Fine-tuning your heart: a novel method for measuring interoceptive accuracy

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MT is supported by the European Research Council Consolidator Grant (ERC-2016-CoG-724537) under the FP7 and the NOMIS Foundation Distinguished Scientist Award.

The authors declare no conflict of interest.

ABSTRACT

Interoception research is hampered by the lack of an agreed gold standard test of interoceptive accuracy. To avoid several confounds of heartbeat perception tasks, we devised a novel method of ‘heartbeat matching’, whereby participants use a custom-made slider to adjust the rate at which a heart icon is pulsing on a PC screen, to match this to the pace of their own heart. Because heartbeat counting has been shown to modulate with posture, participants completed both heartbeat matching and a standard heartbeat counting task while standing and when lying down. Accuracy was significantly higher in the heartbeat matching task. Moreover, ability to estimate elapsed time was also more accurate using the matching task but was not significantly correlated with interoceptive accuracy. Participants were more accurate on both tasks when lying down. However, participants underestimated the pace of their hearts in both methods. We discuss possible interpretations and how these might be distinguished.

Keywords: interoception, interoceptive accuracy, body-awareness, heartbeat perception, interoceptive measure

INTRODUCTION

Interoception is defined as the afferent information arising from within the body that affects cognition, feeling states, and the behaviour of an organism, with or without awareness (Cameron, 2002). Interoceptive signals not only provide us with the fundamental feelings that we exist (Craig, 2010; Damasio, 2010; Anil K. Seth, 2013) but interoceptive signalling is fundamental to all emotional experience (Craig, 2008; Critchley & Harrison, 2013).

Unsurprisingly, disordered interoceptive signalling is implicated in many aspects of mental ill health (S. Khalsa et al., 2018; Paulus, Feinstein, & Khalsa, 2019; Stephan et al., 2016).

A large body of research has investigated individual differences in awareness of interoceptive sensations and has found links to diverse outcomes such as: the reported intensity of emotional experience (Barrett, Quigley, Bliss-Moreau, & Aronson, 2004; Duschek, Werner, Reyes del Paso, & Schandry, 2015; Pollatos & Schandry, 2008); empathy for pain (Grynberg & Pollatos, 2015); the ability to divide attention (Matthias, Schandry, Duschek, & Pollatos, 2009); intuitive decision-making (B. D. Dunn et al., 2010; Kandasamy et al., 2016; Werner et al., 2013); and how soon people stop work in freely paced exercise (Herbert, Ulbrich, & Schandry, 2007). Awareness of interoceptive sensations has been linked to anxiety (Domschke, Stevens, Pfleiderer, & Gerlach, 2010; Paulus & Stein, 2010), depression (B. Dunn, Dalgleish, Ogilvie, & Lawrence, 2007), alexithymia (Ernst et al., 2013) and eating disorders (Klabunde, Acheson, Boutelle, Matthews, & Kaye, 2013).

Methods for assessing individual differences in awareness of interoception, however, remain controversial. The principle measures employ heartbeat perception tasks, either by 'heartbeat counting', which requires the individual to count their own heartbeats for short periods (Schandry, 1981), or by 'heartbeat discrimination', where participants are asked whether a series of tones or flashes are presented synchronously or asynchronously with respect to the person's own heartbeat (Schneider, Ring, & Katkin, 1998; Whitehead & Drescher, 1980). Measures using other modalities, for example, respiratory resistance, either do not generally correlate with heartbeat perception (Daubenmier, Sze, Kerr, Kemeny, & Mehling, 2013; Garfinkel, Manassei, et al., 2016) or are cumbersome to administer, such as the water load test (van Dyck et al., 2016), and so have not been widely employed. Tests of respiratory output, muscular effort and taste sensitivity have also recently been piloted (Murphy, Catmur, & Bird, 2017). However, the majority of the studies

in the extensive existing literature on interoception have used cardiac measures. Our aim was therefore to develop a test of cardioception that would be more readily comparable with existing, well-established measures.

Both the methods of heartbeat perception outlined above have disadvantages. Heartbeat discrimination requires participants to integrate exteroceptive signals, such as auditory tones or visual flashes, with sensations from the heart, which, like most interoceptive signals, are experienced at the borders of conscious perception (A K Seth, Suzuki, & Critchley, 2011). The demands that this introduces may explain why heartbeat discrimination ability declines with age (S. S. Khalsa, Rudrauf, & Tranel, 2009), a result not observed for heartbeat counting (Ainley, Tajadura-Jiménez, Fotopoulou, & Tsakiris, 2012). The results of heartbeat perception are analysed using signal detection methods, providing a measure of d' or simply percentages of hits and false alarms (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). However, the majority of people perform at chance on the task. Moreover, there are debates about the correct timing at which a train of stimuli will be perceived as synchronous with the heartbeat. Typically heartbeat discrimination tasks are two-alternative-forced-choice and assume that a stimulus presented 250ms after the beat (to allow for the time that the pulse takes to travel from the heart to the finger tip) will be perceived as synchronous, while 500ms is the asynchronous condition (Garfinkel et al., 2015). A six-alternative-forced-choice method has been advocated, in order to allow for individual differences in where the beat may be felt within the body (J Brener & Ring, 1995). This, however, makes testing very long, given that 40+ trials in each condition are recommended (Kleckner, Wormwood, Simmons, Barrett, & Quigley, 2015). Most studies with heartbeat perception have therefore been confined to healthy adults.

Heartbeat counting is equally open to criticism. It has frequently been suggested that people perform the task by simply counting at some rhythm that they believe reflects their own heart rate (Ring & Brener, 1996; Ring, Brener, Knapp, & Mailloux, 2015). For example, people may simply count in seconds, which is a familiar rhythm sufficiently close to the pace of a resting heart to provide a possible model. Specifically, it has been shown that participants modulate their counting following feedback, suggesting that their perception is biased by prior beliefs about their heart rate (Ring et al., 2015). Likewise, people with heart

pacemakers do not adjust their rate of counting when their heart rate is altered via remote control, without their knowledge (Windmann, Schonecke, Fröhlig, & Maldener, 1999).

Furthermore, there is a need to investigate awareness of interoception in children (Koch & Pollatos, 2014) and in individuals with learning disabilities (Garfinkel, Tiley, et al., 2016).

Heartbeat discrimination imposes a cognitive load that is unsuitable for such groups (Eshkevari, Rieger, Musiat, & Treasure, 2014), while heartbeat counting may be confounded by the limited counting skills of young children (Koch & Pollatos, 2014). As a result of such criticisms, Cameron has declared that ‘There is no obvious gold standard paradigm’ for heartbeat perception’ (Cameron, 2002, p145).

For this experiment we therefore developed and tested, the Heartbeat Matching Task, a novel heartbeat perception task that is suitable for use with a wide range of individuals. Participants were presented, on a PC screen, with an icon of a heart that pulsed rhythmically. Their task was to move a custom-made slider in order to adjust the pace of the flashing heart until it followed their own perceived heartbeat (see *Materials & Methods* for details).

We hypothesised that this new Heartbeat Matching Task would be an improvement on existing tasks, for a number of reasons. Firstly, a notable feature of heartbeat counting tasks is that most people under-report the correct number of beats (Ring et al., 2015). One reason for this is due to lapses in attention. An advantage of our task is that people are not required to count heartbeats, which removes the possibility that they may lose count or miss beats. Secondly, although our task requires some interoceptive/visual integration, it is not affected by the delay between the R wave and when the participant senses the beat, which is a confound of two-forced-choice heartbeat discrimination tasks (Jasper Brener & Ring, 2016). Thirdly, when participants try to detect their own heartbeats, many report that the signal fades as they attend to it (Ainley, Apps, Fotopoulou, & Tsakiris, 2016) because the sensation ‘remains in most cases a vague phenomenon’ (Ádám, 2010, p122). By allowing the participant as much time as they choose to adjust the pulsing stimulus on the screen to mirror their own heartbeat, we avoid potential under-reporting caused by such fluctuations in awareness.

Our experiment drew on the findings of Ring and colleagues who reported that accuracy in

heartbeat counting improves when people lie down, compared with when they stand up (Ring & Brener, 1996). However, this is potentially artefactual and driven purely by changes in actual heart rate rather than counting rate. Given that heart rates slow when people lie down, they should then count fewer beats in each given interval of the heartbeat counting task. Ring and colleagues (1996) reported that, on the contrary, their participants counted the same number of beats in both postures, which the authors interpreted as participants counting at some rate which reflects their beliefs about their heart rate, rather than being related to what is actually happening to their heartbeats during the task. We therefore tested our participants in two postures to check whether our heartbeat matching task improves on this potential confound, by determining whether participants were able to accurately track changes in their heart rate with posture.

Our hypotheses were: (i) that participants would accurately track changes in their heart rate with posture for our novel heartbeat matching task, but not the heartbeat counting task (as has been previously shown); and (ii) that participants would judge their heart rates more accurately overall using the heartbeat matching task compared to the standard heartbeat counting task; and (iii) that the heartbeat matching task would not be confounded by time estimation accuracy, unlike the heartbeat counting task.

MATERIALS AND METHODS

Participants

A total of 42 healthy volunteers were recruited to take part in this experiment via Royal Holloway University of London's Department of Psychology subject database. In total, 5 participants were excluded: 1 participant for not being able to feel their heart at all during the session; 2 participants for not understanding the task instructions; and 2 more were excluded as outliers on the heartbeat matching task. All analyses were conducted on 37 subjects (females = 19; mean age = 25; age range = 19-39). All participants gave informed written consent prior to taking part in the experiment. The experiment was approved by the internal ethics procedure at Royal Holloway University of London.

Experimental Design

Participants completed two different tasks to measure interoceptive accuracy: heartbeat counting (Schandry, 1981); and our new heartbeat matching task. Participants repeated these tasks in two different postures: standing up and lying down (Figure 1). The order of these postural conditions was counterbalanced across participants. However, in each posture, participants always completed the heartbeat counting task before the heartbeat matching task, to ensure the heartbeat matching task did not influence the participant's counting. When lying down, a purpose-built frame was used to suspend a computer screen above the participants so they could see the same visual display as when standing. Prior to starting the tasks, participants were asked to stand or lie quietly for 3 minutes, in order to acclimatise their bodies to the change in posture. After completing the interoceptive tasks in each posture, participants were asked how strongly they could feel their heart beating, on a scale from 0-100. They then sat down at a computer to complete two control time-estimation tasks.

Physiological recordings

A standard 3-lead electrocardiogram (ECG) was attached to each participant's chest throughout the experiment in order to record cardiac activity (Powerlab, AD instruments). During both interoceptive tasks, the ECG trace was thresholded in LabChart in order to detect the R-peaks online. This was read into MATLAB 2016 (**MathWorks, Inc., Mass., USA**), in real-time, in order to count heartbeats during the heartbeat counting task and control the presentation of the visual stimulus during the heartbeat matching task. Blood pressure (BP) was recorded at the end of each 3min acclimatisation period, in each posture, before participants completed the interoceptive tasks (BP wrist unit, Boots Pharmaceuticals). Diastolic and systolic blood pressure were each averaged over two repetitions in order to improve the reliability of the measure. Due to equipment failure, no blood pressure data was available for 3 participants.

Task Design and Analysis

Heartbeat counting task. Following the procedure of Schandry (1981), participants were instructed to silently count their own heartbeats for 6 short trials of 25s, 30s, 35s, 40s, 45s and 50s, presented in random order. Given that the specific nature of the instruction can affect the outcome in heartbeat counting (Ehlers, Breuer, Dohn, & Fiegenbaum, 1995), we used a standard instruction: ‘Silently count your heartbeat simply by listening to your body. You are not allowed to take your pulse while you do this’. Participants were told that they could have their eyes open or eyes closed and were instructed to breathe normally throughout and not to attempt to take their own pulse. An auditory cue signalled when to start and stop counting. Participants indicated their response using a button box. Immediately after giving their response they were asked to report how confident they were about their answer, on a visual analogue scale (VAS) of 0-100.

Heartbeat Matching Task (see video). Participants were shown a red cartoon heart which appeared to be beating on a computer screen. The beating heart was created by presenting a small image of a heart in the centre of the screen and, after a specified interbeat interval (IBI), a larger heart was superimposed and briefly presented for 100ms. The interval between each beat was controlled by a sliding device (built in-house using an Arduino UNO), which was connected to MATLAB using the Arduino toolbox. Moving the slider to the left increased the IBI, which slowed the rate at which the heart pulsed on the screen. Moving the slider to the right decreased the IBI, which increased the rate at which it pulsed. Participants were instructed to try to feel their own heart beating (without taking their pulse) and to slowly move the slider so that the pace of the beating heart on the screen matched their current heart rate. The minimum possible heart rate that participants could match was 40 beats per minute (bpm) and the maximum was 150bpm. Immediately after giving their response, they were asked to report how confident they were about their answer, on a visual analogue scale (VAS) of 0-100. This was repeated for 6 trials of 25s, 30s, 35s, 40s, 45s and 50s, presented in random order. Participants could take as long as they wished to complete each trial.

Time-estimation counting task. This task was designed to match the heartbeat counting task as closely as possible. Participants were instructed to count the number of seconds between two auditory cues. Participants indicated their response using a button box. Immediately after giving their response they were asked to report how confident they were

in their answer on a visual analogue scale (VAS) of 0-100. This was repeated 3 times, for time intervals of 22s, 31s and 43s, presented in random order.

Time-estimation matching task. This task was designed to match the heartbeat matching task as closely as possible. A clock flashed on the screen (created in the same way as the beating heart) at a rate dictated by the position of the slider. Participants were instructed to move the slider until the clock was flashing in seconds (at a rate of 60bpm). Immediately after giving their response they were asked to report how confident they were in their answer on a visual analogue scale (VAS) of 0-100. This was repeated 3 times for the same short intervals as above. Participants could take as long as they wished to complete each trial.

Blood pressure

To identify the physiological effects of each posture, blood pressure (BP) was measured in each posture prior to completing the interoceptive tasks, after the participant had acclimatised to the posture for 3 minutes. BP was analysed using a 2-way repeated measures ANOVA with BP type (diastolic vs systolic) and posture (standing vs lying) as factors.

Data Analysis

For each of the interoceptive tasks, the following dependent variables (DVs) were recorded: reported heart rate (rHR) which was the counted or the matched heart rate in beats per minute; the participant's actual heart rate (aHR). From these, their interoceptive accuracy (IAcc) was calculated for each trial (t) and then an average was taken over the 6 trials using the following equation (Schandry, 1981):

$$\frac{1}{6} \sum_{t=1}^6 1 - \left(\frac{|rHR_t - aHR_t|}{aHR_t} \right)$$

This produced an overall measure of mean IAcc for each task.

Similar measures were collected for the time estimation tasks. However, in this case the DV was in seconds. For the time estimation counting task, time estimation accuracy (TAcc) was averaged across the three trials using the number of seconds reported (rS) and the actual number of seconds in the given trial (aS), according to the following equation:

$$\frac{1}{3} \sum_{t=1}^3 1 - \left(\frac{|rS_t - aS_t|}{aS_t} \right)$$

For the time estimation matching task, the ‘reported rate in seconds’ was given by the rate of pulsing of the clock selected by the participant. Time estimation accuracy (TAcc) was calculated using the following equation:

$$\frac{1}{3} \sum_{t=1}^3 1 - \left(\frac{|rS_t - 60|}{60} \right)$$

All of these DVs were entered into separate 3-way mixed ANOVAs, with POSTURE and TASK as within-subject factors and ORDER (of posture) as a between-subjects factor. Effect sizes were calculated as generalised eta-squared (η_g^2).

RESULTS

Actual heart rate and blood pressure (BP) were modulated by posture

BP was analysed using a 2-way repeated measures ANOVA with BP type (diastolic vs systolic) and posture (standing vs lying) as factors. As expected, there was a significant main effect of BP type, $F(1,33)=2363$, $p<0.001$, $\eta_g^2=0.79$, with systolic BP (mean $\pm$ standard deviation(M $\pm$ SD)=103 $\pm$ 11mm Hg) higher than diastolic BP (M $\pm$ SD=67 $\pm$ 11 mm Hg), for every participant. There was a significant main effect of posture, $F(1,33)=78.36$, $p<0.001$, $\eta_g^2=0.32$, and a significant interaction between posture and BP type, $F(1,33)=13.13$, $p<0.001$, $\eta_g^2=0.015$. Both diastolic and systolic BP were higher when standing compared to lying, however there was a greater difference in diastolic BP between postures than in systolic BP (diastolic BP lying: M $\pm$ SD=59 $\pm$ 6mm Hg; diastolic BP standing: M $\pm$ SD=75 $\pm$ 10mm Hg; systolic BP lying: M $\pm$ SD=98 $\pm$ 8mm Hg; systolic BP standing: M $\pm$ SD=108 $\pm$ 12mm Hg).

Heart rate was measured throughout the interoceptive tasks. Mean heart rate (taken from the average over the six trials in each task) was analysed using a 3-way mixed ANOVA, with task and posture as within-subject factors and order of posture as a between-subjects factor (Figure 2A, D). As expected, there was a significant main effect of posture, $F(1,35)=243.56$, $p<0.001$, $\eta_g^2=0.51$, indicating that the average heart rate across tasks was significantly

slower when participants were lying down compared to standing up ($M \pm SD$ standing = 88.26 ± 12.68 bpm; $M \pm SD$ lying = 67.80 ± 8.86 bpm). There was also an unexpected significant main effect of task, $F(1,35)=8.66$, $p=0.006$, $\eta_g^2=0.002$, such that mean heart rate was slightly faster for the heartbeat counting task ($M \pm SD=78.07 \pm 15.54$) compared to the heartbeat matching task ($M \pm SD=77.00 \pm 15.18$). This probably occurred because the heartbeat counting task was always completed first, in order to ensure that the heartbeat matching task did not influence the participant's counting. However, the difference in mean heart rate between these tasks and the effect size here was very small. There was no significant main effect of order ($p=0.82$). There was a significant interaction between posture and order, $F(1,35)=15.51$, $p<0.001$, $\eta_g^2=0.062$. An analysis of the post-hoc pairwise comparisons revealed that there was no significant difference in mean heart rate between the two lying conditions or between the two standing conditions, regardless of order. There was, however, a greater difference in HR between the two postures when participants stood first. Participants' heart rates often continue to decrease throughout an experimental session; lying down first accelerated this decrease.

Reported heart rate was not modulated by posture in either task

The same 3-way mixed ANOVA was used to analyse the effect of posture, task and order on reported heart rate. For the heartbeat counting task, reported heart rate was calculated as the average number of heartbeats counted in the total of six trials divided by the total number of seconds. For the heartbeat matching task, the visual heart rate selected on each trial was averaged over the six trials. Interestingly, there was no significant effect of posture on reported heart rate ($p=0.80$; Figure 2B, E). Therefore, even though the average heart rate was greater in the standing condition compared to the lying condition, participants did not, on average, increase their reported heart rate to reflect this. There was a significant main effect of task on reported heart rate, $F(1,35)=13.24$, $p<0.001$, $\eta_g^2=0.11$, such that participants estimated that their heart rate was slower in the heartbeat counting task ($M \pm SD=52 \pm 15$ bpm) compared to the heartbeat matching task ($M \pm SD=61 \pm 11$ bpm). There was no significant main effect of order ($p=0.25$) and no significant interactions.

Interoceptive accuracy was higher when lying down compared to standing up

In order to determine the relationship between participants' reported heart rate and their actual heart rate, we calculated IAcc using these two dependent variables (see *Materials & Methods*). Using the same 3-way mixed ANOVA, we found that IAcc was significantly higher when lying down ($M \pm SD = 0.80 \pm 0.13$) compared to standing up ($M \pm SD = 0.64 \pm 0.19$), $F(1,35) = 54.20$, $p < 0.001$, $\eta_g^2 = 0.20$ (Figure 2C,F). When standing up, participants underreported their actual heart rate to a greater extent than when lying down. There was a significant main effect of task on IAcc, $F(1,35) = 13.22$, $p < 0.001$, $\eta_g^2 = 0.075$, such that participants were more accurate in the heartbeat matching task ($M \pm SD = 0.76 \pm 0.15$ bpm) compared to the heartbeat counting task ($M \pm SD = 0.68 \pm 0.20$ bpm). There was no significant main effect of order ($p = 0.96$) and no significant interactions.

Participants were more confident when lying down

Confidence ratings were averaged over the six trials for each task and posture and analysed using the same 3-way mixed ANOVA. There was a significant main effect of posture, $F(1,35) = 10.92$, $p = 0.002$, $\eta_g^2 = 0.031$ (Figure 3A). Participants rated themselves as more confident at reporting their heart rate when lying down ($M \pm SD = 62 \pm 14$) compared to standing up ($M \pm SD = 57 \pm 14$). There was no significant main effect of task ($p = 0.27$) or order ($p = 0.39$). There was a significant interaction between posture and task, $F(1,35) = 6.60$, $p = 0.02$, $\eta_g^2 = 0.014$; however, none of the pairwise comparisons were significant. We also asked participants to rate on a scale from 0-100 how much they thought they could actually feel their heart when in each posture. Participants reported that they could feel their heart significantly better when lying down compared to standing up (paired sample t-test: $t(31) = 4.20$, $p < 0.001$; lying: $M \pm SD = 62 \pm 21$; standing: $M \pm SD = 49 \pm 19$; Figure 3B).

We used Spearman rank correlations to determine if there was any relationship between participants' confidence ratings, their rating of subjective feeling (i.e. how well they said they could feel their heart beating) and IAcc, for each posture and across both tasks. There was more correspondence between these measures for the heartbeat counting task compared to the heartbeat matching task (see Table 1). However, after correcting for multiple comparisons, only one relationship was significant: there was a significant positive

relationship between IAcc and ratings of subjective feeling in the heartbeat counting task when standing ($\rho=0.5$, $p=0.003$). There was also a significant relationship between both confidence and IAcc and also between ratings of feeling and IAcc in the heartbeat counting task when lying down (confidence: $\rho=0.42$, $p=0.01$; feeling: $\rho=0.42$, $p=0.02$) but these did not survive correction for multiple comparisons (alpha level = 0.006).

		Confidence	Feeling
Heartbeat Counting IAcc	Standing	0.30	0.49**
	Lying	0.42*	0.42*
Heartbeat Matching IAcc	Standing	-0.15	0.13
	Lying	0.07	0.30

Table 1. Correlation coefficients for correlations between IAcc and confidence ratings and subjective feeling ratings for the heartbeat counting task and heartbeat matching task when standing and lying. * $p<0.05$, uncorrected; ** $p<0.05$, corrected (alpha level =0.006).

Time estimation was more accurate using the matching task compared to counting

Time estimation accuracy (TAcc) was calculated as a control for IAcc to ensure that participants understood both tasks and because accurate time estimation is a potential confound of heartbeat counting. TAcc was calculated using the same method as IAcc for both tasks. A paired t -test showed that TAcc was significantly more accurate when using the matching task ($M\pm SD=0.83\pm 0.11$) compared to the counting task ($M\pm SD=0.77\pm 0.13$, $t(36)=2.69$, $p=0.01$, $\eta_g^2=0.064$; Figure 4).

Time estimation accuracy was not correlated with interoceptive accuracy using the matching task

In order to determine if there was a relationship between TAcc and IAcc, we calculated the correlation coefficients between these variables for both postures and for both tasks. As has frequently been reported, for the heartbeat counting task, TAcc and IAcc were significantly correlated, in both postures (standing: $r=0.38$, $p=0.02$; lying: $r=0.49$, $p=0.002$).

Significantly, however, for the heartbeat matching task there was a trend but the relationships were not significant (standing: $r=0.31$, $p=0.06$; lying: $r=0.27$, $p=0.11$; Figure 5).

DICUSSION

In this study, we developed and tested a novel method for measuring interoceptive accuracy, which aimed to address some of the confounds involved in the heartbeat tracking (heartbeat counting) tasks, which are the most commonly used tests of cardioception. In our novel task, participants were required to match the pace of a pulsing, on-screen, heart icon to the rhythm of their own heart. We tested participants on our heartbeat matching task, compared with the classic heartbeat counting task, when standing and lying down. Overall, interoceptive accuracy (IAcc) was higher for the heartbeat matching task than for the heartbeat counting task, confirming our hypothesis that participants would judge their heart rates more accurately using our novel heartbeat matching task compared to the standard heartbeat counting task. In line with previous research, IAcc measured by both tasks was lower when people were standing compared to lying down and participants expressed more confidence in their answers when lying than when standing. However, on average, participants did not accurately track the change in heart rate with posture for either task, as shown by no significant change in reported heart rate across postures (as calculated from the number of heartbeats they counted, or the pulsing heart rate that they matched). Similar findings by Ring and Brener (1996) have been interpreted to mean that the difference in IAcc between postures was driven by an increase in actual heart rate (when standing) rather than by more accurate detection of heart beats.

The standard heartbeat counting task has been criticised for a number of reasons. Our heartbeat matching task improves on the heartbeat counting task, by counteracting several of these confounds. Firstly, there is the possibility, when counting, that participants may simply lose concentration and that they may miss beats if their perception of their heartbeat fluctuates over time. Our task allows them as much time as they need to match their heart rate to the pulsing icon. Secondly, our task removes any possibility that an individual might arrive at an accurate number of heartbeats by estimating the length of the counting interval and using knowledge of their resting heart rate. A specific virtue of our

task is that it is also suitable for use with children and patient groups. In common with other heartbeat perception tasks, such as the heartbeat discrimination task, also known as the Whitehead task (Whitehead & Drescher, 1980), which requires participants to judge whether a train of stimuli is presented in synchrony with their heartbeat, our task requires the integration of an exteroceptive (visual) stimulus with an interoceptive (cardiac) modality but is much less demanding because participants are allowed as long as they wish to ‘feel’ their heart rate and match this to the visual stimulus. In the heartbeat matching task, participants aim to minimise the error between what they feel and what they see in order to identify a matching rhythm. This mirrors common predictive coding theories of perception and the *‘fluctuating, context sensitive, changes in the precision of sensory sampling’* that underpin interoceptive active inference (Allen, Levy, Parr, & Friston, 2019, p2). It may therefore provide a more implicit, yet intuitive and accurate, measurement of heartbeat perception.

Our results also show that time estimation accuracy (i.e. when participants were required to estimate seconds) was higher for our novel matching task than for the equivalent counting task. This suggests that both the matching tasks (heartbeat matching and matching seconds) have less measurement error, potentially through a reduction in the load on short term memory (e.g. there is no need to keep a mental record of heartbeats/seconds counted). As has previously been reported for counting tasks, we found that accuracy in time estimation significantly correlated with heartbeat counting. This correlation has previously been interpreted as indicating that the participant’s familiarity with counting in seconds confounds their heartbeat counting score. Potentially people simply count seconds in the heartbeat counting task (60bpm) and report this as their number of heartbeats, or they use their ability to estimate elapsed time and their knowledge of resting heart rate to accurately judge their heartbeat (Ring et al., 2015). Importantly, using our novel matching task, the correlation between time estimation accuracy and interoceptive accuracy was not significant, implying that our matching method is much less likely to be subject to this confound.

Although overall interoceptive accuracy was higher for the heartbeat matching task, a closer inspection of the dependent variables used to calculate interoceptive accuracy showed that for both tasks, participants’ reported heart rate remained the same in both postures despite a significant change in actual heart rate (lower when lying down. As a

result, our finding that IAcc for both tasks was higher when lying down compared to standing up indicates that the difference in IAcc between postures was driven solely by the change in actual heart rate. It is important to note that the higher IAcc for the heartbeat matching task compared to the heartbeat counting task was not driven by this same effect (i.e. by greater actual heart rate with no change in reported heart rate), because the difference in mean actual heart rate between the tasks was very small (1bpm) and there was a much larger difference in mean reported heart rate between tasks (9bpm). This finding more likely reflects better precision in the matching task compared to the counting task and therefore is a more accurate representation of IAcc.

The inability, in the heartbeat counting task, to track changes in heart rate induced by posture has been previously shown. This finding implies that reported heart rates in cardioception tasks may be driven by a prior belief about heart rate rather than by accessing the actual sensory information from the heart. However, an alternative explanation is that in the lying condition participants are better able to feel their heartbeat; as a result they become more accurate and the apparent constancy in reported heart rate is an artefact. This raises the question of what individuals are actually reporting when completing these tasks. We discuss these two possible interpretations in turn.

The first hypothesis suggests that participants are relying on prior beliefs to complete the heartbeat perception tasks. For example, it has been established that participants report far fewer heart beats when they are explicitly told to count only those heartbeats that they truly feel (and not to interpolate), which suggests that, to some extent, participants rely on some sort of prior rhythm to complete these tasks (Ehlers et al., 1995). A complication is that such priors might derive from the experience of feeling the heart beating when lying down. Indeed, this is the posture in which our participants reported that they could most strongly feel their hearts beating. Therefore, prior beliefs about our own heart rate may be learned from the repeated experience of lying in bed at night, when exteroceptive input is reduced such that the perception (even implicitly) of our heart beating is at its strongest. Alternatively, the prior might result from the experience of counting in seconds or watching a clock hand. This latter interpretation is supported by the correlation we found between time estimation accuracy and IAcc in the heartbeat counting task, which suggests that the better able people are to count seconds the better their

apparent performance in heartbeat counting. Importantly, however, the relationship between IAcc and time estimation accuracy was not significant in the heartbeat matching task. A further complexity in this study is that mean heart rate when lying down, and across both tasks, was around 60bpm, which makes it difficult to tease apart these potential sources of possible ‘priors’.

The second hypothesis is that participants were truly reporting the heartbeats they felt during these tasks, but that when lying down their heart rate was slower and stronger and therefore fewer heartbeats were missed compared to when standing. Moreover, when lying down, people have additional somatosensory input from the rear chest wall, which is in contact with the mat. In support of this, participants not only reported higher confidence when lying down compared to standing up, but they said that they could feel their hearts beating more clearly. When standing up they reported greater uncertainty in the perception of their heartbeats. Participants might then have been missing more beats when standing due to the increased speed of the heart and also their reduced certainty about its perception. Potentially, this suggests that, when they are standing up, individuals may be more inclined to rely on prior beliefs about their heart rate. We observed that participants had higher blood pressure when standing up compared to lying down. However, in contrast to previous findings, this increased blood pressure did not provide an advantage for heartbeat perception in our study (O’Brien, Reid, & Jones, 1998; Pollatos, Herbert, Kaufmann, Auer, & Schandry, 2007; Schandry & Bestler, 1995). According to this second hypothesis, IAcc when lying down may reflect the true representation of IAcc i.e. when participants were truly feeling their hearts beating.

More studies using this type of paradigm are now essential to resolve these conflicting hypotheses. It will be important, in future, to use computational modelling to disentangle the relative contribution of prior beliefs and subjective feeling to heartbeat perception. This will provide a more accurate representation of heartbeat perception, to separate out those who can really feel their heart from those who are relying on a prior rhythm and not feeling their heart in the moment.

A limitation of the current study is the relatively small sample size. We aim to understand how individual variability in heartbeat perception can predict a given phenotype, such as risk for affective disorders or impulsivity. Here we have reported that

on average participants did not modulate their reported heart rate with posture using the current tasks, however there were some individuals who clearly did. Larger sample sizes are needed to effectively capture individual variability in performance. Furthermore, by expanding the number of trials for each task, future studies will be in a position to consider the relationship between metacognitive awareness in the heartbeat counting and heartbeat matching tasks and the contrasting role that these dimensions of interoceptive ‘ability’ may play (Garfinkel, Tiley, et al., 2016). In addition, an individual’s ability to track modulations in heart rate across postures may be a more important predictor of other behaviours than their IAcc measured in a single posture, or indeed their IAcc measured when lying down rather than sitting (which is frequently used), if participants are better able to feel their heart in that posture. It is essential, therefore, that we not only establish more precisely what these methods are measuring but also that we aim to understand which interoceptive phenotypes and what dimensions of interoception are important for predicting other relevant behaviours (Manjaly et al., 2019).

A further limitation of our study is that we did not counterbalance the order of the tasks (although the order of posture was counterbalanced). Our concern was that participants might use their experience of the pulsing icon in the heartbeat matching task and employ this as a ‘prior’ when performing the heartbeat counting task. However, there is no clear reason why task order would affect our results and inferences.

A final limitation is that this task does not utilise signal detection theory to determine the sensitivity and specificity with which we are measuring heartbeat perception. Optimal psychophysical methods for perception should be able to distinguish between the true positive rate and false positive rate of perception. However, it is extremely difficult to measure the false positive rate of heartbeat detection (the rate of detecting a heartbeat when it is absent), because the heart beats continuously with relatively short interbeat intervals. Future research will aim to compare this heartbeat matching task to an adapted forced choice version to provide more complex analyses of perception to validate this method.

In conclusion, the current methods available to measure interoception are subject to criticism and there is a pressing need to develop novel interoception tasks in order to avoid reporting spurious associations with interoceptive ability in the literature. The current study

provides preliminary evidence for the utility of our novel heartbeat matching task as an improvement over the most frequently used heartbeat counting task, and a promising avenue of future research. The advantages of the heartbeat matching task include that it has less methodological confounds, therefore may more accurately represent participant's heartbeat perception, yet it is quick and easy to administer, suitable for small children, the elderly and patient groups.

FIGURES

Figure 1. Experimental protocol. Participants acclimatised to each posture before completing the heartbeat perception tasks for 3 minutes. The order in which participants assumed each posture was counterbalanced across participants. The order of task completion was always fixed such that participants completed the heartbeat counting task before the heartbeat matching task. This was to ensure the matching task did not bias participant's counting. Both tasks were completed twice: once in each posture. Blood pressure (BP) was measured prior to completing the tasks in each posture and heart rate was measured throughout using ECG. The time estimation tasks were completed at the end of the experimental protocol once seated.

Figure 2. Interoceptive accuracy (IAcc) increased when lying down for both heartbeat perception tasks. Boxplots showing the distribution of actual heart rate (bpm; A+D), guessed heart rate (B+E) and IAcc (C+F) across subjects from the heartbeat matching task (top panel, blue) and heartbeat counting task (bottom panel, pink) when participants were standing up (dark) and lying down (pale). Individual data points are overlaid. There was a significant mean decrease in heart rate across participants when lying down compared to standing ($p < 0.001$), however there was no significant difference in participant's matched or counted heart rate ($p = 0.796$). IAcc is the difference between these measures divided by their sum, therefore the significant increase in IAcc ($p < 0.0001$) seen when participants were lying down compared to standing was driven by changes in actual heart rate rather than guessed heart rate.

Figure 3. Participants could feel their heart beating more and were more confident when lying down. A) Distribution of subjective confidence ratings averaged over all trials for each participant for both heartbeat perception tasks and each posture. Overall confidence ratings were significantly higher when participants were lying down compared to standing up ($p=0.002$). There was a significant interaction between confidence ratings and task ($p=0.015$) however no pairwise comparisons were significant after correction for multiple comparisons. B) Participant's rated that they felt their heart more when lying down compared to standing up ($p<0.001$).

Figure 4. Time estimation accuracy was higher for the heartbeat matching compared to the heartbeat counting task. Distribution of TAcc scores for each participant for each heartbeat perception task. TAcc was significantly higher for the heartbeat matching task compared to the heartbeat counting task ($p=0.011$).

Figure 5. Correlations between IAcc and TAcc for both tasks and postures. Scatter plots showing the association between heartbeat matching TAcc and IAcc when standing (A) and lying (B) and between heartbeat counting TAcc and IAcc when standing (C) and lying (D). TAcc and IAcc were significantly correlated for the heartbeat counting task in both postures (standing: $r=0.38$, $p=0.02$; lying: $r=0.49$, $p=0.002$), but not for the heartbeat matching task (standing: $r=0.31$, $p=0.06$; lying: $r=0.27$, $p=0.11$).

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