# Altered interoceptive processing in smokers: Evidence from the heartbeat tracking task

**Running Head:**

**Altered interoception in smokers**

**Authors:**

**Farah Hina and Dr Jane E Aspell**

**Author affiliation and address:**

**School of Psychology and Sport Science, Anglia Ruskin University, Cambridge, CB1 1PT**

**Corresponding Author: jane.aspell@anglia.ac.uk**

**Abstract Word Count: 165**

**Manuscript Word Count: 5473**

**Tables: 1**

## Abstract

Neuroimaging evidence suggests that interoceptive processing might be altered in nicotine addiction, however this has not yet been confirmed with behavioral measures. Therefore, we investigated the perception of internal bodily states in smokers (n=49) and people who had never smoked (n=51), by measuring interoceptive accuracy (IAcc) and interoceptive sensibility (IS). IAcc was measured with a heartbeat tracking task and a heartbeat discrimination task. Performance on the heartbeat tracking task may be influenced by one's ability to estimate an elapsed time interval so this was controlled by also administering a time-estimation (TE) task. IS was measured using two sub-scales from the Multidimensional Assessment of Interoceptive Awareness (MAIA). All smokers completed the Revised Fagerström Test for Nicotine Dependence (FTND-R) to measure addiction severity. Non-smokers performed significantly better than smokers on the heartbeat tracking task. There were no significant group differences observed for the remaining variables. Furthermore, none of the variables predicted addiction severity. This is the first demonstration of behavioural differences in interoception between smokers and non-smokers.

*Keywords: Addiction, Interoception, Smoking, Heartbeat detection, Interoceptive sensibility.*

Highlights

- We found lower interoceptive accuracy in smokers on the heartbeat tracking measure.
- No significant group differences were found for heartbeat discrimination or interoceptive sensibility.
- Clinically, the observation of decreased interoceptive accuracy in smokers could lead to new treatment approaches aiming to alter awareness of interoceptive signals.

## Introduction

Cigarette smoking modifies several bodily states, for example it causes persistent increases in blood pressure and heart rate (Groppelli, Giorgi, Omboni, Parati & Mancia, 1992), and has powerful sensory effects on the airways (Westman, Behm & Rose, 1996). Furthermore, nicotine withdrawal symptoms include decreased heart rate and gastrointestinal discomfort (Kenny & Markou, 2001). The processing of such internal bodily sensations is termed 'interoception'.

*Interoception* refers to a collection of processes by which the physiological condition of the body is communicated to the brain: afferent signals are received, processed, and integrated to directly or indirectly affect the behavior of an organism, with or without conscious awareness (Craig, 2002). There is a growing body of evidence to suggest that interoception is a multi-dimensional construct (Garfinkel, Seth, Barrett, Suzuki & Critchley, 2015). Interoceptive *accuracy (IAcc)* describes the objective detection of internal bodily sensations measured behaviourally with heartbeat perception tasks (e.g. Schandry, 1981; Whitehead, Drescher, Heiman & Blackwell, 1977). Meanwhile, interoceptive sensibility (IS; Garfinkel et al. 2015) refers to self-reported awareness of internal bodily sensations (measured via questionnaires, e.g. Mehling et al 2012; Porges, 1993). It is important to note, as Garfinkel et al. (2015) have also highlighted, that the measures of IAcc and IS do not always correlate.

There are several reasons for hypothesizing that disturbed interoceptive processing is associated with addiction to nicotine (smoking). Firstly, research suggests other forms of addiction are associated with disturbed interoception. For example, Ateş Çöl, Sonmez and Vardar (2016) found that participants with an addiction to alcohol displayed lower levels of IAcc (measured by the 'heartbeat tracking task'; Schandry, 1981) in comparison to healthy, control participants.

However, there was a significant difference between the smoking habits of the two experimental groups, with a greater proportion of individuals in the 'alcohol-addicted' group also addicted to smoking cigarettes. It is therefore conceivable that the differences between the two conditions were caused by a combination of alcohol and smoking addictions, or exclusively by an addiction to smoking. Another study by Sönmez *et al.* (2017) found that participants with an addiction to either alcohol, heroin, or synthetic cannabinoids also demonstrated lower levels of IAcc (measured with the heartbeat tracking task), in comparison to healthy controls. However, significant differences in smoking habits were also present, and additionally, participants were undergoing inpatient treatment for addiction (including pharmacological therapies that may affect bodily states) at the point of testing. In contrast, a recent study conducted by Betka et al. (2018; smoking status of participants unknown) found that heavy (non-clinical) alcohol consumption was not associated with IAcc. Together, the findings from these studies suggest that addiction specifically, rather than non-clinical consumption of a substance, is associated with impaired IAcc. However, further research is required to confirm this hypothesis, and whether this is applicable to nicotine addiction.

Secondly, a relationship between the insula - a crucial brain region for interoceptive processing (Craig, 2002; Critchley, Weins, Rotshtein, Öhman & Dolan, 2004) - and smoking has been identified by a number of studies, although there is some debate as to how this relationship impacts the IAcc of smokers. Some studies suggest that drug addiction sensitizes the insula, which would predict enhanced IAcc in smokers. For example, Naqvi, Rudrauf, Damasio and Bechara (2007) observed that smokers with brain damage involving the insula were significantly more likely than smokers with brain damage not involving the insula to undergo a 'disruption of smoking addiction'– that is, the ability to cease smoking with ease, immediately, and without persistent cravings or relapses. In contrast, more recent neuroimaging studies have been interpreted to suggest that nicotine addiction is associated with reduced interoceptive signalling within the insular cortex, which would therefore predict diminished IAcc in smokers (Droutman, Read & Bechara, 2015). Smoking has been associated with significant reductions in the thickness of the right insula (Morales, Ghahremani, Kohno, Hellemann & London, 2014), and nicotine dependence scores have been shown to negatively correlate with gray-matter volume of the bilateral anterior insula (Wang *et al.*, 2019).

Research on interoceptive processing has focused mainly on cardiac detection, and there is an implicit assumption that cardiac detection (possibly due to the frequent adoption of such tasks) represents a marker of 'general' interoceptive ability (Tsakiris & Critchley, 2016). Specifically, the heartbeat tracking task (Schandry, 1981) and the heartbeat discrimination task (Brener & Kluvitse, 1988; Whitehead *et al.*, 1977) are the most commonly utilised tasks (Tsakiris & Critchley, 2016). These tasks are generally considered to be both valid and reliable, with good test-retest reliability (Knoll & Hodapp, 1992). However, psychometric weaknesses have been acknowledged (Tsakiris & Critchley, 2016). Moreover, both the heartbeat tracking and discrimination tasks can be confounded by participants' abilities to estimate time, and their knowledge/expectations about their own heart rate (Knapp-Kline & Kline, 2005; Ring, Brener, Knapp & Mailloux, 2015). Meanwhile, many studies utilising the heartbeat discrimination task have documented floor effects, as it is the more difficult of the two tasks (Brenner & Ring, 2016). These confounds can generally be mitigated by combining more than one such task, or using appropriate control conditions (Ainley, Brass & Tsakiris, 2014; Tsakiris & Critchley, 2016). Therefore, our study utilised both methods, in addition to a self-report measure of interoceptive sensibility: the MAIA questionnaire (Mehling et al., 2012); we also used a time estimation task (Shah, Hall, Catmur & Bird, 2016).

There is a paucity of research investigating the roles of interoceptive processing in nicotine addiction, and no studies have examined whether there are differences between smokers and non-smokers. Therefore, the aim of the present study was to examine whether smokers exhibit differences in interoceptive processing using behavioral and self-report methods. A better understanding of the role of altered interoceptive processing in smoking might eventually lead to treatment approaches and it could also contribute to a full understanding of possible predisposing factors for engaging in addictive behaviour. Considering the previous findings on interoception and addiction, our first hypothesis was that smokers would demonstrate lower levels of IAcc and IS than non-smokers. Given current neuroimaging evidence (Bi *et* al., 2017; Morales *et al.*, 2014), our second hypothesis was that there would be a negative relationship between the two measures: as FTND-R score (a measure of the severity of addiction to nicotine) increases, IAcc and IS will decrease.

## Method

1. Participants

The sample (N = 100) consisted of 49 cigarette smokers (21 males and 28 females) and 51 non- smokers (19 males and 32 females), aged between 19 and 68 (M = 25.67, SD = 8.71). The required sample size was decided on the basis of a power calculation computed using a standardised tool, G-power (Faul, Erdfelder, Buchner, & Lang, 2009): with an expected power of 0.8 and a medium (0.3) effect size this indicated 50 participants per group would be sufficient for t-test analyses. The inclusion criteria for smokers was that the participants had to smoke cigarettes daily, and to have been doing so for at least one year, while non-smoker participants had to have never had a habit of smoking cigarettes or any other substance. These classifications were determined on the basis of verbal self-reports from participants. Additionally, participants with any psychiatric, neurological, cardiovascular disorders or current or previous addictions to any substances other than nicotine were excluded. We did not find any significant differences between mean age of non-smokers (*M* = 25.3, *SD* = 1.31) and smokers (*M* = 25.9, *SD* = 1.15), *t*(98) = -.347, *p* = .730, or resting heart rate of non-smokers (*M* = 71.9, SD = 12.9) and smokers (*M* = 73.5, *SD* = 14.0), *t*(98) = -.620, *p* = .537 . The groups were proportionately similar in terms of gender distribution (non-smokers group = 37.3% male, smokers group = 42.8% male). All participants in the smoker group abstained from smoking for one hour prior to participation. Overall, the procedure took an average of 30 minutes, therefore it was not deemed necessary to take measures of nicotine withdrawal.

All participants gave written informed consent. Participants were offered payment at a rate of £7 per hour or participation credits. The protocol was approved by the local Psychology Departmental Research Ethics Panel.

## 2. Apparatus and Procedure

2.1. *Multidimensional Assessment of Interoceptive Awareness questionnaire* (MAIA; Mehling *et al*., 2012). The MAIA is a self-report measure of IS that comprises eight inter-related sub-scales that provide a multi-dimensional profile of interoceptive processing, with each sub-scale assessing a different facet of IS. All participants completed the two sub-scales which were deemed most relevant to the hypothesis: the ‘noticing’ and ‘attention regulation’ scales. The ‘noticing’ scale consists of four items, and was selected because it measures the subjective perception of the ability to perceive and focus on bodily sensations, specifically testing awareness of comfortable, uncomfortable and neutral sensations. Questions include, ‘When I am tense I notice where the tension is located in my body'. Meanwhile, the 'attention regulation' scale consists of seven items and measures the ability to control and maintain attention towards bodily sensations. Questions include, 'I can pay attention to my breath without being distracted by things happening around me.' Answers for both scales are given on a 6-point Likert scale, ranging from 'never' to 'always'. In the present study, Cronbach's α was 0.70 for the 'noticing' scale, and 0.82 for the 'attending' scale, which is comparable to previous assessments (Mehling et al., 2012), and indicates good levels of internal consistency reliability (Kline, 2005).

2.2. *Revised Fagerström Test for Nicotine Dependence* (Korte *et al.*, 2013). The FTND-R was completed by all smokers to measure the severity of addiction to nicotine. The FTND-R has moderate levels of validity and reliability, and significantly predicts bio-chemical measures of cigarette-smoking addiction, such as carbon monoxide (CO) levels in the bloodstream (Korte *et al.*, 2013). It is comprised of six questions with responses recorded on 4- point Likert scales. Questions include, 'How many cigarettes a day do you smoke?' In the present study (*M* = 2.52, *SD* = 3.36, *Min* = .00, *Max* = 12.00), Cronbach's α was 0.69, which is in keeping with previous findings (Korte *et al.*, 2013) and indicates appropriate internal consistency reliability (Kline, 2005).

2.3. *Heartbeat tracking task* (Schandry, 1981). Chart 5 software (Windows) and a Powerlab data acquisition unit (ADInstruments, Germany) were connected to a PC to measure cardiac events during the heartbeat tracking task. Three disposable electrocardiography (ECG) electrodes (positioned on the chest in the Einthoven lead II configuration) relayed R-wave output through shielded wires. The electrodes were self-attached by participants under their clothes, using a visual diagram. Throughout this task, participants were seated in an upright position and asked to attempt to sense their heart beating from the inside of their body, without using a manual pulse. Once they had identified a sensation that they felt indicated their heart beating, participants were asked to count the number of heartbeats occurring in four discrete time intervals of 25, 35, 45, and 55 seconds (presented in a random order across participants). The beginning and end of each trial was signalled by an auditory start/stop cue. Participants were unaware of how long they were counting for, and no performance-related feedback was given

2.4. *Time estimation task* (Shah et al., 2016). Performance on the heartbeat tracking task might be confounded by one's ability to judge the duration of time intervals, and some evidence suggests that smokers may have poorer time estimation abilities than non-smokers, particularly during periods of abstinence (Ashare & Kable, 2015; Klein, Corwin & Stine, 2002; Sayette, Loewenstein, Kirchner & Travis, 2005). We controlled for this by asking half of the participants (randomly selected) in both groups ($n$ = 50) to complete a time estimation task. Participants were asked to estimate elapsed time during three discrete time intervals of 19, 37, 49 seconds, presented in a random order across participants (as in Shah, et al., 2016). Again, participants were unaware of how long they were counting for, and no performance-related feedback was given.

2.5. *Heartbeat discrimination task (*Brener & Kluvitse, 1988; Whitehead *et al.*, 1977). This task was executed using software developed in-house (http://lnco.epfl.ch/expyvr) and the same disposable ECG electrodes, which were connected to a laptop with built-in speakers. Participants had to listen to a series of tones (lasting 100 ms each) and state verbally to the experimenter whether they thought the tones in each trial were synchronous or asynchronous to their own heartbeat. For the synchronous condition, the software produced a tone that was synchronous with the R-wave of the QRS complex of the ECG to create a rhythm that was concurrent to the participant's own heartbeat. The software computed, at 60Hz, the instantaneous derivative of the

ECG signal (buffered data) to detect the high-amplitude signal change between the Q and R peaks of the ECG. Continuous adjustment of the algorithm to cumulatively averaged extrema allowed for an automatic adaptation to inter-participant differences and signal amplitude variations. The imprecision of the R-peak detection in the software is maximally 1 frame (20 ms). As the beep has a fixed duration of 100 ms, the 'mid-point' of the beep therefore occurs on average at 80 +/- 10 ms after the R peak. This is therefore close to synchronous with the theoretical blood flow at the aortic root, and thus with the systolic heart contraction. Previous research has shown that participants do not feel their heartbeats as synchronous with an external stimulus unless there is a delay of around 100-250 ms between it and the R-peak of the ECG (Brener & Kluvitse, 1988; Wiens and Palmer, 2001) For some participants, stimuli presented as late as 400 ms after the R-peak can be judged as synchronous (Brener and Kluvitse 1988; Yates et al., 1985). Given the wide variations between individuals in the relative timings required for optimal synchronicity, our beeps are therefore likely not perfectly synchronous with the perceived heart beats for all participants, but nevertheless should be within the range (100-400ms post R-peak) of what is usually judged as synchronous. For the asynchronous condition, the software produced a tone that was either 80% or 120% of the speed of the two preceding R-waves to create a rhythm that was asynchronous to the participant's own heartbeat. In this condition the system computes, online, a running average of the participant's ECG frequency. This frequency is then continuously used as a reference for computing the timing of the beeps (80% or 120% of the ECG frequency). The timing between the peaks of these two out-of-phase signals of different frequency (e.g. for a participant's ECG at 72 beats per minute, the beeping at 80% will be at a rate of 57.6 BPM) is therefore continuously changing between zero and half of the period of the faster of the two signals (i.e. between 0 and 347 ms in the above example). Generating asynchrony in this dynamic way therefore precludes the possibility of the beeps and R-peaks being synchronous and is therefore better than simply employing a fixed delay between the two signals (which would correspond to a constant phase shift and could, for participants with HRs of certain frequencies, lead to the asynchronous condition being synchronous). Each trial was comprised of 20 tones. Participants were presented with 16 trials, of which eight were synchronous and eight were asynchronous (ordered randomly). The eight asynchronous trials were divided into four that were at 80% of the participant's R-wave signal rate, and four that were at 120%, also with a random order. Each participant had one practice trial to allow for familiarization with the procedure (the synchronicity of this trial was assigned randomly). Participants completed the task without the use of a manual pulse, and no performance- related feedback was given. An identical task was used in recently published papers by Piech *et al.* (2017) and Mul et al., (2018).

2.6. *Transformation of raw data.* Four separate processes were used to transform the raw data from each task into IAcc and IS scores that could be analyzed. Firstly, an IAcc score (*M* = .69, *SD* = .167, *Min* = .26, *Max* = .98) for the heartbeat tracking task was calculated by comparing the number of cardiac events that participants counted with the number of R-waves observed for each of the four trials, in accordance with the formula: 1⁄4 ∑ (1 – [recorded heartbeats – counted heartbeats]/recorded heartbeats), as used by Schandry (1981). Absolute values are utilised, so that scores range from 0 to 1, those closer to 1 indicate higher IAcc. Similarly, the time estimation task scores (*M* = 75, *SD* = 16.6, *Min* = 18.8, *Max* = 100) were computed as percentage accuracies, in accordance with the formula: 1/3 ∑ (1 – [actual elapsed time – estimated elapsed time]/actual elapsed time), as used by Shah *et al.* (2016). Secondly, an IAcc score for the heartbeat discrimination task (*M* = 58, *SD* = .163, *Min* = .25, *Max* = 1) was calculated by dividing the number of correct answers by the total number of trials to generate a percentage accuracy score.

Scores again range from 0 to 1, with those closer to 1 indicating higher IS. We also ran an additional analysis between the two groups to calculate d-prime scores i.e. the measure of sensitivity. The formula used to calculate d-prime score was: d = z(H) - z(F), where H represents 'Hit' and F represents 'False alarm`. Finally, two IS scores were recorded for each participant, with 'noticing' (*M* = 3.23, *SD* = .82, *Min* = .5, *Max* = 5) and 'attention regulation' (*M* = 2.97, *SD* = .75, *Min* = .57, *Max* = 4.86) performance represented by the mean response from each scale respectively. Scores range from 0 to 5, those closer to 5 indicate higher IS.

## 3. Design

The first level of the experiment was quasi-experimental: participants were divided into two groups, smokers and non-smokers. Both groups completed the same four measures of IAcc and IS: two MAIA sub-scales, and two heartbeat perception tasks (see section 2).

The second level of the experiment was correlational. Participants within the 'smoker' group completed the FTND-R (Korte, Capron, Zvolensky & Schmidt, 2013) as a measure of nicotine-addiction severity, and the relationship between this score and the IS scores from the two MAIA sub-scales and IAcc scores from the two heartbeat perception tasks was then considered.

## 4. Statistical analysis

Data were analyzed with SPSS statistics (IBM, Version 20.0).

*4.1. Interoceptive accuracy (IAcc).* Data from the heartbeat tracking and discrimination tasks and the MAIA 'attending' scale met assumptions of normality. Therefore, to test whether IAcc differs between smokers and non-smokers i.e. on the heartbeat tracking task and the heartbeat discrimination task, we used independent-samples t-tests. Because of the multiple comparisons (k), a Bonferroni adjustment was applied to reduce the chance of Type I error, such that $p = (1 - \alpha)k \approx 1 - k\alpha = \alpha/k = .01$. Data from both tasks met assumptions of normality

*4.2. Interoceptive sensibility (IS).* To test whether IS differs between smokers and non-smokers i.e. on the MAIA 'Noticing' and 'Attending' scale, two separate tests were utilised. For the Attending scale, we used independent-samples t-tests while there were outliers in scores from the MAIA 'noticing' scale, and the distribution for the non-smokers was skewed and Kurtotic (the z-scores for skewness and kurtosis were 4.14 and 3.36, respectively). Therefore, a Mann-Whitney U test was run to determine if there were differences in IS scores from the MAIA 'noticing' scales between the two groups and median 'noticing' scores were computed.

*4.3. Time Estimation measure.* There were also outliers in the time estimation data, and the distribution was skewed and kurtosed for both groups (for the smokers group, the z-scores for skewness and kurtosis were 3.38 and 3.08, respectively, and for the non-smokers group, the z-scores for skewness and kurtosis were 3.45 and 3.15). Therefore, a Mann-Whitney U test was run to determine if there were differences in time estimation accuracy scores between the two groups.

*4.4. Correlation analysis.* We computed Spearman's rank-order correlations to see whether there was any relationship between the FTND-R scores and the IAcc and IS scores from the heartbeat perception tasks and the MAIA scales respectively for the 'smokers' group ($n = 49$).

## Results

5.1. *Hypothesis one.* Our analyses revealed partial support for our first hypothesis as we found significant group differences on one measure of IAcc only, i.e. for the heartbeat tracking task, non-smokers (0.74 ± 0.15) performed better than smokers (0.65 ± 0.18); a statistically significant difference of 0.09 (95% CI, 0.03 to 0.15), $t(98) = 2.77$, $p = 0.007$, $d = 0.55$. For the heartbeat discrimination task, there was no statistically significant difference between the two groups $t(98) = 1.26$, $p = 0.209$, $d = 0.25$. The d-prime analysis also revealed no statistically significant differences between the two groups $t(98) = .28$, $p = 0.78$, $d = 0.06$.

Similarly, the difference in scores from the MAIA 'attending' scale (0.67; 95% CI, -0.23 to 0.37) was not significantly different between groups $t(98) = 0.445$, $p = 0.657$, $d = 0.09$. Median 'noticing' scores were not statistically different between smokers (*Mdn* = 3.50) and non-smokers (*Mdn* = 3.50), $U = 1228.0$, z = -.149, $p = .881$.

The findings from the time estimation data demonstrated no statistically significant difference between the groups after Bonferroni correction $U = 187.0$, z = -2.435, $p = .015$. Furthermore, time estimation was not significantly correlated with IAcc scores from the heartbeat tracking task for the both the groups: smokers, $r_s(23) = .215$, $p = .302$; non-smokers, $r_s(23) = .162$, $p = .440$, respectively. This suggests that the difference between smokers and non-smokers on the heartbeat tracking task was not due to differences in time estimation accuracy.

5.2. *Hypothesis two.* We found no support for our second hypothesis. We did not find a statistically significant correlation between the FTND-R scores and the IAcc scores from the heartbeat tracking task, $r_s(47) = .179$, $p = .218$, or the heartbeat discrimination task, $r_s(47) = .188$, *p* = .197. Similarly, we did not find a statistically significant correlation between the FTND-R scores and the IS scores from the MAIA 'noticing' $r_s(47) = .160$, $p = .271$; or 'attending' scales, $r_s(47) = .188$, $p = .197$.

## Discussion

The current study sought to examine the associations between smoking and interoceptive accuracy (IAcc) and interoceptive sensibility (IS). We found that the IAcc of participants in the 'non-smokers' group performed significantly better on the heartbeat tracking task than participants in the 'smoker' group. However, no significant differences between groups were observed for the heartbeat discrimination task, or the MAIA measures of IS. Meanwhile, within the 'smoker' group, neither IAcc or IS, were associated with nicotine-addiction severity. Hence, we found partial support for our first hypothesis (our finding of a significant group difference on one measure of IAcc only), but no support for our second hypothesis.

The observed difference in IAcc on the heartbeat tracking measure between the 'smoker' and 'non-smoker' groups is the first behavioural demonstration of such a difference in smoking population. It is partially consistent with our hypothesis that smoking would be associated with lower IAcc. The finding also aligns with recent studies, which point towards a link between addiction and deficits in IAcc (alcohol-addiction, Ates Col *et al*., 2016; substance-use addiction, Sönmez *et al.*, 2017), and supports previous research demonstrating that in participants with addictions, some interoceptive brain areas show functional differences (Avery *et* al., 2016; smoking addiction, Bi *et* al., 2017; Droutman *et al.*, 2015) and have structural abnormalities (drug addiction, Goldstein *et* al., 2009; smoking addiction, Morales *et al.*, 2014). With support growing for the hypothesis that interoceptive processing may be disturbed in addiction (Ates Col *et al*., 2016; Sönmez *et al.*, 2017), it has been argued that an enhanced conceptualisation of addiction should include compromised interoception, alongside other addiction-relevant constructs (Goldstein *et* al., 2009, Verdejo-Garcia, Clark & Dunn, 2012).

A crucial question remains: how does compromised interoceptive processing relate to addiction in general? Verdejo-García and Bechara (2009) integrate the evidence for disturbed interoception and altered decision-making processes in substance addicts, to explain the underlying mechanisms of substance addiction using the Somatic Marker Hypothesis (Damasio, 1996). According to this theory, complex decision making processes are contingent upon emotion-based bodily signals – 'somatic markers' – which are processed in structures such as the ventromedial prefrontal cortex, the insula, and the amygdala. It may be that structural and functional differences in regions such as the insula render substance addicts less sensitive to bodily signals conveying the negative consequences of certain courses of action; which in turn increases the probability of engaging in risky drug-taking behaviours (Verdejo-García & Bechara, 2009; Verdejo-Garcia *et al*., 2012). The identification of deficits in IAcc found on the heartbeat tracking measure for smokers in the current study corroborates this theory.

Whilst we identified significant differences between smokers and non-smokers on the heartbeat tracking measure of IAcc, no such differences were identified for the self-report (MAIA) measures of IS. Our failure to find commonalities between IS and IAcc is not a unique finding; a poor correspondence between behavioural (heartbeat perception tasks) and self-report measures of interoceptive processing has been previously identified (Garfinkel *et al.*, 2015; Forkmann *et al*., 2016). Indeed, Garfinkel *et al.* (2015) present empirical support for a dissociation between IAcc and IS, which they conceptualised as two of three distinct constructs within interoceptive processing: interoceptive *accuracy*; interoceptive *sensibility*; and a metacognitive measure of overall interoceptive processing (quantifying the relationship between subjective interoceptive sensibility and objective interoceptive accuracy). This three-dimensional model of interoception is underpinned by evidence of distinct patterns of functional connectivity in relation to objective performance and subjective beliefs (Barttfield *et al.,* 2013). In reference to the present study, it could be that group differences in performance on the objective heartbeat tracking task reflect underlying group differences in areas associated with heartbeat perception, such as the right anterior insula (Critchley *et al.* 2004), whilst areas underlying the subjective interpretation of such bodily signals, (for example, the orbitofrontal areas; Flemming, Huijgen & Dolan, 2012) could remain unaffected, explaining the lack of group differences in IS. The metacognitive awareness construct was not tested in this study and we acknowledge this limitation. It would be interesting to test this in smokers in future.

In terms of the two heartbeat perception tasks that were utilized in the present study, it is important to note that while some previous studies have found correlations between the heartbeat perception tasks (Hart, McGowan, Minati & Critchley, 2013; Knoll & Hodapp, 1992) others have not (Betka *et al.,* 2018; Forkmann *et al*., 2016; Michal *et al*., 2014; Schulz, Lass-Hennemann, Sütterlin, Schächinger & Vögele, 2013). Whilst we identified significant group differences on the heartbeat tracking task, no such differences were found on the heartbeat discrimination task. The tasks are assumed to measure IAcc in fairly equivalent ways, but actually require quite distinct psychological processing (Forkmann *et al*., 2016). The heartbeat tracking task requires some sense of the duration of time intervals, which we controlled for with the time estimation task. We found no difference in performance on the time estimation task between smokers and non-smokers, however this was only tested in a sub-set (half) of the sample and we acknowledge the limitation of this. In contrast to the heartbeat tracking task, the heartbeat discrimination task requires a comparison of the timing of events across two different sensory modalities (cardiac interoceptive and auditory). For this reason, the heartbeat discrimination task is generally considered to be a harder and very different task, with most participants performing close to chance level (Brenner & Ring, 2016; Knapp-Kline & Kline, 2005; Phillips, Jones & Snell, 1999). Indeed, other studies have also identified group differences for the heartbeat tracking task, but not for the heartbeat discrimination task (e.g. Kandasamy *et al.*, 2016; Mul, Stagg, Herbelin & Aspell, 2018). It is possible that there may also or alternatively be a conceptual reason for the failure to find a group difference for the heartbeat discrimination task. While the discrimination task requires participants to pay attention to two modalities (auditory and interoceptive) the tracking task requires attention to only one (interoceptive). We can therefore speculate that smokers have more difficulty in maintaining selective attention on one signal modality as compared to splitting attention across two signal modalities, however, to the best of our knowledge, this has not yet been investigated empirically

Our second main finding did not support our prediction: IAcc and IS were not found to be significant predictors of the FTND-R score. This aligns with some recent research (Sönmez *et al.*, 2017), but contrasts with other research where a negative relationship between interoception and addiction was identified (smoking; Bi *et al.*, 2017; Morales et al., 2014). It is important to note that the dataset was divided in half for the correlational analyses. Therefore, the result may be a reflection of low statistical power. Moreover, there are two aspects of the FTND-R data that are worth pointing outL (i) the low variance, (ii) low scores (i.e. low nicotine dependence). These aspects may have limited our ability to identify associations between addiction severity and IAcc and IS. In terms of variance, possible scores on the FTND-R range from 0 to 16, but in our dataset there were no scores greater than 12. Likewise, nicotine dependence was somewhat low as the mean in our sample was 2.52. We acknowledge these limitations and understand that with a sample showing greater variance and with at least some individuals showing high nicotine dependence, we may have found significant group differences on the interoceptive measures, and the predicted correlation in hypothesis 2. However, it should also be noted that a previous study found poor correlation between FTND-R scores and nicotine dependence based on the International Classification of Diseases-10 (Hughes et al., 2004). In order to overcome all these limitations, we suggest that future studies could attempt to recruit participants with greater levels of nicotine dependence, use alternative assessments such as CO levels which may produce more nuanced data or more importantly, consider another measure, cotinine, a nicotine metabolite, which is a weak predictor of difficulty in quitting and is an objective measure (Hughes et al., 2004).

Clinically, the observation of decreased IAcc in smokers could lead to new treatment approaches aiming to alter awareness of interoceptive signals. This is important because current national smoking cessation programmes are associated with modest results (Centre HSCI, 2014). For example, cessation programs could be enhanced by including therapies aimed at improving awareness of the body, such as biological feedback education, body-focused meditations, and mindfulness interventions (Farb, Segal & Anderson, 2013; Paulus, Stewart & Haase, 2013; Verdejo-Garcia *et al.,* 2012). It is conceivable that enhancing interoceptive processing might help smokers cease smoking. If smokers were to become more aware of interoceptive sensations, including aversive respiratory sensations, such as coughing, that might be due to smoking, this may provide additional motivation for them to quit. By enhancing smokers' sensitivity to their internal signals, this may also cause them to pay more attention to their bodily sensations and lead to enhanced self-regulation and concern for their health (Bournemann et al., 2015; Farb et al., 2015). In addition, while emotion regulation dysfunctions have been associated with the development of cigarette smoking (Szasz et al., 2012), previous research has highlighted the significant role of interoception in the ability to access, process and regulate emotions in addiction treatment (for substance-use disorder; Price & Smith-DiJulio, 2016). Indeed, this pilot research suggests that the use of a Mindful Awareness in Body-Oriented Therapy intervention was viewed by addicts as an essential component of relapse prevention.

Future research is also required to clarify whether additional variables that could make one more likely to smoke cigarettes and perform poorly on the heartbeat tracking task (for example, trait anxiety or impulsivity) could be responsible for the observed association between smoking and tracking task performance in the present study. Furthermore, work is also required to ascertain the causal direction of the relationship between interoception and smoking, which was unidentifiable both in the present study, and within previous studies on the topic, given the correlational nature of the research designs utilised. A cue-induced craving paradigm, longitudinal design, or testing participants who no longer meet the criteria for addiction to cigarette smoking may facilitate clarification.

## Conclusion

To conclude, this is the first demonstration of significant behavioural differences between smokers and non-smokers on an interoceptive accuracy measure (the heartbeat tracking task). Additionally, the non-significant difference in the time-estimation task between smokers and non-smokers suggests that the significant difference on the heartbeat tracking task was genuine and not due to variant time estimation abilities between the two groups. However, as no significant group differences were observed for the remaining interoceptive measures, further research on the relations between interoception and smoking is certainly warranted. These findings open up several possible avenues for future research on potential treatment approaches.

**Acknowledgements**

Farah Hina is grateful to the Wellcome Trust for providing support in the form of a Biomedical Vacation Scholarship (grant number: 206882/Z/17/Z). We are indebted to Jennifer Todd for her very important input into the project.

## References

Ainley, V., Brass, M., Tsakiris, M., 2014. Heartfelt imitation: High interoceptive awareness is linked to greater automatic imitation. Neuropsychologia. https://doi.org/10.1016/j.neuropsychologia.2014.05.010

Ashare, R.L., Kable, J.W., 2015. Sex differences in time perception during smoking abstinence. Nicotine Tob. Res. https://doi.org/10.1093/ntr/ntu260

Ateş Çöl, I., Sönmez, M.B., Vardar, M.E., 2016. Evaluation of interoceptive awareness in alcohol-addicted patients. Noropsikiyatri Ars. https://doi.org/10.5152/npa.2015.9898

Avery, J.A., Burrows, K., Kerr, K.L., Bodurka, J., Khalsa, S.S., Paulus, M.P., Simmons, W.K., 2017. How the Brain Wants What the Body Needs: The Neural Basis of Positive Alliesthesia. Neuropsychopharmacology. https://doi.org/10.1038/npp.2016.128

Barttfeld, P., Wicker, B., McAleer, P., Belin, P., Cojan, Y., Graziano, M., Leiguarda, R., Sigman, M., 2013. Distinct patterns of functional brain connectivity correlate with objective performance and subjective beliefs. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1301353110

Betka, S., Van Praag, C.G., Paloyelis, Y., Bond, R., Pfeifer, G., Sequeira, H., Duka, T., Critchley, H., 2018. Impact of intranasal oxytocin on interoceptive accuracy in alcohol users: An attentional mechanism? Soc. Cogn. Affect. Neurosci. https://doi.org/10.1093/scan/nsy027

Bi, Y., Yuan, K., Guan, Y., Cheng, J., Zhang, Y., Li, Y., Yu, D., Qin, W., Tian, J., 2017. Altered resting state functional connectivity of anterior insula in young smokers. Brain Imaging Behav. https://doi.org/10.1007/s11682-016-9511-z

Bornemann, B., Herbert, B. M., Mehling, W. E., & Singer, T., 2015. Differential changes in self-reported aspects of interoceptive awareness through 3 months of contemplative training. *Front.* Psychol. https://doi.org/10.3389/fpsyg.2014.01504

Brener, J., Kluvitse, C., 1988. Heartbeat Detection: Judgments of the Simultaneity of External Stimuli and Heartbeats. Psychophysiology. https://doi.org/10.1111/j.1469-8986.1988.tb01891.x

Brener, J., Ring, C., 2016. Towards a psychophysics of interoceptive processes: The measurement of heartbeat detection. Philos. Trans. R. Soc. B Biol. Sci. https://doi.org/10.1098/rstb.2016.0015

Craig, A. D., 2002. How do you feel? Interoception: the sense of the physiological condition of the body. Nat. Rev. Neurosci. https://doi.org/10.1038/nrn894

Craig, A.D., 2003. Interoception: The sense of the physiological condition of the body. Curr. Opin. Neurobiol. https://doi.org/10.1016/S0959-4388(03)00090-4

Critchley, H.D., Wiens, S., Rotshtein, P., Öhman, A., Dolan, R.J., 2004. Neural systems supporting interoceptive awareness. Nat. Neurosci. https://doi.org/10.1038/nn1176

Damasio, A.R., 1996. The somatic marker hypothesis and the possible functions of the prefrontal cortex. Philos. Trans. R. Soc. B Biol. Sci. https://doi.org/10.1098/rstb.1996.0125

Droutman, V., Read, S.J., Bechara, A., 2015. Revisiting the role of the insula in addiction. Trends Cogn. Sci. https://doi.org/10.1016/j.tics.2015.05.005

Farb, N.A.S., Segal, Z. V., Anderson, A.K., 2013. Mindfulness meditation training alters cortical representations of interoceptive attention. Soc. Cogn. Affect. Neurosci. https://doi.org/10.1093/scan/nss066

Farb, N., Daubenmier, J., Price, C. J., Gard, T., Kerr, C., Dunn, B. D., ... & Mehling, W. E. (2015). Interoception, contemplative practice, and health. *Front.* Psychol. https://doi.org/10.3389/fpsyg.2015.00763

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. Behav Res Methods, https://doi.org/10.3758/BRM.41.4.1149.

Fleming, S.M., Huijgen, J., Dolan, R.J., 2012. Prefrontal Contributions to Metacognition in Perceptual Decision Making. J. Neurosci. https://doi.org/10.1523/jneurosci.6489-11.2012

Forkmann, T., Scherer, A., Meessen, J., Michal, M., Schächinger, H., Vögele, C., Schulz, A., 2016. Making sense of what you sense: Disentangling interoceptive awareness, sensibility and accuracy. Int. J. Psychophysiol. https://doi.org/10.1016/j.ijpsycho.2016.09.019

Garfinkel, S.N., Seth, A.K., Barrett, A.B., Suzuki, K., Critchley, H.D., 2015. Knowing your own heart: Distinguishing interoceptive accuracy from interoceptive awareness. Biol. Psychol. https://doi.org/10.1016/j.biopsycho.2014.11.004

Goldstein, R.Z., Bechara, A., Garavan, H., Childress, A.R., Paulus, M.P., Volkow, N.D., 2009. The Neurocircuitry of Impaired Insight in Drug Addiction. Trends Cogn. Sci. https://doi.org/10.1016/j.tics.2009.06.004

Groppelli, A., Giorgi, D., Omboni, S., Parati, G., Manciat, G., 1992. Persistent blood pressure increase induced by heavy smoking. J. Hypertens. https://doi.org/10.1097/00004872-199205000-00014

Hart, N., McGowan, J., Minati, L., Critchley, H.D., 2012. Emotional Regulation and Bodily Sensation: Interoceptive Awareness Is Intact in Borderline Personality Disorder. J. Pers. Disord. https://doi.org/10.1521/pedi_2012_26_049

Hughes, J.R., Oliveto, A.H., Riggs, R., Kenny, M., Liguori, A., Pillitteri, J.L., MacLaughlin, M.A., 2004. Concordance of different measures of nicotine dependence: Two pilot studies. Addict. Behav. https://doi.org/10.1016/j.addbeh.2004.02.031

Kandasamy, N., Garfinkel, S.N., Page, L., Hardy, B., Critchley, H.D., Gurnell, M., Coates, J.M., 2016. Interoceptive Ability Predicts Survival on a London Trading Floor. Sci. Rep. https://doi.org/10.1038/srep32986

Kenny, P.J., Markou, A., 2001. Neurobiology of the nicotine withdrawal syndrome. Pharmacol. Biochem. Behav. https://doi.org/10.1016/S0091-3057(01)00651-7

Klein, L.C., Corwin, E.J., Stine, M.M., 2003. Smoking abstinence impairs time estimation accuracy in cigarette smokers. Psychopharmacol Bull.

Knapp-Kline, K., Kline, J.P., 2005. Heart rate, heart rate variability, and heartbeat detection with the method of constant stimuli: Slow and steady wins the race. Biol. Psychol. https://doi.org/10.1016/j.biopsycho.2004.09.002

Knoll, J.F., Hodapp, V., 1992. A Comparison between Two Methods for Assessing Heartbeat Perception. Psychophysiology. https://doi.org/10.1111/j.1469-8986.1992.tb01689.x

Korte, K.J., Capron, D.W., Zvolensky, M., Schmidt, N.B., 2013. The Fagerström Test for Nicotine Dependence: Do revisions in the item scoring enhance the psychometric properties? Addict. Behav. https://doi.org/10.1016/j.addbeh.2012.10.013

Mehling, W.E., Price, C., Daubenmier, J.J., Acree, M., Bartmess, E., Stewart, A., 2012. The Multidimensional Assessment of Interoceptive Awareness (MAIA). PLoS One. https://doi.org/10.1371/journal.pone.0048230

Michal, M., Reuchlein, B., Adler, J., Reiner, I., Beutel, M.E., Vögele, C., Schächinger, H., Schulz, A., 2014. Striking discrepancy of anomalous body experiences with normal interoceptive accuracy in depersonalization-derealization disorder. PLoS One. https://doi.org/10.1371/journal.pone.0089823

Morales, A.M., Ghahremani, D., Kohno, M., Hellemann, G.S., London, E.D., 2014. Cigarette exposure, dependence, and craving are related to insula thickness in young adult smokers. Neuropsychopharmacology. https://doi.org/10.1038/npp.2014.48

Mul, C., Stagg, S.D., Herbelin, B., Aspell, J.E., 2018. The Feeling of Me Feeling for You: Interoception, Alexithymia and Empathy in Autism. J. Autism Dev. Disord. https://doi.org/10.1007/s10803-018-3564-3

Naqvi, N. H., Rudrauf, D., Damasio, H., & Bechara, A. (2007). Damage to the insula disrupts addiction to cigarette smoking. Science. https://doi.org/ 10.1126/science.1135926

Paulus, M.P., Stewart, J.L., Haase, L., 2013. Treatment Approaches for Interoceptive Dysfunctions in Drug Addiction. Front. Psychiatry. https://doi.org/10.3389/fpsyt.2013.00137

Phillips, G.C., Jones, G.E., Rieger, E.J., Snell, J.B., 1999. Effects of the presentation of false heart-rate feedback on the performance of two common heartbeat-detection tasks. Psychophysiology. https://doi.org/10.1017/S0048577299980071

Piech, R.M., Strelchuk, D., Knights, J., Hjälmheden, J. V., Olofsson, J.K., Aspell, J.E., 2017. People with higher interoceptive sensitivity are more altruistic, but improving interoception does not increase altruism. Sci. Rep. https://doi.org/10.1038/s41598-017-14318-8

Porges, S.W., 1993. Body Perception Questionnaire (BPQ). Stress Int. J. Biol. Stress.

Price, C., Smith-Dijulio, K., 2016. Interoceptive Awareness Is Important for Relapse Prevention. J. Addict. Nurs. https://doi.org/10.1097/JAN.0000000000000109

Ring, C., Brener, J., Knapp, K., Mailloux, J., 2015. Effects of heartbeat feedback on beliefs about heart rate and heartbeat counting: A cautionary tale about interoceptive awareness. Biol. Psychol. https://doi.org/10.1016/j.biopsycho.2014.12.010

Sayette, M.A., Loewenstein, G., Kirchner, T.R., Travis, T., 2005. Effects of smoking urge on temporal cognition. Psychol. Addict. Behav. https://doi.org/10.1037/0893-164X.19.1.88

Schandry, R., 1981. Heart Beat Perception and Emotional Experience. Psychophysiology. https://doi.org/10.1111/j.1469-8986.1981.tb02486.x

Schulz, A., Lass-Hennemann, J., Sütterlin, S., Schächinger, H., Vögele, C., 2013. Cold pressor stress induces opposite effects on cardioceptive accuracy dependent on assessment paradigm. Biol. Psychol. https://doi.org/10.1016/j.biopsycho.2013.01.007

Shah, P., Hall, R., Catmur, C., Bird, G., 2016. Alexithymia, not autism, is associated with impaired interoception. Cortex. https://doi.org/10.1016/j.cortex.2016.03.021

Sönmez, M.B., Kahyacı Kılıç, E., Ateş Çöl, I., Görgülü, Y., Köse Çınar, R., 2017. Decreased interoceptive awareness in patients with substance use disorders. J. Subst. Use. https://doi.org/10.3109/14659891.2016.1143048

Szasz, P.L., Szentagotai, A., Hofmann, S.G., 2012. Effects of emotion regulation strategies on smoking craving, attentional bias, and task persistence. Behav. Res. Ther. https://doi.org/10.1016/j.brat.2012.02.010

Tsakiris, M., Critchley, H., 2016. Interoception beyond homeostasis: Affect, cognition and mental health. Philos. Trans. R. Soc. B Biol. Sci. https://doi.org/10.1098/rstb.2016.0002

Verdejo-García, A., Bechara, A., 2009. A somatic marker theory of addiction. Neuropharmacology. https://doi.org/10.1016/j.neuropharm.2008.07.035

Verdejo-Garcia, A., Clark, L., Dunn, B.D., 2012. The role of interoception in addiction: A critical review. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2012.05.007

Wang, C., Huang, P., Shen, Z., Qian, W., Li, K., Luo, X., Zeng, Q., Guo, T., Yu, H., Yang, Y., Zhang, M., 2019. Gray matter volumes of insular subregions are not correlated with smoking cessation outcomes but negatively correlated with nicotine dependence severity in chronic smokers. Neurosci. Lett. https://doi.org/10.1016/j.neulet.2018.12.013

Westman, E.C., Behm, F.M., Rose, J.E., 1996. Dissociating the nicotine and airway sensory effects of smoking. Pharmacol. Biochem. Behav. https://doi.org/10.1016/0091-3057(95)02027-6

Whitehead, W.E., Drescher, V.M., Heiman, P., Blackwell, B., 1977. Relation of heart rate control to heartbeat perception. Biofeedback Self. Regul. https://doi.org/10.1007/BF009

Yates, A. J., Jones, K. E., Marie, G. V., & Hogben, J. H. (1985). Detection of the heartbeat and events in the cardiac cycle. Psychophysiology.

Table 1. *Correlations between all variables, with results for the 'smokers group' in the top diagonal and for the 'non-smokers group' in the bottom diagonal*

| | (1) | (2) | (3) | (4) | (5) | (6)+ | (7) |
|---|---|---|---|---|---|---|---|
| (1) Heartbeat Tracking | | .015 | .183 | -.004 | .179 | .215 | .531** |
| (2) Heartbeat Discrimination | .278* | | .087 | -.023 | .188 | .548** | .326* |
| (3) MAIA 'Noticing' | -.082 | .165 | | .421** | .160 | -.032 | -.224 |
| (4) MAIA 'Attending' | -.137 | .053 | .523** | | .188 | -.180 | -.188 |
| (5) FTND-R | -- | -- | -- | -- | | -.155 | -.151 |
| (6) Time Estimation+ | -.162 | .378 | -.036 | .099 | -- | | .064 |
| (7) Average Heartrate | -.213 | -.127 | -.006 | .092 | -- | -.105 | |

*Note*. '*Smokers group' n* = 49, 'Non-*smokers group' n* = 51. * $p < .05$, ** $p < .001$. +*n* = 25 for both groups. Cronbach's α for 'FTND-R' = 0.69, 'MAIA Noticing', and 'MAIA Attending' 0.70.