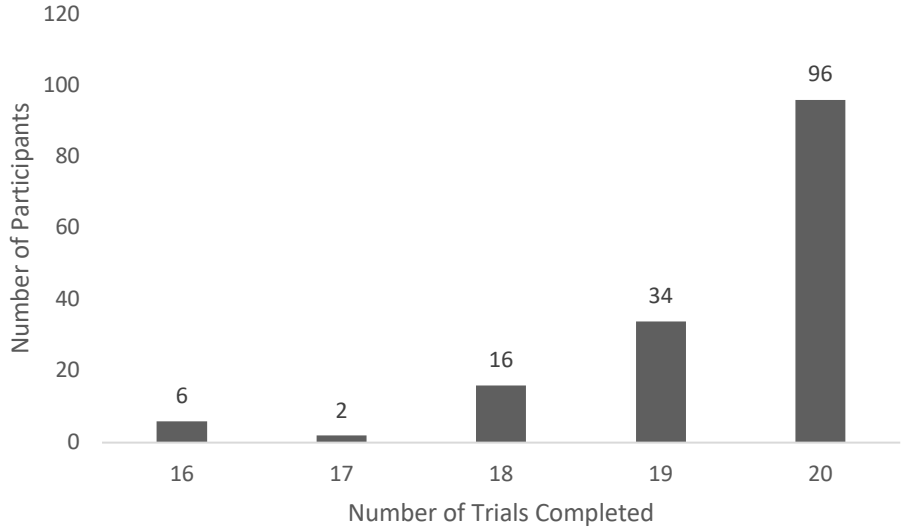

Figure 2. Bar chart showing the number of PAT trials completed by participants.

Table 2

The proportion of FMS participants classified as interoceptive or non-interoceptive when using data for 16 or 18 trials.

	Data up to trial 18 (n = 146)		Data up to trial 16 (n = 154)	
BF > 3				
Interoceptive participants	58	39.7%	112	72.7%
Non-interoceptive participants	45	30.8%	23	14.9%
Unclassified	43	29.5%	19	12.3%
BF > 10				
Interoceptive participants	27	18.5%	109	70.8%
Non-interoceptive participants	-	-	3	1.9%
Unclassified	119	81.5%	42	27.3%
BF > 30				
Interoceptive participants	11	7.5%	104	67.5%
Unclassified	135	92.5%	50	32.5%

Table 3

Correlations between similarity scores and task engagement metrics for all FMS participants, and interoceptive and non-interoceptive participants (BF >3)

All participants			Data up to trial 18 (n = 146)		Data up to trial 16 (n = 154)	
Similarity score	-	Mean time taken on trials	r_s = .27	p = .004	r_s = .22	p = .014
Similarity score	-	Mean engagement during trials	r_s = .35	p < .001	r_s = .30	p = .001
Interoceptive participants (BF >3)			Data up to trial 18 (n = 58)		Data up to trial 16 (n = 112)	
Similarity score	-	Mean time taken on trials	r_s = .26	p = .080	r_s = .25	p = .018
Similarity score	-	Mean engagement during trials	r_s = .33	p = .028	r_s = .29	p = .006
Non-interoceptive participants (BF >3)			Data up to trial 18 (n = 45)		Data up to trial 16 (n = 23)	
Similarity score	-	Mean time taken on trials	r_s = .01	p = .971	r_s = .07	p = .787
Similarity score	-	Mean engagement during trials	r_s = .05	p = .770	r_s = .09	p = .716

Note. *r_s = Spearman correlation coefficient*

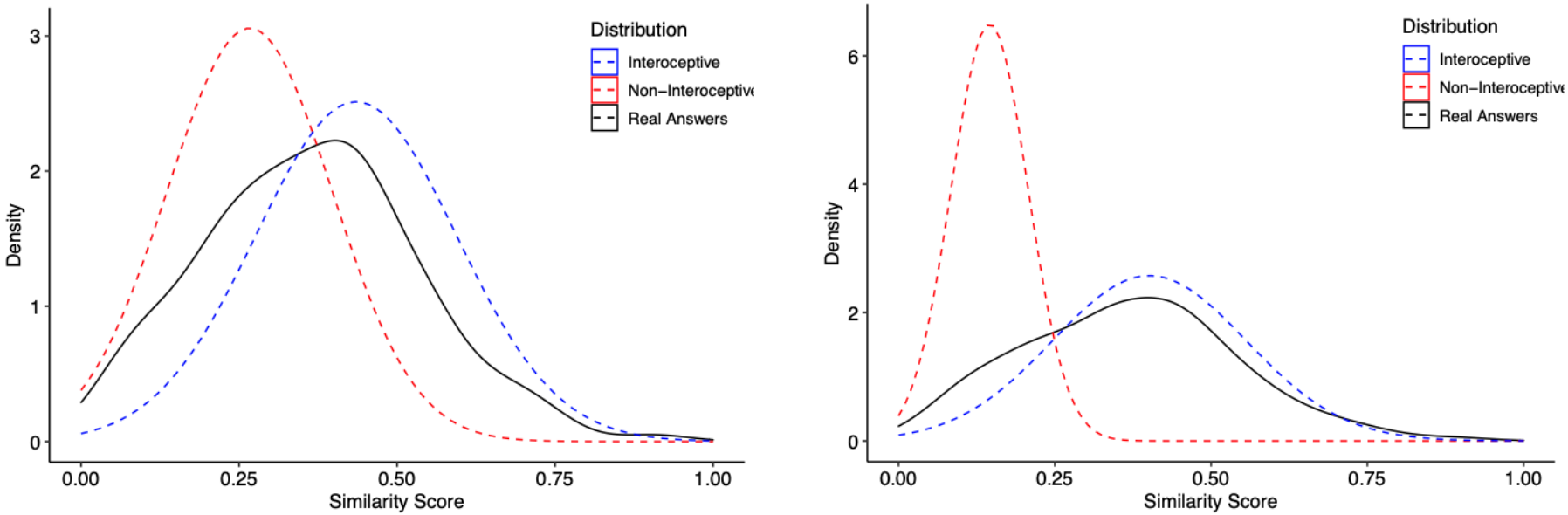

Figure 3. Probability density function of real FMS participants' data (black line, n = 154), estimated distribution of non- interoceptive participants (red line), and interoceptive participants (blue line) for the data up to trial 18 (left) and up to trial 16 (right).

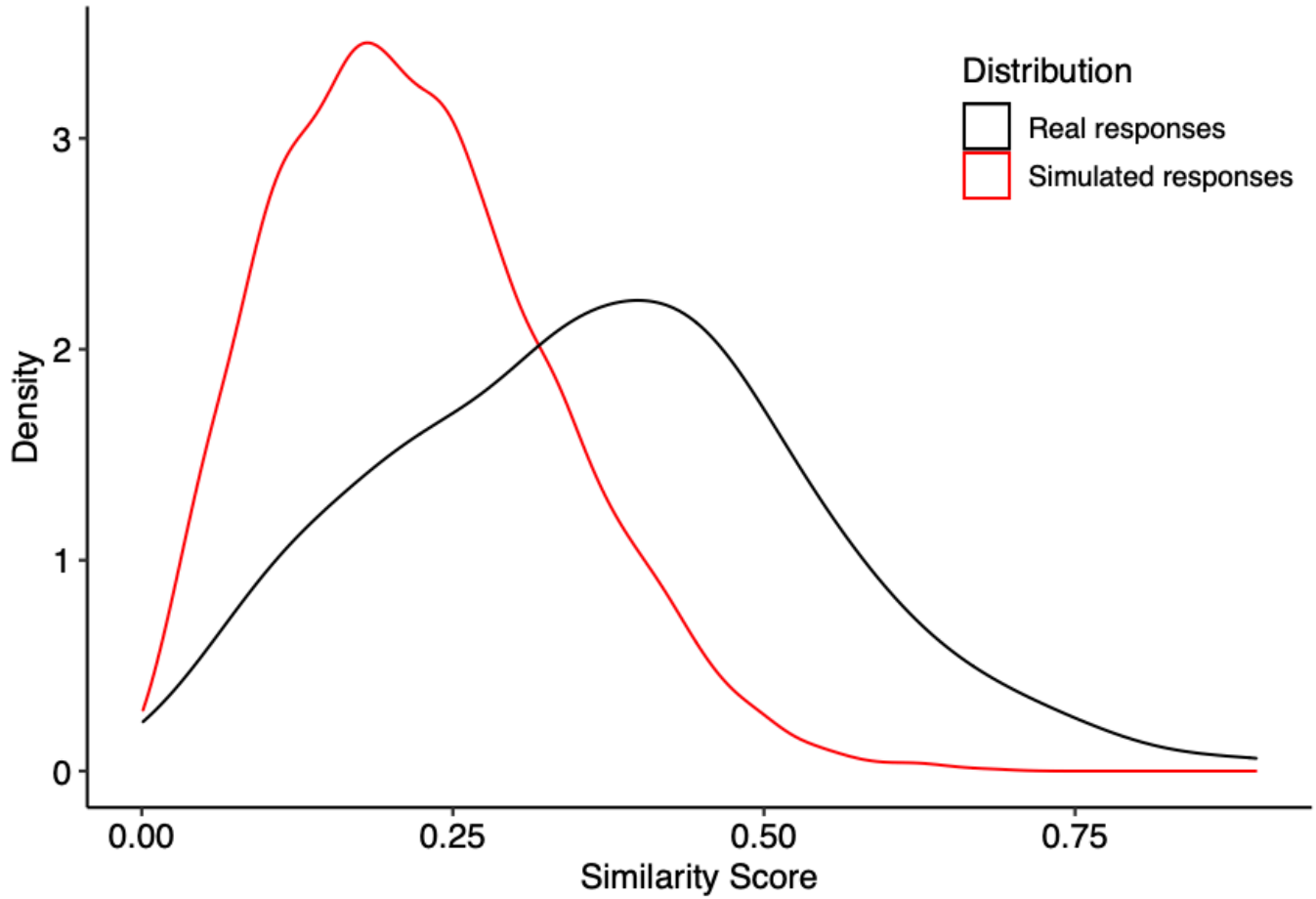

Figure 4. Probability density function of data from simulated participants responding at random (red line) and real FMS participants' data (black line, $n = 154$).

3.2.3. Associations with Physiological Variables.

As shown in Table 4, for the full FMS sample (N = 154), there were no statistically significant group differences for the heart rate variability indices, age, or BMI. However, there were significant differences in mean heart rate across the interoceptive ability groups, across all three BF classifications. Dunn's pairwise tests were computed for the three groups at BF >3 and BF >10. At BF >3, follow up tests indicated that the interoceptive participants (M = 82.21 bpm ± 12.34) had significantly higher heart rates than the non-interoceptive participants (M = 71.82 bpm ± 7.37), p <.001 (Bonferroni-adjusted value)[2]. The differences between the non-interoceptive and the unclassified participants (p = .052), and between the interoceptive and unclassified participants (p = .109) were not statistically significant after Bonferroni correction. At BF >10, interoceptive participants (M = 82.38 bpm ± 12.30) had significantly higher heart rates than the unclassified participants (M = 75.15 bpm ± 4.37), p <.001. There were no statistically significant differences between the remaining group pairings (ps = .098, .296).

Table 4

Kruskal-Wallis and Mann-Whitney U tests to examine group differences in physiological, interoceptive sensibility, and fibromyalgia symptom severity and impact indices across interoceptive, non-interoceptive, and unclassified participants in the total FMS sample.

Variable	BF3	BF10	BF30
Mean heart rate	H(2) = 17.90, p <.001, η^2 = .12	H(2) = 14.63, p <.001, η^2 = .10	U = 3494.00, p <.001, r_{rb} = .34
SDNN	H(2) = 0.16, p = .923, η^2 <.01	H(2) = 1.87, p = .392, η^2 = .01	U = 2664.00, p = .806, r_{rb} = .02
RMSSD	H(2) = 0.47, p = .791, η^2 <.01	H(2) = 0.92, p = .632, η^2 = .01	U = 2747.00, p = .572, r_{rb} = .06
PN50	H(2) = 0.86, p = .652, η^2 <.01	H(2) = 0.14, p = .933, η^2 <.01	U = 2697.50, p = .708, r_{rb} = .04
Age	H(2) = 2.441, p = .295, η^2 = .02	H(2) = 1.756, p = .416, η^2 = .01	U = 2164.50, p = .556, r_{rb} = .06
BMI	H(2) = 0.323, p = .851, η^2 < .01	H(2) = 3.004, p = .223, η^2 = .02	U = 2484.50, p = .885, r_{rb} = .02
PBCS	H(2) = 3.095, p = .213, η^2 = .02	H(2) = 1.453, p = .484, η^2 = .01	U = 2746.50, p = .570, r_{rb} = .06
Mean PAT-related confidence	H(2) = 2.480, p = .289, η^2 = .02	H(2) = 2.502, p = .286, η^2 = .02	U = 2825.00, p = .386, r_{rb} = .09
FSS	H(2) = 1.534, p = .465, η^2 = .01	H(2) = 1.485, p = .476, η^2 = .01	U = 2435.00, p = .262, r_{rb} = -.06
WPI	H(2) = 1.528, p = .466, η^2 = .01	H(2) = 1.710, p = .425, η^2 = .01	U = 2522.00, p = .382, r_{rb} = -.03

[2] This pattern of results was also observed in the pain-free control sample, see Supplementary Materials.

	SSI	H(2) = 1.376, p = .503, η^2 = .01	H(2) = 1.946, p = .378, η^2 = .01	U = 2278.50, p = .104, r_{rb} = -.12
FMIQ-R (weighted total)		H(2) = 2.552, p = .279, η^2 = .02	H(2) = 5.197, p = .074, η^2 = .03	U = 2101.50, p = .027, r_{rb} = -.19
	Function	H(2) = 3.438, p = .179, η^2 = .02	H(2) = 4.884, p = .087, η^2 = .03	U = 2093.00, p = .025, r_{rb} = -.19
	Impact	H(2) = 0.456, p = .796, η^2 <.01	H(2) = 2.996, p = .224, η^2 = .02	U = 2284.00, p = .111, r_{rb} = -.12
	Symptoms	H(2) = 2.250, p = .325, η^2 = .02	H(2) = 4.079, p = .130, η^2 = .03	U = 2114.00, p = .030, r_{rb} = -.19

Note. N = 154. Heart rate variability components: SDNN = Standard Deviation of NN intervals; RMSSD = Root Mean Square of Standard Deviations; PN50 = proportion of NN50 (the number of times successive heartbeat intervals exceed 50 ms) divided by the total number of NN (R-R) intervals. BMI = body mass index. Questionnaire measures: PBCS = Private Body Consciousness Scale; FSS = Fibromyalgia Severity Scale; WPI = Widespread Pain Index; SSS = Symptom Severity Index; FMIQ-R = Revised Fibromyalgia Impact Questionnaire.

3.2.4. Associations with Interoceptive Sensibility Indices. As shown in Table 4, in the full FMS sample (n = 154), there were no statistically significant group differences in PAT-related confidence or PBCS scores across the interoceptive ability groups at BF >3, BF >10, and BF >30.

3.2.5. Task Tolerability and User Experience. One hundred and fifty-three FMS participants provided task-related feedback. Most participants indicated that they found the task instructions extremely clear (n = 77, 50.3%) or somewhat clear (n = 62, 40.5%; see Supplementary Figure 1). Moreover, most participants indicated that they would be extremely happy (n = 109, 71.2%) or somewhat happy (n = 32, 20.9%) to complete the PAT again in the future (see Supplementary Figure 1). Regarding the rationale for being happy to complete the task again, a majority of participants (n = 93) commented about wanting to contribute to research on FMS or help other people with FMS.

However, 54 participants (35.3%) indicated that they had difficulties concentrating for the full length of the task, and 33 participants (21.6%) indicated that they experienced pain related to the task. In terms of the usability of the smartphone application, 45 participants (29.4%) indicated that they experienced a problem downloading the application, and 21 participants (13.7%) indicated that they experienced problems using the application.

Finally, participants had the option to provide additional free text comments about the PAT or the smartphone application. These comments are summarised in full in Supplementary Table 1. In brief, 28 participants commented that the task and/or smartphone application were easy/simple to use; 21 participants commented that they felt they couldn't

sync their heartbeat to the tones; 9 participants commented that heat from their smartphone cameras made their finger and/or phone hot; 8 participants commented that the task was too long; and 7 participants commented that the task caused cramps or stiffness in their hands or fingers.

3.3. Comparisons Between the FMS and Pain-Free Samples

Bayes factor classifications for the pain free sample (n = 94), and assessments of the associations between task performance, physiological indices and task engagement are reported in Supplementary Materials because they are not the primary focus of the present paper. In brief, at a BF threshold of >3, 41 (43.6%) participants were classified as interoceptive, 34.0% were non-interoceptive, and 22.3% were unclassified (see Supplementary Table 3). There was a significant positive association between PAT scores and mean heart rate, and significant group differences in mean heart rate, with interoceptive participants having higher mean heart rates than non-interoceptive participants (see Supplementary Tables 4 and 5).

Chi-squared tests showed significant between-group differences in the distribution of ACR women (n = 108) and pain-free participants (n = 94) who were classified as interoceptive, non-interoceptive and unclassified, with the FMS sample more likely to be classified as interoceptive when participants were grouped at BF >3: $\chi^2(2) = 17.35$, $p < .001$; at BF >10: $\chi^2(2) = 30.65$, $p < .001$; and at BF >30: $\chi^2(1) = 32.62$, $p < .001$.

A one-way independent samples t-test was also used to determine whether there was a statistically significant difference in PAT scores when treated as continuous data between the ACR women (n = 108) and the matched pain-free sample (n = 94). Again, the ACR women had significantly higher PAT scores (M = .378 ± .179) compared to the pain-free sample (M = .335 ± .173), $t(200) = 1.73$, $p = .042$, $d = 0.24$. However, given the aforementioned group differences in resting heart rate and BMI, we explored whether there was a group difference in PAT scores after controlling for these variables. Here, we found that resting heart rate was a significant covariate, $F(1, 195) = 20.01$, $p < .001$, $\eta p^2 = .09$, but BMI was not, $F(1, 195) = 0.08$, $p = .779$, $\eta p^2 = < .001$, and that the group difference in PAT scores was not statistically significant after controlling for these variables, $F(1, 195) = 0.66$, $p = .418$, $\eta p^2 = <.01$.

In terms of the self-report interoceptive indices, median PBCS scores differed significantly across the two groups, with the FMS sample (Mdn = 17.00) tending to report higher scores than the pain-free sample (Mdn = 14.00), $U = 7580.00$, $p <.001$, $r_B = .49$. Likewise, median PAT-related confidence scores differed significantly across the two groups,

with the FMS sample (*Mdn* = 5.63) tending to report higher scores than the pain-free sample (*Mdn* = 4.92), $U = 6170.50$, $p = .004$, $r_B = .22$.

3.4. FMS Within-Group Analyses: Interoception and Fibromyalgia Symptom Severity and Impact

3.4.1. Group Differences in Fibromyalgia Symptom Severity and Impact across Interoceptive and non-Interoceptive Participants. The assumptions of normal distribution (Shapiro-Wilks *p*s < .05) and homogeneity of variances (Levine's *p*s <.05) were both violated, therefore Kruskal-Wallis tests were used to examine group differences between participants who were classified as interoceptive, non-interoceptive, and unclassified under BF >3 and BF >10 in FSS total scores (as well as WPI and SSS scores) and FIQR total scores (as well as the function, impact and symptom subscale scores). Mann-Whitney U tests were used to examine group differences under the BF >30 group classification.

As can be seen from Table 4, for the total FMS sample (*n* = 154), there were no differences in Fibromyalgia Symptom Severity or Impact scores across the interoceptive ability groups when classified at BF >3 and BF >10. However, there were differences between the interoceptive and the unclassified participants when classified at BF >30. Specifically, the unclassified participants had significantly higher total FIQR scores than the interoceptive participants, and this was also the case for the function and symptom subscale scores. However, the effect sizes for all significant results were small. There were no significant differences between the unclassified and interoceptive participants for FIQR impact subscale scores. Furthermore, there were no statistically significant differences between the two groups for FSS total scores, or the WPI or SSI subscales.

As can be seen from Table 5, for the full sample of participants who met the ACR diagnostic criteria (*n* = 116), the shape of results was the same as for the total sample (i.e., there were no differences in Fibromyalgia Symptom Severity or Impact across the interoceptive ability groups when classified at BF >3 and BF >10). However, at BF >30, the unclassified participants had significantly higher total FIQR scores than the interoceptive participants, and this was also the case for the function and symptom subscale scores. Again, the effect sizes for all significant results were small. There were no significant differences between the unclassified and interoceptive participants for impact subscale scores. Furthermore, there were no statistically significant differences between the two groups for FSS total scores, or the WPI or SSI subscales.

There were no significant group differences in any of the interoceptive indices (PAT task scores, mean PAT-related confidence ratings, and PBCS scores) between the participants who did and did not meet the ACR diagnostic criteria for fibromyalgia (see Supplementary Table 2).

Table 5.

Kruskal-Wallis and Mann-Whitney U tests to examine group differences in physiological, interoceptive sensibility, and fibromyalgia symptom severity and impact indices across interoceptive, non-interoceptive, and unclassified participants in the subsample of participants who met the ACR 2016 diagnostic criteria for fibromyalgia.

Variable		BF3	BF10	BF30
FSS		H(2) = 1.298, p = .523, η^2 = .01	H(2) = 1.058, p = .589, η^2 = .01	U = 1360.50, p = .238, r_{rb} = -.08
	WPI	H(2) = 0.737, p = .629, η^2 < .01	H(2) = 0.778, p = .678, η^2 = .01	U = 1411.50, p = .339, r_{rb} = -.05
	SSI	H(2) = 1.979, p = .372, η^2 = .02	H(2) = 3.149, p = .207, η^2 = .03	U = 1269.50, p = .102, r_{rb} = -.14
FMIQ-R (weighted total)		H(2) = 1.667, p = .435, η^2 = .02	H(2) = 5.091, p = .078, η^2 = .04	U = 1190.50, p = .043, r_{rb} = -.20
	Function	H(2) = 3.272, p = 195, η^2 = .03	H(2) = 5.355, p = .069, η^2 = .05	U = 1149.00, p = .025, r_{rb} = -.23
	Impact	H(2) = 0.140, p = .933, η^2 <.01	H(2) = 1.887, p = .389, η^2 = .02	U = 1370.50, p = .256, r_{rb} = -.08
	Symptoms	H(2) = 1.558, p = .459, η^2 = .01	H(2) = 4.378, p = .112, η^2 = .04	U = 1177.00, p = .037, r_{rb} = -.21

Note. n = 116. Heart rate variability components: SDNN = Standard Deviation of NN intervals; RMSSD = Root Mean Square of Standard Deviations; PN50 = proportion of NN50 (the number of times successive heartbeat intervals exceed 50 ms) divided by the total number of NN (R-R) intervals. BMI = body mass index. Questionnaire measures: PBCS = Private Body Consciousness Scale; FSS = Fibromyalgia Severity Scale; WPI = Widespread Pain Index; SSS = Symptom Severity Index; FMIQ-R = Revised Fibromyalgia Impact Questionnaire.

3.4.2 Correlations between FMS symptom indices and the interoceptive indices.

Table 6 shows Spearman's correlations between the interoceptive indices (PAT scores, PAT-related confidence judgements, and PBCS scores) and the fibromyalgia symptom severity and impact indices (total FSS and associated subscale scores, total FMIQ scores and associated subscale scores). As can be seen, there were no statistically significant correlations between the fibromyalgia symptom indices and the PAT scores or PAT-related confidence scores, for either the total FMS sample (n = 154) or the subsample of participants who met the ACR 2016 diagnostic criteria (n = 116). However, there were small significant correlations between PBCS scores and the FMS symptom indices: in the total sample (n =

154), there were small positive correlations between PBCS scores and both FMIQ-R total scores and FMIQ-R symptom subscale scores. In the subsample of participants who met the ACR diagnostic criteria (n = 116), there were small positive correlations between PBCS scores and both FSS total scores and WPI subscale scores. There were also small positive correlations between PBCS scores and FMIQ-R total scores, and FMIQ-R impact and symptom subscales, respectively.

Table 6

Spearman's correlations between interoceptive indices and FM symptom indices in the FMS participants

			Total FMS sample (n = 154)		ACR subsample (n = 116)	
Interoception indices		Fibromyalgia indices	r_s	p	r_s	P
PAT score	-	FSS	-.01	.917	-.09	.315
	-	WPI	.01	.949	-.09	.323
	-	SSS	-.06	.943	-.10	.275
	-	FMIQ-R	-.13	.120	-.11	.226
	-	Function	-.13	.104	-.15	.111
	-	Impact	-.11	.195	-.06	.513
	-	Symptoms	-.11	.160	-.11	.256
	-	PCBS	.13	.117	.26	.005
	-	PAT confidence	-.04	.612	-.06	.511
Confidence	-	FSS	.14	.093	.181	.051
	-	WPI	.14	.081	.179	.054
	-	SSS	.05	.533	.085	.365
	-	FMIQ-R	.13	.122	.121	.197
	-	Function	.07	.359	.05	.622
	-	Impact	.09	.261	.12	.196
	-	Symptoms	.18	.030	.14	.130
	-	PCBS	.13	.116	.17	.075
PBCS	-	FSS	.15	.061	.27	.004
	-	WPI	.13	.114	.21	.022
	-	SSS	.09	.271	.20	.034
	-	FMIQ-R	.20	.015	.26	.005
	-	Function	.11	.172	.12	.198
	-	Impact	.16	.050	.24	.011
	-	Symptoms	.21	.011	.25	.006

Note. PAT = Phase Adjustment Task; PBCS = Private Body Consciousness Scale; FSS = Fibromyalgia Severity Scale; WPI = Widespread Pain Index; SSS = Symptom Severity Index; FMIQ-R = Revised Fibromyalgia Impact Questionnaire.

4. Discussion

The aim of this study was threefold: (1) to determine whether the PAT is a suitable tool for investigating interoception with an FMS sample; (2) to compare cardiac interoceptive accuracy (measured using the PAT) and self-reported interoception/interoceptive beliefs between the FMS sample and an age- and gender-matched pain-free control group; and (3) to identify subgroups of FMS patients based on their interoceptive accuracy levels and explore how FMS symptomology might differ among these groups. Overall, our findings suggest that the PAT is tolerable for an FMS sample, with some necessary adjustments. Additionally, women with FMS were significantly more likely to be classified as interoceptive compared to matched pain-free women under all three Bayes Factor thresholds, and had significantly higher self-reported interoception than the pain-free group. A group difference in PAT scores was also observed when the data were treated continuously, however this difference was not statistically significant after controlling for resting heart rate. Within the FMS sample, a subsample of participants who were classified as interoceptive under a Bayes Factor of >30 (providing very strong evidence of interoceptive accuracy) had lower symptom impact compared to the unclassified participants. Conversely, self-reported interoception was positively correlated with FMS symptom severity and impact across the total sample. In the following discussion we will consider each of these findings in turn.

4.1. Task tolerability and interpretation of scores

In terms of the tolerability of the PAT in an FMS sample, findings from the pilot study and the main study indicated that the task is tolerable with modifications, such as the inclusion of task breaks after each set of five trials, and the adoption of a recommended hand posture (i.e., relaxed open hand, supported by a cushion or chair). These modifications notwithstanding, we still identified a reduction in task performance from trial 17 onwards, which is consistent with the feedback from the pilot study, and with the qualitative and quantitative feedback from the main study: many FMS participants indicated that they found the task long, and felt that they were unable to concentrate for the duration. Accordingly, we used data for the first 16 trials in our analyses, and it may be advisable to use a shortened (16-trial) paradigm in future research with FMS samples. As discussed above, previous simulations have indicated that PAT scores are sufficiently stable when using at least 15 trials (for further discussion, see Supplementary Materials).

In terms of the interpretation of task scores with respect to physiological data, we were able to replicate the findings of Plans, Ponzo and colleagues (2021) for the majority of the physiological variables: there were no statistically significant group differences for the heart

rate variability indices, age, or BMI across the different FMS and pain-free interoceptive ability groups, at any of the BF classifications. However, in contrast to Plans, Ponzo and colleagues (2021), we found significant differences in mean heart rate across the FMS interoceptive ability groups and the pain-free interoceptive ability groups (see Supplementary Materials), across all three BF classifications, with the interoceptive participants having higher heart rates than the non-interoceptive and unclassified participants. This was an unexpected finding, as previous research using the method of constant stimuli task (a task that is similar to the PAT) indicates that greater accuracy is associated with lower heart rates (e.g., Knapp-Kline & Kline, 2005), which, in turn are associated with a greater stroke volume, and greater baroceptor/chest vibration signal. Given that these physiological parameters are reduced at higher heart rates, it is therefore unlikely that there is a direct causal relationship between having a higher heart rate and the likelihood of being interoceptive. Instead, interoceptive individuals have higher attentional demands during the task (there are two signals, in different modalities, for them to attend to, while non-interoceptive people only have one, because they are unable to perceive their heartbeats) and are potentially therefore more anxious. Both attention and anxiety increase heart rate (Gordon et al., 2015; Wang et al., 2014), and thus if there is a causal relationship between cardiac perception in the PAT and increased heart rate (and of course there may not be), it is likely to be in the direction of heartbeat perception causing increased heart rate rather than *vice versa*, potentially facilitating interoceptive accuracy. Notably, previous evidence indicates that individuals with anxiety sensitivity (prevalent in FMS samples) demonstrate a greater propensity to detect heartbeats (Pollock et al., 2006), and individuals with anxiety sensitivity feel particularly anxious when listening to auditory heartbeat cues (Pollock et al., 2006).

4.2. Heightened interoception in the FMS sample compared to the pain-free sample

In terms of the PAT, we found that the FMS sample were more likely to be classified as interoceptive under all three Bayes Factor thresholds. We also observed a small, significant group difference when PAT scores were treated as continuous data.However, this was not statistically significant after controlling for group differences in resting heart rate, and further research is necessary to better understand the link between PAT scores and resting heartrate.. Finally, we also observed higher self-reported interoception and interoceptive beliefs (measured via PAT-related confidence and PBCS scores) in the FMS sample compared to the pain-free group.

Based on an overall picture from the data (i.e., group differences identified in the categorical analyses, group differences in self-reported interoception/interoceptive beliefs,

and the association between interoception and FMS symptomology), it is possible that altered interoceptive processing may be a clinically relevant feature of FMS. This is noteworthy because at present there are no reliable biomarkers or pathognomonic symptoms to diagnose or monitor FMS (Sarzi-Puttini et al., 2020), but there are numerous potential interoceptive biomarkers that could be investigated in relation to FMS (Khalsa & Lapidus, 2016). For example, previous research suggests that FMS samples may have reduced heart rate variability, and alterations in respiratory sinus arrhythmia (a measure of the synchronisation between breathing and heart rate) (Meeus et al., 2013; Staud, 2008; Zamuner et al., 2016).

While the present study did not explore underlying mechanisms, there are several potential factors that may contribute to the heightened interoception observed in FMS compared to pain-free individuals. One possibility is that the heightened interoception might be related to central sensitisation in FMS. Central sensitisation refers to the increased excitability and synaptic efficacy of neurons in central nociceptive pathways (i.e., the amplification of neural signalling within the CNS). In response to behavioural conditioning following an injury or illness, the CNS becomes provoked into a persistent state of heightened reactivity, lowering sensitivity thresholds, which causes hypersensitivity to pain and sensory stimuli (Woolf, 2011). Several key symptoms and consequences of FMS, such as poor sleep, depression, avoidance of activities, and pain-related hypervigilance appear to further sensitise the central nervous system (Woolf, 2011). In support of the hypothesised association between FMS, central sensitisation and interoception, previous research has found that central sensitisation is positively correlated with the tendency to notice internal body signals in adults with chronic pain (Colgan et al., 2022). Another related hypothesis is that there may be structural or functional differences in interoceptive brain regions in FMS – in some cases due to central sensitization (Woolf, 2001) – which lead to a hypersensitivity to internal body sensations. For example, research has found changes in the thalami, the ACC, and both insular regions, which may be linked to higher pain sensitivity, stress, and catastrophising in FMS (e.g., Ceko et al., 2013; Lazaridou et al., 2017; Lutz et al., 2008). While the self-report interoception findings were in line with previous research (Bogaerts et al., 2022; Schmitz et al., 2021; Valenzuela-Moguillansky et al., 2017), the interoceptive accuracy finding contrasts with a minority of previous research studies. That is, in two previous studies, people with FMS have evidenced lower levels of cardiac accuracy (as measured using the heartbeat counting task) compared to matched healthy participants (Di Lernia et al., 2020; Duschek et al., 2015), while other researchers have found no group differences (Borg et al., 2018; Rost et al., 2017; Valenzuela-Moguillansky et al., 2017). The

differences between present and previous findings may be related to differences in the cardiac perception task utilised: the PAT is not directly comparable to other heartbeat perception tasks, the limitations of which have been widely acknowledged (e.g., Desmedt et al., 2020; Murphy et al., 2018; Ring et al., 2015; Zamariola et al., 2018). One key difference is that, unlike the heartbeat counting task, good performance on the PAT is not achievable using non-interoceptive strategies. In the heartbeat counting task, knowledge of one's heart rate means that good performance can be achieved by counting seconds and multiplying by one's heart rate. If it is assumed that patient groups are equally likely to adopt a non-interoceptive strategy to do the task as control groups (i.e., an equal proportion of participants will achieve good performance by 'cheating'), then this could not explain the discrepancy between studies. However, FMS participants are more likely to follow task instructions in order to provide good data to aid research into their condition (as evidence by the free text data in the current study), rather than for money. Research by Desmedt and colleagues (2020) demonstrates substantial non-interoceptive strategies used by control participants on the heartbeat counting task, and the studies using the heartbeat counting task which demonstrated superior performance by control groups as compared to FMS groups did not report using modified task instructions that have been shown to lower the incidence of control participants using non-interoceptive strategies.

4.3. Interoception and FMS symptom impact and severity

Regarding the within-group FMS analyses, our results identified a subgroup of people in the ACR group who demonstrated very strong evidence of being interoceptive (i.e., those who were classified as interoceptive at BF >30), while simultaneously experiencing lower FMS symptom impact, although the effect size was small. This finding appears to be unique to the subgroup of participants with the strongest evidence of being classified as interoceptive, as the association between interoceptive accuracy and FMS symptom impact was not present in total ACR sample correlations. While the present study did not investigate underlying mechanisms, there are a number of possible explanations for this finding. First, better interoceptive accuracy might help individuals with FMS to better regulate their emotions and physiological responses to pain and fatigue (Borg et al., 2018; Schmitz et al., 2021). This could help them to cope more effectively with their symptoms and have a better quality of life. Alternatively, it is possible that people with FMS who are more accurate in sensing their internal bodily sensations are more attuned to their own bodies, and may therefore be more proactive in managing their symptoms. For example, they may be better at identifying triggers that exacerbate their symptoms and making lifestyle changes to avoid or

mitigate those triggers (Kengen et al., 2012; Mannerkorpi et al., 1999). Of course, these ideas are highly speculative, and future research is needed to fully understand the interplay between interoceptive accuracy and symptom impact in FMS. In particular, it is highly likely that interoceptive attention fluctuates, just as FMS symptoms fluctuate, and it would be interesting to utilise an Ecological Momentary Assessment paradigm (e.g., Velkoff & Smith, 2022) to better ascertain the relationship between fluctuations in interoception and FMS symptoms.

Additionally, we found that higher self-reported interoception (as indexed by the PBCS) was associated with increased symptom severity and symptom impact in the ACR subsample of participants, although effect sizes were again small. Though this might seem paradoxical, it is important to note that PAT performance was not statistically associated with PBCS scores in the present study, and the distinction between accuracy and self-reported interoception is widely acknowledged (e.g., Gabriele et al., 2022; Garfinkel et al., 2015; Khalsa et al., 2018; Murphy et al., 2019). In particular, the PAT captures accuracy in the cardiac domain at one point in time, while the PBCS captures the tendency to notice signals across multiple body systems in daily life.

In terms of possible mechanisms, it is plausible that higher scores on the PBCS in FMS may indicate that individuals who are more hypervigilant to their internal bodily sensations have a heightened awareness of their FMS symptoms, which could lead to increased perceptions of symptom severity and impact (Borg, 2015). Indeed, people with FMS tend to consistently report increased subjective hypervigilance and may have a hyperactive threat and self-protection system (Pinto, Greenen et al., 2023; see also López-Solà et al., 2014; Rost et al., 2017). Concurrently, previous research has found that FMS participants tend to report significantly higher noticing of (attention to) internal bodily sensations (Bogaerts et al., 2022; Martínez et al., 2018; Schmitz et al., 2021; Valenzuela-Moguillansky et al., 2017).

An important direction for future research is to more thoroughly examine the nuanced associations between FMS symptoms and different facets of self-reported interoception, as measured by different instruments (e.g., Desmedt et al., 2022; Todd et al., 2022). Current evidence indicates that the relationships between self-reported interoception and FMS symptoms may vary depending on the aspect of self-reported interoception/interoceptive beliefs that is being examined, as well as the measure (as outlined in the Introduction). Notably, Item 1 of the PBCS states, "I am sensitive to internal body tensions." This item, which may be relatively generic when administered in the general population, is more likely to tap into chronic pain-related sensations in FMS samples, which may partially account for

the correlation with FMS symptom severity and impact. That is, in FMS samples, high PBCS scores may be reflective of individuals who are more likely to notice even small changes in their body and experience them as pain or discomfort (Borg et al., 2015, 2018; Köteles & Doering, 2016).

4.4. Limitations and Conclusion

One limitation of the present study is that it was not possible to give a more thorough examination and characterisation of the FMS sample (e.g., quantitative sensory testing profiles) due to the remote testing strategy. A more detailed characterisation of the FMS sample may have facilitated a more nuanced analysis of the role of interoceptive processing in fibromyalgia, and allowed for more detailed sub-group analyses. Another potential limitation is that participants in the FMS group were recruited based on a self-reported previous diagnosis, which could impact the validity of the results, and future work should seek to replicate the present findings using an FMS sample who have had their diagnosis confirmed by a clinician. Nevertheless, this issue is mitigated by the fact that: (1) the FMS sample were required to report the year that they were diagnosed by an appropriate clinician, and the year that they first started experiencing symptoms; (2) participants were recruited via online advertisements with relevant UK pain charities (which further reduces the risk of participants without FMS taking part); and, (3) participants completed The Fibromyalgia Severity Scale, which is valid for research studies: when the criteria are used in people who have a previous diagnosis of fibromyalgia, the criteria allow researchers to be certain that patients have fibromyalgia, so that complex diagnostic work-ups are not required (Wolfe et al., 2016).

A further limitation of the present study design is that we have assessed interoceptive accuracy within the cardiac domain on a single occasion, therefore we cannot assume that the task scores reflect trait-level differences in interoception (for further discussion, see Murphy, 2023). Relatedly, assessing interoceptive accuracy by explicitly asking our samples to attend to heartbeat signals on a single occasion cannot accurately capture individual differences in the propensity to use internal signals in their everyday lives. These issues could be addressed in future research by examining performance on the PAT and tests of interoception in other physiological domains (e.g., respiratory, gastric) across different situations and timepoints. Specifically, the gastric domain may be particularly relevant given that many people with FMS have co-morbid irritable bowel syndrome or other gastric symptoms (Wallace & Halleuga, 2004), and many people with FMS report food intolerance and sensitivities (e.g., Thomson et al., 2023). Moreover, as outlined above, the use of an Ecological Momentary

Assessment paradigm (e.g., Velkoff & Smith, 2022) would provide a more detailed picture of the relationship between fluctuations in interoception and FMS symptoms.

A final point that warrants further discussion is our analysis of the scores from the PAT task. In our results, we examined how differences in group classifications of participants as interoceptive, not interoceptive, or unclassifiable related to a number of different indices (e.g., FMS symptoms, physiological indices, group differences between FMS and pain-free samples). In addition, we also presented analyses of individual differences (i.e., using continuous data) in PAT scores in relation to those indices. While we acknowledge that the down transformation of data into categories reduces variability, and relies on the use of boundary thresholds, there are practical and conceptual reasons why we argue that categorising individuals may be preferable to relying on a continuous score (for further discussion, see Plans, Ponzo et al., 2021). The first relates to the interpretation of scores where individuals are below chance. If two people are below chance (whether this be on the PAT or the HDT), it is arguably not informative to interpret differences between these individuals as meaningful – whilst chance is arbitrary (conventionally an alpha of .05), these differences likely do not reflect individual differences in interoceptive accuracy and instead reflect random noise. Second, while a continuous score may be informative where two individuals are above chance (as this may reflect better perceptual ability for the individual with the higher similarity score), in the absence of an adequately matched control task, it is not possible to determine whether these differences reflect differences in interoception *per se*, or some other factor (e.g., attention/motivation). Third, one strength of the categorisation approach is also a degree of uncertainty surrounding classifications (i.e., the use of the unclassified category), rather than the use of a severe cut-off as has been previously employed. The use of varying thresholds in these analyses (e.g., BF3/10 etc.,) also holds benefits compared to the use of cut-off scores in the literature, as it facilitates examination of our results across thresholds, given that the selection of these is arbitrary. As such, while the selection of any threshold is based on convention, it is arguable that the continuous measure is less interpretable for the above reasons and that the continuous measure is more likely to be influenced by non-meaningful (e.g., artificial) differences between scores (e.g., between two individuals scoring below chance).

In summary, we propose that interoception could play a potential role in the experience and management of FMS symptoms, and using the PAT may prove to be useful for evaluating interoceptive accuracy in this group. However, further research is necessary to better understand the link between PAT scores and resting heartrate. Overall, the finding that

individuals with FMS have higher interoception compared to a pain-free sample, and the finding of associations between interoception and FMS symptom impact and severity, may have implications for understanding the underlying mechanisms of FMS and for developing new treatments that target altered interoceptive processing in this condition. It is likely that the relationship between interoception and FMS symptom severity is complex and multifaceted, and more research is needed to fully understand it. In particular, we suggest conducting future longitudinal studies to explore the connection between fluctuating FMS symptoms and interoceptive processing, perhaps using an ecological momentary assessment paradigm. Further research is also needed to explore the underlying mechanisms by which interoception may be associated with FMS symptoms, and potential ways in which interoceptive biomarkers could be used to diagnoses and manage FMS.

Open practices

The full hypotheses, method and analytic strategy for this study were pre-registered, and can be accessed along with study data here: https://doi.org/10.17605/OSF.IO/8EZY2 (primary research questions), and here: https://doi.org/10.17605/OSF.IO/69GWX (comparison against pain-free group). We have fully reported all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Declaration of competing interest

The authors have no conflict of interest to declare.

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829 **Declaration of Generative AI and AI-assisted technologies in the writing process**

830 The authors did not use generative AI technologies for preparation of this work.

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