Distinguishing between interoceptive abilities and the role of non-interoceptive influencing factors.

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ABSTRACT

The number of studies investigating interoception and its relationships with other factors has increased dramatically in recent years. However, the tasks used to measure interoception are known to require improvement. Further to this, distinctions are starting to be made regarding different types of interoceptive ability as opposed to a single interoceptive factor. This thesis attempts to investigate the relationships between different forms of interoceptive ability, as well as emphasising the importance of implementing control measures when using these tasks to relate one's performance to other abilities such as proprioception. We demonstrate that relationships between the three measures of interoceptive ability (accuracy, sensibility and awareness) are inconsistent within and between tasks. This highlights the importance of not assuming that one interoceptive task indexes all interoceptive abilities. Evidence is presented demonstrating that a combination of control variables, including our tactile perception control task, can be used to predict performance on two heartbeat interoception tasks. We therefore emphasise the importance of using control variables when implementing these tasks as it is clear that the tasks do not purely index interoceptive ability. Finally, we show the emergence of a significant relationship between interoceptive and proprioceptive accuracy when implementating the previously highlighted control measures.

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INTRODUCTION

Interoception, described as an awareness of the body's internal state (Craig, 2002; 2003; 2009), has attracted a vast amount of attention in recent years. A growing body of evidence has suggested links between interoception and a number of different abilities including learning and decision making (Werner, Jung, Duschek, & Schandry, 2009), emotional processing (Fustos, Gramann, Herbert, & Pollatos, 2013; Herbert, Pollatos, Flor, Enck, & Schandry, 2010; Schandry, 1981), and social cognition (Quattrocki & Friston, 2014; Seth, 2013). As a result, importance should be placed on determining the reliability of measures of interoception that are commonly used within the literature. There is a wide selection of tasks that are used interchangeably as an index of interoceptive ability. Thus, validation of these tasks and their relationships with one another is an urgent step for the research field.

Interoception tasks generally measure an individual's accuracy in perceiving a particular internal bodily signal. This can be a challenge in particular interoceptive domains as an objective measure of the signal is needed in order to compare it with the participant's subjective perception of the signal. Signals often included in the definition of interoception are cardiac, respiratory and gastric perception. The perception of cardiac signals is commonly used as the participant's heartbeat can easily be recorded. Examples of tasks in the cardiac domain include the heartbeat counting task (HCT; Schandry, 1981) and the heartbeat discrimination task (HDT; Katkin, Reed, & Deroo, 1983; Whitehead, Drescher, Heiman, & Blackwell, 1977). In the HCT, participants are asked to count the number of times they feel a heartbeat during a series of time intervals and their response is compared to the actual number of heartbeats in order to obtain a score. In the HDT, participants are asked to indicate whether they think a series of tones are synchronous or asynchronous with their heartbeat. Less common approaches include respiratory perception, which can be measured using tasks such as the inspiratory resistance detection task (Garfinkel et al., 2016a), and gastric perception including tasks such as the water load test (Koch, Hong, & Xu, 2000).

The literature commonly relies on the assumption that interoception is a unitary ability across bodily signals. Studies frequently measure an individual's accuracy in perceiving a particular bodily signal and use it as a measure of their general interoceptive accuracy. However, studies investigating this assumption are inconclusive. Some studies have reported correlations between performance on interoceptive tasks in different domains, for example Herbert, Muth, Pollatos and Herbert (2012) found moderate correlations between cardiac and gastric perception. Contrastingly, there are a large number of studies reporting no relationship between these tasks, from the early work of Steptoe and Vögele (1992), who revealed no relationship between participants' ability to identify high blood pressure, shortness of breath or sweaty hands, to more recent reports of poor correlations between interoceptive accuracy tasks in cardiac and respiratory domains (Garfinkel et al., 2016a; Pollatos, Herbert, Mai, & Kammer, 2016). However, differing task demands should not be overlooked and it has been shown that when task demands are well matched, relationships across different domains emerge (Whitehead & Drescher, 1980). Considering the above findings, it would be problematic to assume that interoceptive accuracy is consistent across different domains. This thesis, therefore, focuses purely on the cardiac domain of interoception whilst investigating the relationships between different interoceptive abilities.

A particularly poignant finding for the assessment of relationships between supposed interoception tasks is the low correspondence between tasks indexing interoceptive accuracy, the ability to perceive an internal bodily signal, within the same domain. Phillips, Jones, Rieger and Snell (2003) reported no significant relationship between performance on the HCT and HDT. A further study demonstrating the absence of this relationship is Schulz, Lass-

Hennemann, Sütterlin, Schächinger, and Vögele (2013) who found no correlation between performance on the HCT and two versions of the HDT. They used the previously described auditory version of the HDT and a visual version in which participants judged if the presentation of a red circle was synchronous or asynchronous with their heartbeat. They did, however, find a relationship between the two versions of the HDT. Contrasting to this, Knoll and Hodapp (1992) found a high degree of correspondence between HCT and HDT at the extreme levels of performance but a very poor level of correspondence for participants in the middle range of performance. Further evidence in support of a relationship comes from Hart, McGowan, Minati and Critchley (2013) who reported a significant positive correlation between the HCT and HDT ($r = .36$). Nevertheless, there is a widespread lack of consistency in the literature regarding whether these tasks relate to a unitary ability of interoceptive accuracy. This is potentially problematic for cases in which one of the two tasks is used as an index of cardiac interoceptive accuracy. In this thesis we investigate the relationship between HCT and HDT to bring clarity to the debate within the literature and highlight whether using these measures interchangeably should be a concern.

In addition to the abilities typically classified as interoception such as cardiac and respiratory perception, there is debate as to whether proprioception, the awareness of one's body in space, should be considered interoceptive. Whether proprioceptive accuracy is distinct from interoceptive accuracy is undetermined, with mixed consensus in definitions of interoception and studies investigating whether accuracy in the interoceptive domain is related to accuracy in the proprioceptive domain. Early theories have regarded interoception and proprioception as distinct abilities, with Sherrington (1906) partitioning the senses into interoception, proprioception and exteroception. Indeed, previous studies have reported the absence of a relationship between interoceptive and proprioceptive abilities (Ferentzi et al., 2018). However, some researchers have included proprioception in their definition of interoception. For example, Vaitl (1996) defined interoception as “a general concept, which includes two different forms of perception: proprioception and visceroception”, the latter of which refers to the perception of bodily signals arising specifically from internal organs. Cameron’s (2001) definition describes interoception as the perception of “the afferent information that arises from anywhere and everywhere within the body – the skin and all that is underneath the skin, e.g., labyrinthine and proprioceptive functions – not just the visceral organs”. Leading on from this, Murphy, Catmur and Bird (2017a) reported a relationship between interoceptive accuracy (as measured by the HCT), and muscular awareness (as measured by a force matching task in which participants had to match the weight of a target bucket by adding weight to a test bucket), an ability commonly thought of as proprioceptive. Whilst proprioceptive accuracy can be measured via a number of different methods, one commonly used measure is a position matching task whereby a participant must match the position of a part of their body in the absence of visual information (Goble, 2010). Thus, we have developed a version of this task for the purpose of indexing proprioceptive accuracy. Using this task, we aim to further qualify the relationship between interoceptive and proprioceptive abilities.

Another question surrounding the current measures of interoception is whether the ability used to complete the task is in fact interoceptive. This is particularly relevant for the most commonly used domain of cardiac perception, where tasks have been found to be contaminated by the influence of non-interoceptive processes (Desmedt, Luminet, & Corneille, 2018). There are a number of factors that are thought to contribute to performance on heartbeat perception tasks. Exteroception, the perception of external stimuli such as touch (Sherrington, 1906), is thought to impact task performance. In the case of many interoceptive signals, inferences about the internal state of the body can be made using the exteroceptive signals that accompany them. An individual's tactile sensitivity is thought to contribute to their heartbeat perception (Khalsa, Rudrauf, Sandesara, Olshansky, & Tranel, 2009a), whereby a pulse can be detected via exteroceptive touch receptors. Similarly, a number of physiological factors have been found to impact the detection of the heartbeat signal. These include Body Mass Index (BMI; Rouse, Jones, & Jones, 1988), systolic blood pressure (O'Brien, Reid, & Jones, 1998), and resting heart rate and heart rate variability (Knapp-Kline & Kline, 2005). Further to these factors that affect heartbeat perception in general, there are a number of psychological factors which can impact performance on the HCT specifically. These include knowledge of resting heart rate (Brener & Ring, 2016; Ring & Brener, 1996; Ring, Brener, Knapp, & Mailloux, 2015; Windmann, Schonecke, Fröhlig, & Maldener, 1999) and time estimation abilities (Murphy, Brewer, Hobson, Catmur & Bird, 2018). As the cardiac measures remain the most commonly used interoception tasks, it is important that non-interoceptive factors are further explored in order to determine their contribution to scores on the heartbeat perception tasks.

It is thought that controlling for both the physiological and psychological non-interoceptive factors that have been found to impact performance on the HCT and HDT produces a more 'pure' measure of interoception. Indeed, it has been found that this approach is beneficial when relating performance on the HCT to a common proxy measure of interoception (Murphy et al., 2018). In this case, a relationship between performance on the HCT and the Toronto Alexithymia Scale (TAS-20; Bagby, Taylor, & Parker, 1994) was only found to emerge once the non-interoceptive variables were controlled for. However, this analysis overlooked the contribution of tactile sensitivity in the perception of heartbeat (Khalsa, Rudrauf, Sandesara, Olshansky, & Tranel, 2009a). The relationship between tactile sensitivity and the HDT has previously been investigated (Knapp, Ring, & Brener, 1997) but has not yet been used in conjunction with either the HDT or HCT as a control variable. This is necessary to determine whether controlling for tactile sensitivity alters the relationships of the HCT or HDT. This thesis therefore implements a number of control variables, including a tactile perception control task, whilst investigating the heartbeat perception tasks and their relationships with other variables. To further this research, we apply these control measures to the relationship between interoception and proprioception as no studies at present have controlled for non-interoceptive factors in the exploration of the relationship between these two abilities. Importantly, it may be that the control factors are relevant for proprioceptive research in general. For example, increased age is known to be a factor for decreased proprioceptive ability (Skinner, Barrack & Cook, 1984). This thesis therefore considers the role of control variables for both interoceptive and proprioceptive abilities.

Heretofore we have focused purely on interoceptive accuracy, but there are other aspects of interoceptive ability to be considered. Garfinkel, Seth, Barrett, Suzuki, and Critchley (2015) have proposed a three-dimensional model of interoceptive ability. The model proposes a distinction between interoceptive sensitivity, sensibility and awareness: sensitivity refers to an objective measure of an individual's ability to perceive internal bodily states, indexed through performance on perceptual tasks; sensibility relates to an individual's subjective beliefs of the extent to which they can perceive interoceptive signals; awareness is a metacognitive measure of interoceptive ability which indexes the accuracy of an individual's sensibility for sensitivity. The three dimensions were all found to be distinct and dissociable in a sample of 80 participants. The validity of this distinction across all measures of interoception is of clinical significance as it may be that certain conditions have different relationships with the three forms of interoceptive ability. For example, it has been proposed that anxiety is related to poor interoceptive awareness due to opposing relationships with accuracy and sensibility (Garfinkel et al., 2016b). Being able to distinguish the specific relationships with each form of interoceptive ability may inform us on the mechanisms by which the conditions occur. Alternatively, if it is in fact possible to conflate the abilities into one general interoceptive ability then this would allow researchers to investigate the involvement of interoception in clinical conditions by employing one of the many tasks used commonly in the literature.

If Garfinkel et al.'s (2015) model is applied to the HCT, sensitivity is indexed through the individual's accuracy score, sensibility through confidence ratings on each trial, and awareness as a correlation between score and confidence on each trial. However, alternative methods for indexing interoceptive sensibility include self-report questionnaires featuring items relating to an individual's beliefs about their ability to perceive interoceptive signals. Garfinkel et al. (2015) used the awareness subscale of the Body Perception Questionnaire (Porges, 1993) to index interoceptive sensibility. This questionnaire is comprised of 45 statements relating to awareness of body processes. Participants must indicate on a scale from 1-5 how much they agree with each statement. Examples include "during most situations I am aware of how fast I am breathing" and "during most situations I am aware of how hard my heart is beating". However, this measure can be criticised for its focus on an individual's tendency to pay attention to bodily signals rather than their accuracy in perceiving them. More recently, the Interoceptive Accuracy Scale (IAS, Murphy et al., in press-a) has been developed. It consists of 21 statements relating to an individual's ability to accurately perceive bodily signals, for example "I can always accurately perceive when my heart is beating fast" and "I can always accurately perceive when my blood sugar is low". Participants are asked to indicate on a scale from 1-5 how much they agree with each statement. This measure more explicitly indexes a participant's beliefs regarding how accurately they can perceive bodily signals rather than their tendency to pay attention to them.

Leading on from this distinction between accuracy and attention within interoceptive ability, Murphy, Catmur and Bird (in press-b) have created a 2x2 factorial model which sets a distinction between what is measured (accuracy or attention) and how it is measured (performance or beliefs). This model is displayed in Figure 1. Within the model, tasks measuring objective performance in the perception of signals such as the HCT and HDT would fall under the performance-accuracy category, and self-report measures detailing the individual's beliefs regarding their accuracy such as confidence ratings or the IAS would fall under the beliefs-accuracy category. In terms of attention, experience sampling methods can be used as a measure of performance and the BPQ as a measure of beliefs. For both accuracy and attention, awareness can be calculated by comparing beliefs to performance within the type of measurement. This thesis will focus on interoceptive accuracy; therefore the IAS has been selected over the BPQ. As such, this thesis refers to accuracy as the individual's subjective performance on the interoceptive perception tasks, sensibility as the individual's beliefs regarding how accurate they are at perceiving interoceptive signals, and awareness as the relationship between their sensibility and accuracy.

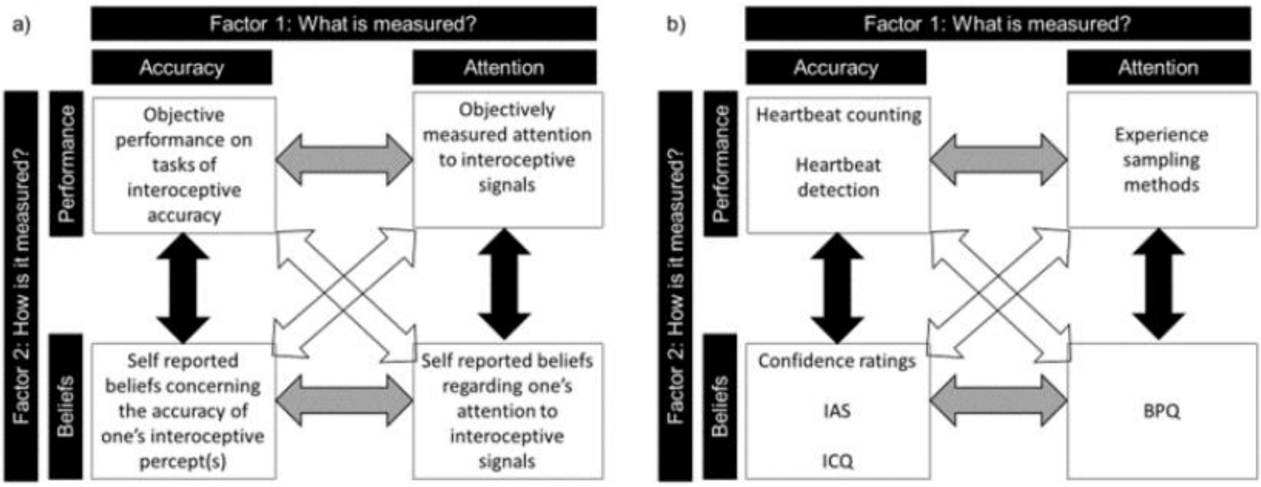

Figure 1. Taken from Murphy et al. (in press-b). A model of interoceptive ability, in which A describes the different interoceptive abilities and B states how these abilities can be measured.

The questions of whether interoceptive ability is unitary, the distinction between types of interoceptive ability, and whether interoceptive tasks index purely interoceptive abilities are important considerations for research in the field of interoception. If they remain unanswered, the literature will continue to base research on unconfirmed assumptions thus potentially invalidating the conclusions drawn. This thesis addresses these points by conducting correlation analyses between different measures of interoceptive ability and controlling for variables previously determined to impact performance on interoceptive tasks. Chapter 1 tests two hypotheses: first, that interoceptive accuracy, sensibility and awareness are distinct; second, that accuracy, sensibility and awareness are correlated across the HCT and HDT. This will make an important contribution to the literature by informing researchers whether the distinctions made between accuracy, sensibility and awareness are valid, and if certain tasks can be used interchangeably in interoception research. Leading on from this, Chapter 2 first quantifies the extent to which a battery of non-interoceptive factors account for variance in the performance on the HCT and HDT and then verifies whether controlling for these factors alters the relationships observed in Chapter 1. The former is important for informing the literature on which control variables are important to consider when attempting to index interoceptive abilities. The latter aims to clarify whether correlations are only found between the HCT and HDT or different measures of interoceptive ability when non-interoceptive factors have been accounted for. The final chapter of this thesis tests the hypothesis that interoceptive accuracy and proprioceptive accuracy are related and investigates the impact of controlling for certain factors on the relationship observed. This will demonstrate whether the use of control variables can clarify the conflicting opinion in the literature regarding the relationship between interoception and proprioception. All variables used in this thesis are listed in Figure 2.

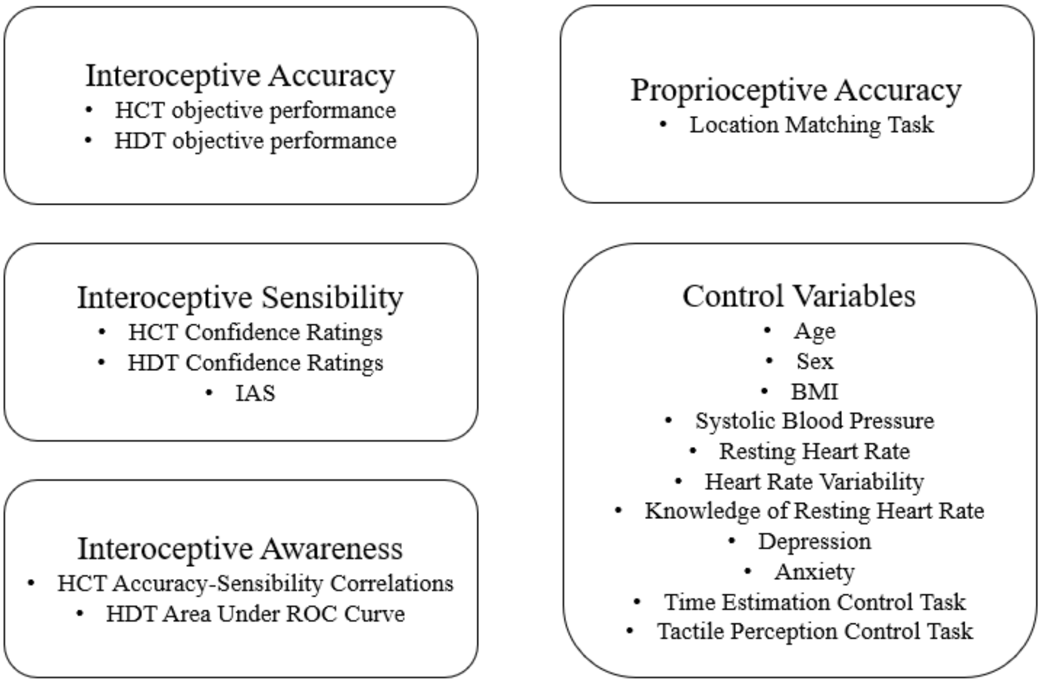

Figure 2. A list of the variables used throughout this thesis and the tasks used to index them.

CHAPTER 1 – CURRENT MEASURES OF INTEROCEPTION

1.1 INTRODUCTION

Despite the wide variety of interoceptive measures currently used in the literature, inconsistent correlations have been found between them. This chapter focuses on the relationships between measures devised from the HCT, HDT, and the IAS.

As previously discussed, there are a number of different interoceptive abilities that can be indexed when studying interoception. Garfinkel et al. (2015) proposed a three-dimensional model which separates interoceptive ability into sensitivity, sensibility and awareness. In this model, sensitivity refers to the individual's objective ability to perceive interoceptive signals, sensibility refers to their beliefs regarding how accurately they can perceive interoceptive signals, and awareness refers to how well their sensibility predicts their sensitivity. Garfinkel et al. (2015) indexed interoceptive sensitivity as the objective performance on both the HCT and HDT, interoceptive sensibility by the BPQ and task confidence ratings, and interoceptive awareness by the Receiver Operating Characteristic (ROC) curve produced by the HDT data in addition to confidence-accuracy correlations from the HCT data. These abilities were found to be distinct and dissociable in a dataset of 80 participants. However, it should be noted that when sensibility is indexed using confidence ratings, a relationship is more often found between sensibility and accuracy (e.g., Forkmann et al., 2016). Indeed, Murphy et al. (in press-a) report a significant relationship between interoceptive awareness and confidence ratings, in addition to a significant relationship between interoceptive awareness and HCT-Accuracy, thus bringing into question the distinctions made by Garfinkel et al. (2015). It is important to determine the validity of this model as the distinctions are being applied in clinical research to investigate which interoceptive abilities are related to a number of clinical conditions (e.g. Garfinkel et al., 2016b). If it is possible to conflate the three proposed abilities, this would allow researchers to use only one of the many common measures of interoception. However, if the distinction is valid, it emphasises the importance of not using the tasks interchangeably to index a general interoceptive ability. It would also allow us to learn more about the mechanisms of the conditions studied if we were able to determine exactly which interoceptive ability is related.

A new approach by Murphy et al. (in press-b) proposes a distinction between interoceptive accuracy, the objective measure of a participant's ability to perceive interoceptive signals, and interoceptive attention, the tendency of the participant to attend these signals. Through this distinction, Murphy et al. (in press-b) have proposed a 2x2 factorial model which separates out what is measured (accuracy or attention) and how it is measured (performance or beliefs). Awareness can be calculated for both accuracy and attention by comparing beliefs to performance within the type of measurement. This thesis selectively focuses on interoceptive accuracy as opposed to interoceptive awareness, and hence applies Garfinkel et al.'s (2015) distinction specifically to accuracy. Here, interoceptive accuracy, in place of Garfinkel et al.'s (2015) interoceptive sensitivity, is indexed by objective performance on the HCT and HDT. Interoceptive sensibility is indexed using confidence ratings across all trials on the HCT and HDT, in addition to the IAS. Interoceptive awareness is reported as correlations between accuracy and sensibility on the HCT and the area under the ROC curve produced using data from the HDT. The former calculation of awareness is used for the HCT as scores are obtained for both accuracy and sensibility. However, the latter is required for the HDT as it is a two-alternative forced choice task in which the output contains hits, misses, false alarms and correct rejections as opposed to scores.

A further consideration of this chapter is whether the same interoceptive ability correlates across heartbeat perception tasks. This is a relevant analysis for the advancement of the literature as HCT and HDT accuracy scores are often used interchangeably as an index of interoceptive accuracy. An implicit assumption is therefore made that these abilities are correlated. Early reports by Knoll and Hodapp (1992) suggested that at the extreme levels of performance a strong correlation exists between accuracy on the HCT and HDT, but this does not hold for participants in the middle range of performance. A significant correlation of .36 between HCT-accuracy and HDT-accuracy has also been reported (Hart et al., 2013). However, studies that have correlated these two accuracy scores have produced mixed findings. A study by Philips et al. (2003) tested participants on both the HCT and HDT. No significant relationship was found between the two interoceptive accuracy measures. In addition, Schulz et al. (2013) conducted a study in which participants completed the HCT, an auditory version of the HDT where tones and heartbeats were presented either synchronously or asynchronously, and a visual version of the HDT where the tones were substituted for the presentation of a red circle. Whilst a relationship was found between the two versions of the HDT (r = .63), suggesting that these tasks index the same ability, no relationship was found between HCT and the auditory HDT (r = .22), nor the HCT and visual HDT (r = .08). Considering these inconsistent findings, it is important to establish whether or not accuracy on the HCT and HDT correlate before using them interchangeably in future studies as a measure of interoceptive accuracy. Whilst these studies have focused on interoceptive accuracy, this is also applicable for the other measures of interoceptive ability that are indexed from the HCT and HDT: sensibility and awareness.

In addition to the measures obtained from the HCT and HDT, questionnaire measures are commonly used to index interoception. Questionnaires such as the IAS fall under the category of interoceptive sensibility as they relate to an individual's beliefs regarding their interoceptive ability. Through validating the IAS, Murphy et al. (in press-a) investigated correlations between the IAS and HCT-accuracy, in addition to previously established self-report measures of interoceptive sensibility. When investigating the relationship with the HCT, they found a significant correlation between IAS and accuracy performance (r = .27) but failed to find a significant relationship with the measure of interoceptive sensibility taken during the HCT, confidence ratings ($r = .03$). However, a replication study within their paper revealed a significant correlation between confidence ratings and the IAS ($r = .41$). At present, the relationship between the IAS and HDT has yet to be reported. This thesis addresses these gaps in the literature by investigating the relationships between the IAS and sensibility measures from both the HCT and HDT.

This chapter investigates the relationships between accuracy, sensibility and awareness within the two heartbeat perception tasks in order to test the hypothesis that they are dissociable abilities. Based on previous work by Garfinkel et al. (2015) we predict that, for both the HCT and HDT, there will be no correlation between accuracy, sensibility and awareness scores. Such a pattern of results would be in line with Garfinkel et al.'s (2015) proposed model of interoceptive ability. If, however, we were to observe correlations between these abilities this would force us to critically question the proposal that they are distinct. In addition, we investigate the relationships between these abilities across tasks in order to quantify their correlations and determine whether it is valid to use them interchangeably. A correlation between accuracy as indexed by the HCT and HDT, if found, would justify the interchangeable use of the HCT and HDT. Due to this frequent interchangeable use in the literature, we predict that there will be significant correlations between HCT-Accuracy and HDT-Accuracy. The same predictions are made for sensibility and awareness. It should be noted that if significant correlations are not found, this would bring into question the assumption that scores on the HCT and HDT can be used interchangeably as indices of interoceptive accuracy, sensibility and awareness. Finally, in the exploration of measures of sensibility, we hypothesise that significant correlations will be found between the IAS and confidence ratings on the HCT and HDT. If this is the case, it would strengthen the use of the IAS as a measure of interoceptive sensibility.

1.2 METHODS

1.2.1 Participants

We recruited 47 university students (age: min = 18 years, max = 32 years, M = 20.70, SD = 2.38) from the University of Birmingham. Of these participants, 9 were male, 34 were female and 1 participant preferred not to answer. All volunteers were screened for and excluded on the basis of cardiovascular disease and neuropsychological conditions. Participants were all fluent in English and had corrected-to-normal vision. They were told to avoid alcohol 24 hours prior to the study and caffeine 6 hour prior to the study. Informed consent was given by all participants, who were reimbursed for their time with either course credits or payments of £8 an hour. The study was approved by the STEM Ethics Committee at the University of Birmingham (ERN_16-0281AP4).

1.2.2 Design

Participants completed all of the tasks during the same test session. The tasks were completed in the following order: HDT, HCT, IAS. Control tasks and measurements were conducted at the end of the session, data from which are discussed in Chapter 2 (Experiments 2-4). The dependent variables were HDT performance (Accuracy, Sensibility, Awareness), HCT performance (Accuracy, Sensibility, Awareness), and IAS score.

1.2.3 Materials

The HDT and HCT were programmed in MatLab using Psychophysics Toolbox Version 3 (Brainard, 1997). A Contec CMS50D+ pulse oximeter clipped to the participant's middle finger on their non-dominant hand was used to record their heart rate during the heartbeat tasks.

1.2.4 Procedure

Participants completed the tasks in a quiet testing cubicle with soft white noise of approximately 65 decibels played through headphones.

1.2.4.1 Heartbeat Discrimination Task

Participants were sat at a desk with a pulse oximeter clipped to the middle finger of their non-dominant hand. They were told to sit upright with their hands resting still on the table and instructed to close their eyes and not use their fingers to feel for their pulse during the task. In each trial, they heard 10 tones which were either synchronous or asynchronous with their heartbeat. They were then asked to indicate whether they thought the tones were synchronous or asynchronous with their heartbeat, and to rate their confidence on a continuous sliding scale ranging from "not confident at all" to "very confident". The position chosen on the scale was then translated into a confidence rating out of 100. Participants completed 40 trials, with 20 synchronous trials and 20 asynchronous trials presented in a random order.

As per Garfinkel et al. (2016a), the conditions were generated by playing a tone 250 ms after the R-wave, an upward deflection within the QRS wave of a heartbeat, for the synchronous condition and 550 ms after the R-wave for the asynchronous condition. This was determined by the assumption that there is an average delay of 250 ms between the R-wave and the arrival of the pressure wave at the finger as detected by the pulse oximeter (Payne, Symeonides, Webb & Maxwell, 2006). Thus, the synchronous condition tone occurred at the beginning of the pressure wave and the asynchronous condition tone after a 300 ms delay.

1.2.4.2 Heartbeat Counting Task

Participants were sat at a desk with a pulse oximeter clipped to the middle finger of their non-dominant hand. They were asked to count the number of heartbeats they felt during a given time interval. During this interval, they were told to sit upright with their eyes closed and their hands resting still on the table. Participants were told that they should not use their fingers to feel for their pulse, nor should they count seconds or guess. The task was completed across four different time intervals of varying length, each of which were signified by a tone played at the start and the end of the interval. The lengths of the time intervals were counterbalanced across three tasks- the HCT and two control tasks which are discussed in the subsequent chapter. The three sets of time intervals were as follows: 22, 32, 42, 97 s; 25, 35, 45, 100 s; 28, 38, 48, 103 s. The four different time intervals occurred in a random order for each participant. Participants were asked to enter the number of heartbeats they had felt during each time interval and indicate their confidence in their response on a continuous sliding scale ranging from “not confident at all” to “very confident”. The position chosen on the scale was then translated into a confidence rating out of 100. They were told that if they could not feel any heartbeats then they should put zero as their answer.

1.2.4.3 Interoceptive Accuracy Scale

Participants completed the IAS, a questionnaire consisting of 21 statements relating to the individual’s ability to accurately perceive bodily signals. Statements include “I can always accurately perceive when my heart is beating fast” and “I can always accurately perceive when my blood sugar is low". The full list of statements is included in Appendix A. Responses were given in the form of agreement ratings on a scale ranging from 1 to 5, where 1 represented 'Strongly Disagree' and 5 represented 'Strongly Agree'. Scores were calculated as a sum of the participants' responses, with 105 being the maximum possible score. This was taken as a measure of interoceptive sensibility where the maximum score reflected the highest possible interoceptive sensibility.

1.2.4.4. Control Tasks and Measurements

The procedure for this section of the study is detailed in Chapter 2 as the data were not analysed in this chapter.

1.3 DATA ANALYSIS

1.3.1 Score Calculations

1.3.1.1 Heartbeat Discrimination Task

For each individual, HDT-Accuracy was indexed using d prime (d'), a measure of discriminability calculated with the hit (H) and false alarm (FA) rates of an individual's performance ($d' = z(H)-z(FA)$). A higher score indicates that the signal, in this case heartbeat, could be more readily detected. HDT-Sensibility was indexed using the average confidence ratings for each trial. For HDT-Awareness the participant's ROC curve was created by plotting hit rate against false alarm rate at the different confidence ratings. The integral of the ROC curve, which provided the area under the curve, was used to index HDT-Awareness. The greater the area under the curve, the greater the interoceptive awareness.

1.3.1.2 Heartbeat Counting Task

Scores for the HCT were calculated using the following formula: SUM(1–(|Objective measure – participant's estimate|/Objective measure)) x 100. This allowed for a range of scores between 0 and 400 across the four time intervals, with 400 reflecting a perfect score. The participants' scores were taken as measures of HCT-Accuracy with higher scores indicating higher levels of interoceptive accuracy. HCT-Sensibility was indexed using the average confidence rating across the 4 trials, and HCT-Awareness as the correlation between the score and confidence rating on each trial.

1.3.2 Exclusions

Data on the HDT from 8 participants were removed due to the fact that they experienced 10 or more trials in which 3 or more of the 10 tones were timed incorrectly. This was identified through a discrepancy check incorporated into the task's code. For 12 other participants, their score was created using only the trials where fewer than 2 tones were timed incorrectly, resulting in scores comprised of data from 38 trials for 4 participants, 37 trials for 5 participants, 36 trials for 1 participant, 35 trials for 1 participant and 34 trials for 1 participant. Heartbeat data from 3 participants was lost due to a malfunction with the pulse oximeter. The sample size for each specific analysis is detailed in the results section.

1.3.3 Descriptive Statistics

Scores on each of the variables (HDT performance (Accuracy, Sensibility, Awareness), HCT performance (Accuracy, Sensibility, Awareness), and IAS score were calculated for each participant, descriptive statistics for which are presented in Table 1. A square transform was applied to the variable HDT-Sensibility and a cube transform to HCT-Awareness in order to correct for deviations from the normal distribution. All other variables returned a non-significant Kolmogorov–Smirnov test indicating that they did not significantly deviate from a normal distribution. Z-scores were then computed for all variables to allow for direct comparison.

Table 1

Descriptive statistics for the HCT, HDT and IAS (untransformed and transformed data)

Variable	N	Mean	SD	Skew	Kurtosis
HCT-Accuracy	44	212.47	107.86	-.18	-.91
HCT-Sensibility	44	47.06	21.25	-.02	.94
HCT-Awareness	42	0.31	0.61	-.62	-.96
HCT-Awareness (cube transform)	42	3.52	2.88	.13	-1.59
HDT-Accuracy	36	0.18	0.50	.16	-.08
HDT-Sensibility	36	58.94	12.50	-.85	4.51
HDT-Sensibility (square transform)	36	3625.67	1392.87	.82	3.25
HDT-Awareness	34	0.51	0.03	-.07	.71
IAS	44	78.93	10.62	-.12	-.75

1.3.4. Analyses

Pearson's correlations were conducted to investigate the relationships between the three measures of interoceptive ability within the HCT and HDT respectively, in addition to the relationships between the different measures of interoceptive accuracy, sensibility and awareness across tasks. Significant relationships are displayed in Figure 3.

For analyses where no significant correlation was found, a further correlation analysis was employed within a Bayesian framework using JASP (JASP Team, 2018) in order to assess whether it is accurate to claim that there is no relationship between the two variables. Bayes Factors (BF_{01}), which provide a ratio of the likelihood for the observed data under the null hypothesis compared to the alternative hypothesis (Dienes, 2016), are reported. Values of 3-10 and 1-3 are taken as moderate and anecdotal evidence for the null hypothesis respectively (Lee & Wagenmakers, 2014).

1.4 RESULTS

1.4.1 Correlations between HCT measures

Within the HCT measures, a significant correlation was found between HCT-Sensibility (M = 47.06, SD = 21.25, N = 44) and HCT-Accuracy (M = 212.47, SD = 107.86) ($r(41) = .34$, $p = .022$) and HCT-Sensibility (M = 49.31, SD = 18.99, N = 42) and HCT-Awareness (untransformed data: M = 0.31, SD = 0.61; transformed data: M = 3.52, SD = 2.88) ($r(44) = -.35$, $p = .025$). No significant correlation was found between HCT-Accuracy (M = 220.74, SD = 102.90, N = 42) and HCT-Awareness (untransformed data: M = 0.31, SD = 0.61, N = 42; transformed data: M = 3.52, SD = 2.88, N = 42): $r(41) = -.19$, $p = .221$. The BF_{01} value for the correlation between HCT-Accuracy and HCT-Awareness was 2.53, providing anecdotal evidence in support of the null hypothesis that the variables are not related.

1.4.2 Correlations between HDT measures

Within the HDT measures, significant correlations between HDT-Accuracy (M = 0.19, SD = 0.44, N = 34) and HDT-Awareness (M = 0.51, SD = 0.03) ($r(33) = .64$, $p < .001$) and HDT-Sensibility (untransformed data: M = 57.62, SD = 11.34, N = 34; transformed data: M = 3445.25, SD = 1146.91) and HDT-Awareness (M = 0.51, SD = 0.03) ($r(33) = .42$, $p = .013$) were found. The correlation between HDT-Accuracy (M = 0.18, SD = 0.50, N = 36) and HDT-Sensibility (untransformed data: M = 58.94, SD = 12.50; transformed data: M = 3625.67, SD = 1392.87) was non-significant: $r(35) = -.14$, $p = .441$. Further, the BF_{01} value for the relationship between HDT-Accuracy and HDT-Sensibility was 3.48, providing moderate evidence in support of the null hypothesis that HDT-Accuracy and HDT-Sensibility are not correlated.

1.4.3 Correlations between measures of interoceptive accuracy

No correlation was found between the two measures of interoceptive accuracy, HDT-Accuracy (M = 0.18, SD = 0.50, N = 36) and HCT-Accuracy (M = 219.75, SD = 109.52): $r(35) = .02$, $p = .909$. The BF_{01} value of 4.79 provided moderate evidence in support of the null hypothesis.

1.4.4 Correlations between measures of interoceptive sensibility

A significant correlation was found between HDT-Sensibility (untransformed data: M = 58.94, SD = 12.50, N = 36; transformed data: M = 3625.67, SD = 1392.87) and HCT-Sensibility (M = 48.50, SD = 21.25): $r(35) = .70$, $p < .001$. In addition, the correlation between IAS score (M = 78.36, SD = 10.85, N = 36) and HDT-Sensibility was significant (untransformed data: M = 58.94, SD = 12.50; transformed data: M = 3625.67, SD = 1392.87) : $r(35) = .39$, $p = .020$. No correlation was found between IAS score (M = 78.93, SD = 10.62, N = 44) and HCT-Sensibility (M = 47.06, SD = 21.25): $r(43) = .09$, $p = .569$. The BF_{01} value for the relationship between IAS score and HCT-Sensibility was 5.55, providing moderate evidence in support of the null hypothesis.

1.4.5 Correlations between measures of interoceptive awareness

The correlation between the two measures of interoceptive awareness, HDT-Awareness (M = 0.51, SD = 0.03, N = 33) and HCT-Awareness (untransformed data: M = 0.38, SD = 0.60; transformed data: M = 3.88, SD = 2.93), was non-significant: $r(32) = -.07$, p

= .720. The BF_{01} value of 4.34 indicated that there is moderate evidence in support of the null hypothesis.

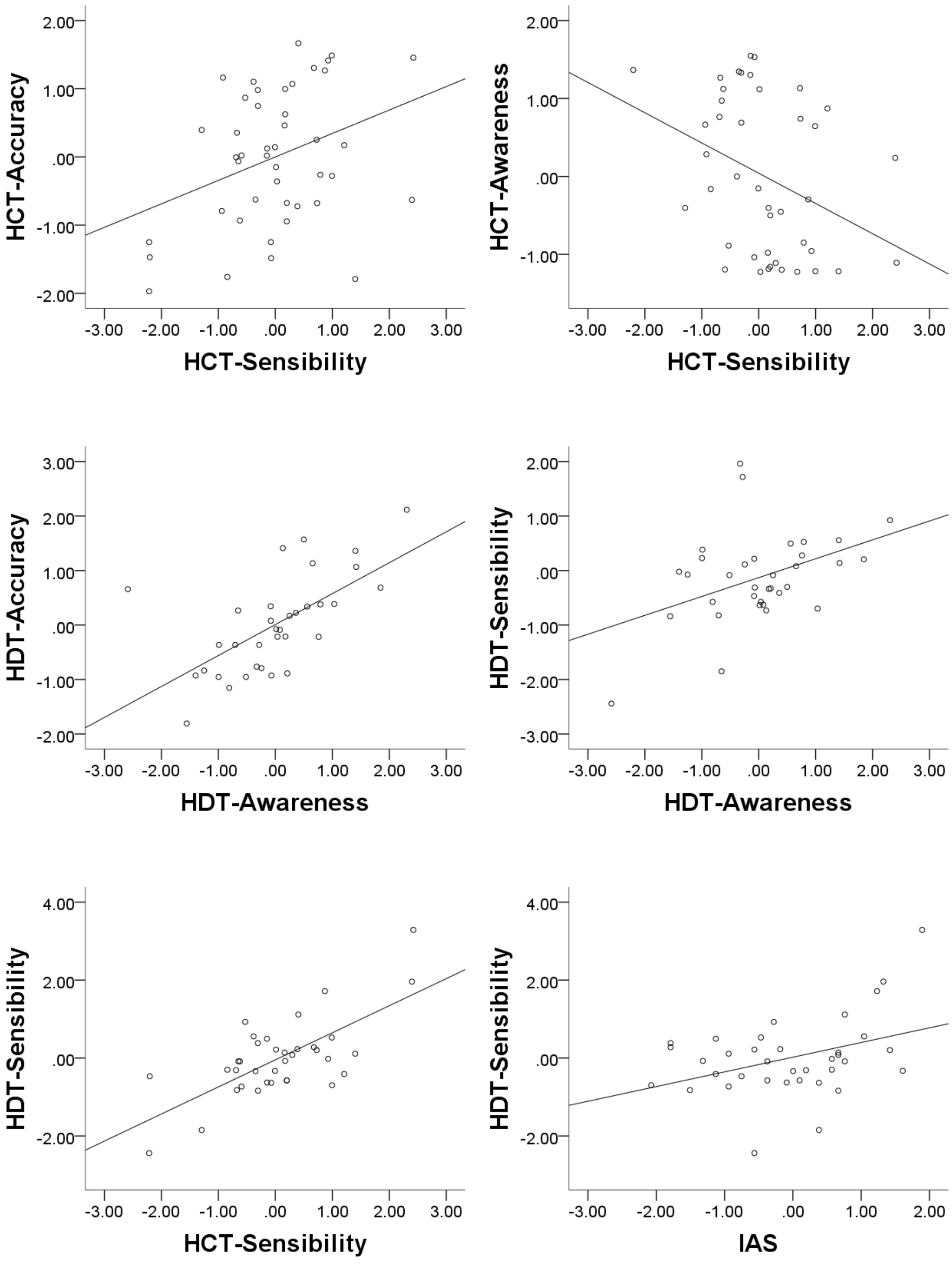

Figure 3. Scatter graphs displaying the significant correlations found in Chapter 1, using transformed z-scored variables.

1.5 DISCUSSION

This chapter explored the correlations between different measures of interoceptive ability within our dataset. First, we aimed to test whether the distinctions made by Garfinkel et al. (2015) do in fact relate to independent abilities. Correlation analyses conducted on both the HCT and HDT data revealed conflicting results.

Whilst the correlation between HDT-Accuracy and HDT-Sensibility was non-significant with moderate evidence in support of the null hypothesis as indicated by the BF_{01} value, the correlation between HCT-Accuracy and HCT-Sensibility was significant in the positive direction. Here, the HDT data support the theory of distinct abilities but this is conflicted by the findings from the HCT data. It should be noted that Garfinkel et al. (2015) used the BPQ as the measure of sensibility, alongside both the HCT and HDT as measures of accuracy, meaning the exact variables in the analysis differ. We therefore replicated their HDT finding with an alternative measure of HDT-Sensibility but failed to do so with the HCT. The significant relationship found between HCT-Accuracy and HCT-Sensibility supports findings that a relationship between sensibility and accuracy is more commonly found when sensibility is indexed via confidence ratings (Forkmann et al., 2016).

Subsequent analysis showed similar conflicting findings in the relationship between Accuracy and Awareness. No correlation was found between HCT-Accuracy and HCT-Awareness, which supports Garfinkel et al.'s (2015) proposal using a different heartbeat perception task. However, Bayesian analysis revealed that there was only anecdotal evidence in support of the null hypothesis, thus it is not clear that these abilities are completely unrelated. We did, however, find a significant positive relationship between HDT-Accuracy and HDT-Awareness, opposing the proposal of Garfinkel et al. (2015) that they are distinct abilities. Here it should be noted that we employed 40 trials for the HDT compared to 15 used by Garfinkel et al. (2015), suggesting that our task was a more reliable measure of HDT performance.

A particularly problematic finding for Garfinkel et al. (2015) is that significant relationships were found between Sensibility and Awareness for both the HCT and HDT data. Interestingly, this relationship was positive for the HDT data but negative for the HCT data. In addition to opposing the findings by Garfinkel et al. (2015), the inconsistency in the direction of the relationship highlights the difficulty in interoception research for generalising across tasks.

These mixed findings bring into question the model proposed by Garfinkel et al. (2015) as it is clear from this data that accuracy, sensibility and awareness are not found to be distinct across all tasks. To support Garfinkel et al.'s (2015) proposal, the abilities should appear distinct regardless of the measures used to falsify the model. It may be that this model emerges in particular circumstances, but it cannot be generalised to all tasks of interoception. It should be noted that Garfinkel et al. (2015) employed 6 trials during the HCT as opposed to our 4 trials, thus it may be considered that their measure was a more accurate reflection of HCT performance and subsequently the correlations (or lack of) between the different interoceptive abilities indexed by the HCT. In addition, Garfinkel et al. (2015) had a sample size of 80 compared to our sample size of 42. However, considering the emergence of a significant correlation with a moderate effect size in our sample it is unlikely that the present study was underpowered. This would suggest that Garfinkel et al.'s (2015) distinction should be brought into question and is problematic for studies that rely on this distinction by proposing relationships between clinical conditions and a specific interoceptive ability (e.g. Garfinkel et al., 2016b).

Despite these inconsistent findings regarding the independence of each interoceptive ability, we investigated whether measures supposedly indexing these specific abilities were related across tasks. Importantly, we found no significant relationship between HCT-Accuracy and HDT-Accuracy, with moderate evidence in support of the null hypothesis as indicated by the BF_{10} value. This supports the idea that accuracy cannot be generalised across the HCT and HDT, indicating that they fail to index the same ability. Indeed, it is clear that the tasks require a number of different abilities aside from the joint reliance on heartbeat perception. Specifically, the long duration of the HCT trials and requirement to keep track of heartbeats means that the HCT relies on sustained attention and working memory in a way that HDT does not. This contrasts to the HDT where reliance in put on the multisensory integration of tones and heartbeats, something which the HCT does not require. Indeed, Knapp et al. (1997) reported that simultaneity judgements for tones and lights accounted for 24.3% of variance in the HDT. Therefore, it is understandable that performance on these tasks would differ, not due to the underlying interoceptive ability required but rather the associated non-interoceptive task demands. It should be noted that test-retest reliability has been established for both the HCT (Ferentzi et al., 2018) and the HDT (Brener, Ring & Liu, 1994) meaning that it is unlikely that the absence of a relationship is due to inconsistency in scores within the same participant across time. Our findings emphasise the importance of not assuming that performance on one of these tasks can be taken as a generalisable measure of heartbeat perception.

Whilst this finding was replicated for Awareness whereby no significant correlation was found between HCT-Awareness and HDT-Awareness, the same was not found for Sensibility. A significant positive correlation was found between HCT-Sensibility and HDT-Sensibility. This seems intuitive as the HCT and HDT index confidence in the same way;

confidence ratings as a score out of 100 on each trial. Therefore, the demands on the participants are the same in both tasks. In both cases, participants are required to reflect on their performance and indicate how confident they are with their response. Their ability to do this is likely to be similar across tasks, thereby explaining the significant relationship between only the sensibility measures across tasks. Therefore, it is fair to assume that sensibility can be generalised between the HCT and HDT. However, it could be considered that this is simply a measure of an individual's general confidence. This idea is rejected by a report from Murphy et al. (in press-a) that no significant relationship was found between confidence scores on the time estimation control task and the HCT. This suggests that the confidence reported is task-specific rather than a measure of general confidence.

By investigating questionnaire measures of sensibility in addition to confidence ratings, we found a significant relationship between the IAS, a questionnaire measure of interoceptive sensibility, and HDT-Sensibility. This further validates the IAS as an interoceptive sensibility questionnaire. However, despite a significant relationship between HDT-Sensibility and HCT-Sensibility, no significant relationship was found between the IAS and HCT-Sensibility. Moderate evidence was found to support the null hypothesis in this case. This implies that further investigation should take place to more fully understand the relationships between these three variables, especially as Murphy et al. (in press-a) reported mixed results between samples for the relationship between the IAS and HCT confidence ratings.

This chapter presents evidence in conflict with the model of interoceptive ability proposed by Garfinkel et al. (2015). Whilst the abilities appeared distinct for some tasks, this was not consistent across all measures which is problematic for the assumption that this model applies to interoceptive abilities across all tasks. Further, these supposedly distinct abilities were typically not found to correlate across tasks. This is a particularly important finding for the literature as it should discourage researchers from selecting one method and labelling it as a general measure of interoceptive ability. However, it may be considered that non-interoceptive factors are responsible for the presence or absence of a relationship between different interoceptive abilities. For example, significantly related abilities may have common factors such as BMI, or the differences in non-interoceptive task demands – such as multisensory integration - between the HCT and HDT may have prevented a relationship being observed. Chapter 2 addresses this hypothesis by investigating these correlations whilst controlling for a variety of non-interoceptive control variables.

CHAPTER 2 – HEARTBEAT PERCEPTION CONTROL MEASURES

2.1 INTRODUCTION

Whilst the HCT and HDT are frequently used to index interoceptive ability, they have been criticised on the basis that they are not 'pure' measures of interoception. A variety of non-interoceptive factors are reported to affect the detection of the heartbeat signal. For example, individuals with a higher BMI were found to be less successful at heartbeat discrimination (Rouse et al., 1988), something the researchers attributed to the role of the somatosensory system and the subsequent differences in cardiac sensation as a result of body composition. High systolic blood pressure is also thought to improve heartbeat perception (O'Brien et al., 1998), which the authors suggest may be due to increased availability of peripheral sensation. Specifically, the increased blood pressure may lead to increased pulse pressure and cardiac output, resulting in enhanced somatosensory cues for heartbeat perception. Further, a decrease in resting heart rate and heart rate variability (Knapp-Kline & Kline, 2005) has been found to positively impact performance on heartbeat detection. The authors theorise that decreased resting heart rate may allow individuals more time to process the heartbeat signals, and decreased heart rate variability enables individuals to have accurate expectations regarding their heart rate. Despite these findings, many researchers fail to control for these variables when indexing interoceptive ability via heartbeat perception tasks. Thus, when using heartbeat perception as a measure of interoception, the contribution of non-interoceptive factors is often overlooked.

For the HCT, a number of psychological variables have been found to impact performance. One's knowledge of resting heart rate can either benefit or impair performance on the task depending on the accuracy of the belief (Brener & Ring, 2016; Ring et al., 2015;

Ring & Brener, 1996; Windmann et al., 1999), as participants may use this as a cue for how many heartbeats they expected to have felt during the time interval. In addition, time estimation abilities have been found to influence performance as many participants will rely on counting seconds as a method of estimating the number of heartbeats in the time interval (Murphy et al., 2018). These are also important factors to control for when investigating interoceptive abilities.

Indeed, Murphy et al. (2018) employed these and additional control variables when exploring the relationship between interoception and alexithymia, the inability to identify and describe one's own emotions (Nemiah, Freyberger, & Sifneos, 1976). They conducted a partial correlation between the HCT and the TAS, controlling for age, BMI, systolic blood pressure, resting heart rate, heart rate variability, knowledge of resting heart rate, time estimation, depression and anxiety. The partial correlation analysis revealed a significant relationship between the HCT and the TAS where a Pearson's correlation failed to do so. This implies that the previous failure to observe a relationship between interoception and alexithymia was due to the variance accounted for by non-interoceptive factors. The emergence of a significant relationship in the partial correlation analysis emphasises the importance of controlling for these variables when using heartbeat tasks as a measure of interoception. Further, they found that time estimation and knowledge of resting heart rate significantly correlated with the HCT. This indicates that these factors in particular should be focused on when controlling for the non-interoceptive variance in HCT scores.

One important factor that has been overlooked in the above analysis is the contribution of tactile sensitivity in the perception of the heartbeat signal (Khalsa et al., 2009a), whereby a pulse can be detected via exteroceptive touch receptors. Participants may score highly on the HCT simply by tuning into the tactile sensation of their pulse in parts of their body such as their finger. Whilst Garfinkel et al. (2016a) reported no correlation between a simple tactile acuity task and the HDT, Knapp, Ring and Brener (1997) found that tactile sensitivity accounted for 8.5% of variance in HDT performance. Despite this finding, researchers often overlook the contribution of tactile sensitivity to heartbeat perception task performance. Indeed, tactile sensitivity has not yet been used as a control variable in conjunction with either the HDT or HCT, meaning that whilst its relationship with heartbeat perception has been reported, it has not yet been utilised in the creation of a more 'pure' index of interoceptive accuracy. Here we address this by reporting and controlling for our own version of a tactile perception control task closely matched to the HCT in which participants are asked to count the number of vibrations they feel in a given time interval.

Significant improvement in the HCT and HDT could arise by controlling for the variety of non-interoceptive factors which are associated with them. As shown by Murphy et al. (2018), significant relationships between interoception and other abilities can arise when these variables are controlled for. It follows that the relationships reported in Chapter 1 may benefit from conducting partial correlations in substitution for Pearson's correlations. It may be that the absence of correlations between variables in Chapter 1 is due to the fact that the HCT and HDT are not pure measures of interoception. Specifically, it is likely that the HCT and HDT are subject to different non-interoceptive influencing factors and controlling for these may reveal significant relationships between interoceptive abilities across tasks. Conducting partial correlations, something which is yet to be done in the literature with these variables, may rectify this.

This chapter attempts to quantify the contribution of each control variable to both HCT and HDT Accuracy via regression analyses in which the control variables act as predictors of performance on the heartbeat perception tasks. Experiment 1 investigates the role of the control tasks used in Murphy et al. (2018) in addition to our tactile perception control task in predicting HCT-Accuracy. Here, we predict that a combination of non-interoceptive factors will significantly predict HCT-Accuracy, with our tactile perception control task acting as a significant predictor. Experiment 2 attempts to replicate these findings in an independent sample. The same method used in Experiment 2 is then applied to the HDT in Experiment 3. Again, we predict the emergence of a significant model predicting HDT-Accuracy but consider that a different combination of factors will be important due to the differing task demands between the HCT and HDT. We expect that our tactile perception control task will also be a significant predictor of this task. Finally, Experiment 4 echoes Murphy et al.'s (2018) analysis by conducting partial correlations between the variables reported in Chapter 1 whilst controlling for the control variables investigated in this chapter. Here, we hypothesise that controlling for non-interoceptive factors will affect the relationships previously observed. Specifically, we expect significant relationships to be found between the HCT and HDT.

2.2 EXPERIMENT 1 – HEARTBEAT COUNTING TASK CONTROL MEASURES

2.2.1 Methods

2.2.1.1 Participants

For Experiment 1, we recruited 45 participants, 5 male and 40 female, in the age range 18-25 (M = 19.67, SD = 1.30). The sample of participants in this experiment was independent of the sample reported in Chapter 1 but were subject to the same screening criteria.

2.2.1.2 Design

Participants completed all of the tasks during the same test session. The tasks were completed in the following order: HCT, tactile perception control task, time estimation control task, and the non-interoceptive control variables (see section 2.2.1.4.). The dependent variable was HCT-Accuracy and the other measures acted as predictor variables.

2.2.1.3 Materials

The HCT, tactile perception control task, and time estimation control task were programmed in MatLab using Psychophysics Toolbox Version 3 (Brainard, 1997). A Contec CMS50D+ pulse oximeter clipped to the participant's middle finger on their non-dominant hand was used to record their heart rate during the HCT. Systolic blood pressure was taken using an Omron M2 Basic blood pressure monitor.

In the tactile perception control task, a tactile speaker was used to deliver vibrations to the participant's middle finger on their non-dominant hand. The speaker was programmed using Arduino to deliver vibrations at one of three different intensity levels that had been determined through previous pilot testing in a small sample of participants (Easy = 34.8 W/m^2; Moderate = 20.0 W/m^2; Difficult = 13.9 W/m^2). Appendix B sets out the intensity calculations in further detail.

2.2.1.4. Procedure

Participants completed the tasks in a quiet testing cubicle with soft white noise of approximately 65 decibels played through headphones.

Heartbeat Counting Task

Participants completed the HCT as set out in Chapter 1. However, these participants were not explicitly told to put zero as their answer if they could not feel any heartbeats.

Tactile Perception Control Task

Participants were sat at a desk and asked to lightly place the middle finger on their non-dominant hand over the tactile speaker. They were first introduced to the sensation of the vibrations in an example trial in which they felt 28 vibrations at an intensity of 34.8 W/m^2 at 200 Hz with gaps of 1 second in between vibrations. One vibration equated to one segment of vibrations delivered for 150 ms. This allowed participants to work out the optimum pressure they would need to apply with their finger in order to best feel the vibrations. In the experimental trials, vibrations were delivered to the finger at 50 Hz for 150 ms, with randomised gaps between 1 and 2.5s. Here, participants were asked to count the number of vibrations they felt during four different time intervals for each of the intensity levels, where one vibration equated to one segment of vibrations lasting 150 ms. As mentioned in Chapter 1, the time intervals used were counterbalanced across the three tasks (HCT, tactile perception control task and time estimation control task), with three sets of four time intervals used (22, 32, 42, 97 s; 25, 35, 45, 100 s; 28, 38, 48, 103 s). The four different time intervals occurred in a random order for each participant. Participants repeated the same four time intervals for the Easy, Moderate and Difficult intensity conditions.

Time Estimation Control Task

In this task, participants were asked to count the number of seconds that had passed during four different time intervals. The durations of the time intervals were determined through the aforementioned counterbalance procedure.

Control Tasks and Measurements

A number of measurements were taken which acted as control variables. Physiological control variables included age, sex, BMI (obtained through height and weight measurements), systolic blood pressure (the average of three recordings from an Omron M2 Basic blood pressure monitor), resting heart rate (calculated using the heart rate measurements taken by the pulse oximeter during the HCT) and heart rate variability (calculated using the mean inter-beat intervals obtained from the pulse oximeter recordings during the HCT).

Psychological control variables included knowledge of resting heart rate, indexed by the absolute difference between the participant's estimate and average resting heart rate (reported in large studies of human physiology; 72.26; Agelink et al., 2001; Ramaekers, Ector, Aubert, Rubens, & Van de Werf, 1998), and depression and anxiety using the Depression, Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995).

2.2.2 Data Analysis

2.2.2.1 Score Calculations

Heartbeat Counting Task

Scores for the HCT were calculated as set out in Chapter 1.

Tactile Perception Control Task

Scores for each condition of the tactile perception control task (Easy, Moderate and Difficult) were calculated using the following formula: SUM(1–(|Objective measure – participant's estimate|/Objective measure)) x 100, allowing for a maximum score of 400 across the four trials combined and a minimum score of zero.

Time Estimation Control Task

Participants were assigned a score on each of the 4 trials of the task, calculated using the following formula: SUM(1–(|Objective measure – participant's estimate|/Objective measure)) x 100. These scores were added together, whereby 400 indicated a perfect score.

2.2.2.2. Descriptive Statistics

Table 2 presents the descriptive statistics for each variable. Transformations were applied to correct skewness (log transforms to knowledge of resting heart rate and heart rate variability, and an exponential transform to Easy Tactile) and Z-scores for all variables were computed.

Table 2

Descriptive statistics for HCT and control variables (untransformed and transformed data)

Variable	N	Mean	SD	Skew	Kurtosis
Age	45	19.67	1.30	2.43	7.85
Sex	45	1.11	0.32	2.56	4.77
BMI	45	22.13	5.51	3.15	14.08
Systolic Blood Pressure	45	103.47	10.96	-0.73	0.17
Knowledge of Resting Heart Rate	45	14.25	16.71	2.21	4.88
Knowledge of Resting Heart Rate (log transform and z-score)	45	-0.15	0.29	0.77	0.12
Depression	45	4.67	5.09	1.31	0.72
Anxiety	45	5.13	4.05	1.04	0.53
Time Estimation	45	300.54	51.32	-0.06	-0.35
Easy Tactile	45	342.63	83.85	-2.39	6.14
Easy Tactile (exponential transform and z-score)	45	1.34	0.59	-0.80	-0.52
Moderate Tactile	45	233.58	130.20	-0.27	-1.37
Difficult Tactile	45	245.33	130.75	-0.54	-0.94
Resting Heart Rate	45	83.72	11.86	-0.88	1.49
Heart Rate Variability	45	0.04	0.04	2.18	5.74
Heart Rate Variability (log transform and z-score)	45	-1.61	0.46	-0.10	-0.66
HCT-Accuracy	45	274.52	75.25	-0.39	-0.82

2.2.2.3 Analyses

To determine whether individual differences in the HCT could be predicted with the control variables, a stepwise backwards method regression was run to identify which combination of control measures were able to predict HCT-Accuracy. The chosen model was identified as the first significant model from the backwards regression. Subsequently, a hierarchical regression model was employed to explore the significance of the addition of the tactile perception control task, as opposed to the variables previously selected by Murphy et al. (2018). For this regression, the other factors within the significant model from the stepwise backwards regression were entered at stage 1 and the tactile perception control task score was entered at stage 2. The R^2 change was taken as a measure of model improvement.

2.2.3 Results

From the stepwise backwards regression, the chosen model, which contained time estimation, Easy Tactile, resting heart rate, Moderate Tactile, BMI, knowledge of resting heart rate, heart rate variability, age and anxiety as predictor variables, was found to significantly predict HCT-Accuracy (R^2 = .21, $F(9, 35) = 2.20$, p = .039). The regression model is displayed in Figure 4 and Table 3 reports the beta coefficients for each variable.

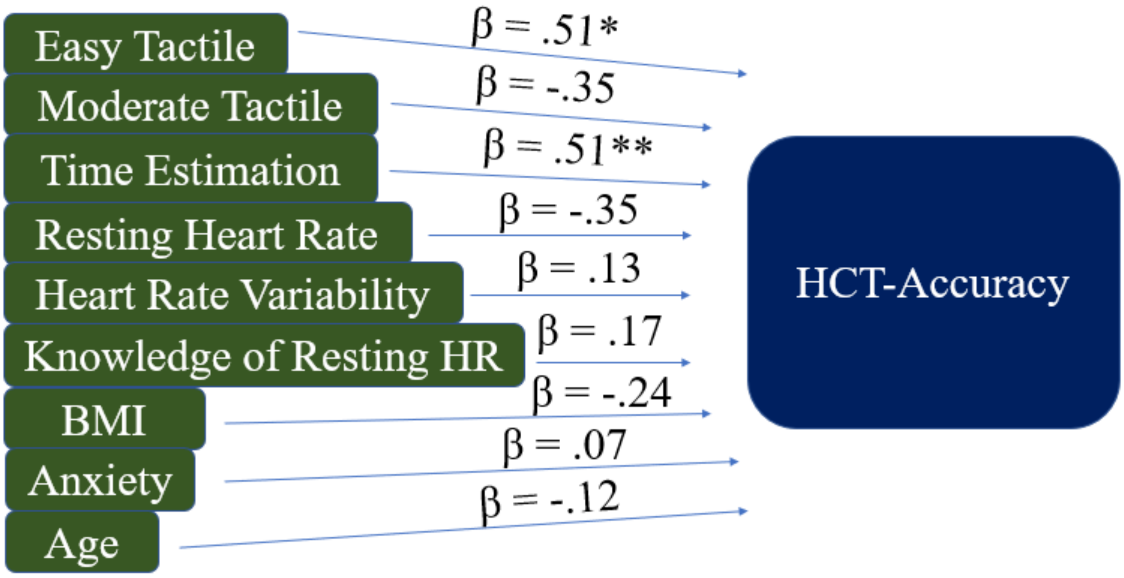

Figure 4. The significant regression model predicting HCT-Accuracy, with standardised beta coefficients. * indicates $p < .05$; ** indicates $p < .01$.

Table 3

*Beta coefficients for each variable in the significant regression model. * indicates p < .05; ** indicates p < .01.*

Variable	***β***	***β*(std. Err.)**	**Standardised *β***	***t***	***p***
Time Estimation	.59	.17	.51	3.42	.002**
Easy Tactile	.86	.37	.51	2.37	.024*
Resting Heart Rate	-.36	.18	-.35	-1.95	.059
Moderate Tactile	-.41	.25	-.35	-1.66	.105
BMI	-.24	.14	-.24	-1.68	.103
Knowledge	.61	.52	.17	1.17	.249
Heart Rate Variability	.13	.17	.13	.73	.471
Age	-.12	.15	-.12	-.80	.430
Anxiety	.07	.15	.07	.48	.635

It was then assessed whether the inclusion of the tactile perception control tasks significantly improved this prediction. In the above analysis, performance on the tactile perception control task (Easy condition) was a significant predictor of HCT-Accuracy: β = .51, t = 2.37, p = .024. Due to its significant prediction of HCT-Accuracy, the contribution of this specific intensity of the tactile perception control task was investigated further. A hierarchical regression showed that Easy Tactile accounted for an additional 10% of variance in HCT-Accuracy (R^2 change = .10, F(1,35) = 5.61, p = .024).

2.2.4 Interim Discussion

In this experiment we have shown that individual differences in HCT-Accuracy can be significantly predicted by a model containing a variety of non-interoceptive variables: time estimation, Easy Tactile, resting heart rate, Moderate Tactile, BMI, knowledge of resting heart rate, heart rate variability, age and anxiety. This emphasises that these control variables are an important consideration for studies attempting to index interoceptive accuracy without the influence of non-interoceptive factors. The model fails to provide evidence for the importance of sex, systolic blood pressure and depression in the prediction of HCT-Accuracy. However, it is likely that our relatively small sample size inhibited the observation of the effects of the variables.

Attention to the standardised beta coefficients shows that we successfully replicated findings by Murphy et al. (2018) which demonstrated that time estimation is a significant positive predictor of HCT-Accuracy. This further indicates that time estimation is a key variable that predicts HCT-Accuracy and emphasis should be placed on its use as a control task for the HCT. However, we failed to replicate Murphy et al.'s (2018) significant relationship between HCT-Accuracy and knowledge of resting heart rate within this sample. This may be due to the much larger sample size of 287 participants used in their study.

A particularly interesting finding from this experiment is that our tactile perception control task (Easy condition) was found to significantly predict HCT-Accuracy. The positive relationship indicates that the better an individual is at the tactile perception control task, the better their performance on HCT-Accuracy. This finding therefore further emphasises the importance of considering tactile perception when administering heartbeat perception tasks such as the HCT. Future studies should therefore utilise the tactile perception control task, in addition to controlling for the aforementioned control variables, to obtain a more accurate index of interoceptive accuracy.

2.3 EXPERIMENT 2 – HEARTBEAT COUNTING TASK REPLICATION

2.3.1 Methods

2.3.1.1 Participants

Experiment 2 tested the same participants as those detailed in Chapter 1. A post hoc power analysis of the regression model from Experiment 1 using GPower (Faul & Erdfelder, 1992) indicated that the significant model had a power level of 0.92 and an effect size (f^2) of 0.58. An a priori calculation determined that to achieve power of at least 0.9 future experiments would need a total of 44 participants. The sample of 47 participants used in Experiment 2 was therefore deemed sufficient.

2.3.1.2 Design

The same design was followed as set out in Experiment 1. However, the participants first completed the HDT, data from which is discussed in Experiment 3.

2.3.1.3 Materials

The experiment used the same equipment as Experiment 1. However, in Experiment 2, the Tactile Perception Control Task was run at 2 intensities. The first intensity used was the same as the Easy intensity from experiment 1 (34.8 W/m^2), the intensity at which the tactile perception control task was found to be a significant predictor of HCT-Accuracy. The second intensity used, Easy-Moderate, fell in between the Easy and Moderate intensities from Experiment 1 (24.3 W/m^2). This was chosen to explore an additional intensity closer to the

Easy intensity in an attempt to find the optimum level to use in this task. The intensity calculations are detailed in Appendix B.

2.3.1.4 Procedure

Experiment 2 followed the same procedure as Experiment 1 but differed in three aspects: participants first completed the HDT as detailed in Chapter 1 (analysed in Experiment 3); they only completed 2 intensity levels during the tactile perception control task, starting with Easy and continuing onto Easy-Moderate; knowledge of resting heart rate was indexed by the absolute difference between participant's estimate and their own resting heart rate as opposed to the average resting heart rate of the general population.

2.3.2 Data Analysis

2.3.2.1 Score Calculations

Scores on the HCT, tactile perception control task and time estimation control task were calculated as set out in Chapter 1 and Experiment 1.

2.3.2.2 Exclusions

As in Chapter 1, heartbeat data from 3 participants was lost, meaning that data from 44 participants were analysed.

2.3.2.3 Descriptive Statistics

Table 4 presents the descriptive statistics for each variable across all participants tested. Log transforms were applied to anxiety and knowledge of resting heart rate, a reciprocal transform to age and a cube transform to Easy-Moderate Tactile. Descriptive statistics on each variable for the 44 participants analysed in this chapter are presented in Table 5. Z-scores were computed for all variables prior to analysis.

Table 4

Descriptive statistics for the HCT, HDT and control variables (untransformed and transformed data)

Variable	N	Mean	SD	Skew	Kurtosis
Age	47	20.70	2.38	2.62	10.47
Age (reciprocal transform)	47	0.05	0.00	-1.35	3.41
Sex	46	1.78	0.42	-1.42	0.01
BMI	47	22.33	2.51	0.77	1.73
Systolic Blood Pressure	47	108.77	10.98	0.42	0.19
Knowledge of Resting Heart Rate	47	17.28	17.62	1.87	3.57
Knowledge of Resting Heart Rate (log transform)	47	1.01	0.50	-0.63	0.47
Anxiety	47	4.00	3.74	1.01	0.82
Anxiety (log transform)	47	0.56	0.37	-0.24	-1.09
Depression	47	3.15	3.22	1.01	0.36
IAS	47	78.96	10.59	-0.15	-0.81
Easy Tactile	44	361.69	51.17	-1.52	1.33
Easy-Moderate Tactile	44	300.05	126.65	-1.28	0.23
Easy-Moderate Tactile (cube transform)	44	38698030.86	23908986.28	-0.62	-1.23
Time Estimation	44	306.66	63.05	-0.69	-0.36
Resting Heart Rate	44	77.44	10.17	0.35	-0.30
Heart Rate Variability	43	0.07	0.05	0.64	-0.13
HCT-Accuracy	44	212.47	107.86	-0.18	-0.91
HDT-Accuracy	36	0.18	0.50	0.16	-0.08

Table 5

Descriptive statistics for HCT-Accuracy and control variables (untransformed and transformed data)

Variable	**Mean**	**SD**
HCT-Accuracy	212.47	107.86
Age	20.77	2.43
Age (reciprocal transform)	0.05	0.01
Sex	1.79	0.41
BMI	22.36	2.54
Systolic Blood Pressure	108.57	10.89
Knowledge of Resting Heart Rate	13.80	11.47
Knowledge of Resting Heart Rate (log transform)	0.96	0.46
Anxiety	3.95	3.82
Anxiety (log transform)	0.55	0.37
Depression	3.25	3.29
Easy Tactile	361.69	51.17
Easy-Moderate Tactile	300.05	126.65
Easy-Moderate Tactile (cube transform)	38698030.86	23908986.28
Time Estimation	306.66	63.05
Resting Heart Rate	77.44	10.17
Heart Rate Variability	0.07	0.05

2.3.2.4 Analyses

The same stepwise backwards regression analysis used in Experiment 1 was run on this dataset. An additional replication check was also conducted in which a regression model was run containing the variables from the significant model in Experiment 1. The group demographic differences between the datasets used in the two experiments were analysed using t-tests and Levene's tests. Further explorative analyses were conducted in which the initial analysis was repeated following participant exclusions based on either responding with 'zero' on one or more trials, or their gradient between time interval duration and score.

2.3.3 Results

In an attempt to replicate the results found in Experiment 1, a stepwise backwards regression was run on the data. No models were found to significantly predict HCT-Accuracy (see appendix C).

We carried out a further replication check by running a regression containing the variables from the significant model in Experiment 1 (time estimation, Easy Tactile, resting heart rate, Moderate Tactile, BMI, knowledge of resting heart rate, heart rate variability, age and anxiety). The model did not significantly predict HCT-Accuracy: $R^2 = .01$, $F(9, 33) = 1.02$, $p = .417$.

The lack of a significant model was somewhat surprising, we thus investigated potential differences in group demographics between Experiment 1 and Experiment 2 through t-tests and Levene's tests. Data from Experiment 2 comprised significantly higher means for age, systolic blood pressure and heart rate variability, and significantly lower means for heart rate and HCT-Accuracy, compared to the dataset from Experiment 1. The dataset from Experiment 2 was also found to have larger variance in age, sex and HCT-Accuracy, and smaller variance in BMI and depression, compared to the dataset from Experiment 1. The analyses are detailed in Table 6.

Table 6

*Significant t-tests and Levene's tests between the samples from Experiment 1 and Experiment 2. * indicates p < .05; ** indicates p < .01.*

Variable	**Experiment 1 Mean**	**Experiment 2 Mean**	***t***	***p***	**Levene's test (*F*)**	***p***
Age	19.67	20.77	-2.67	.010*	6.18	.015*
Systolic Blood Pressure	103.47	108.57	-2.20	.030*		
Heart Rate Variability	0.04	0.07	-3.00	.003**		
Resting Heart Rate	83.72	77.44	2.68	.009**		
HCT-Accuracy	274.52	212.47	3.14	.002**	6.00	.016*
Sex	1.89	1.79			6.61	.012*
BMI	22.13	22.36			4.40	.037*
Depression	4.69	3.25			5.39	.023*

An additional difference between this dataset and that used in Experiment 1 is that in this experiment participants were explicitly told to put zero as their answer if they could not feel any heartbeats. To investigate whether the differing instructions affected the results of the analysis, data were removed from any participants who reported that they felt zero heartbeats on at least one trial. This criterion led to the removal of 16 participants, leaving 28 participants to be analysed. A stepwise backwards regression was run on the data and again no models were found to significantly predict HCT-Accuracy (see appendix D).

We conducted additional explorative analyses in order to interpret the data further. Due to an observed steep gradient between time interval duration and score for some participants, in addition to findings by Zamariola, Maurage, Luminet and Corneille (2018) that scores on the HCT can be influenced by time interval duration, we removed data from 10 participants who had a gradient of 0.85 or greater. This was because, if a participant is adhering to the instructions, the gradient between time duration and score should be close to zero. Thus, steep gradients were taken as an indicator that the participant was not performing the task correctly. When the regression analysis was run with the modified dataset, a significant model emerged in which Easy-Moderate Tactile, anxiety, time estimation, age, sex, Easy Tactile and heart rate variability significantly predicted HCT-Accuracy (R^2 = .25, F(7, 24) = 2.47, p = .047). The model is displayed in Figure 5 and beta coefficients for each variable are reported in Table 7.

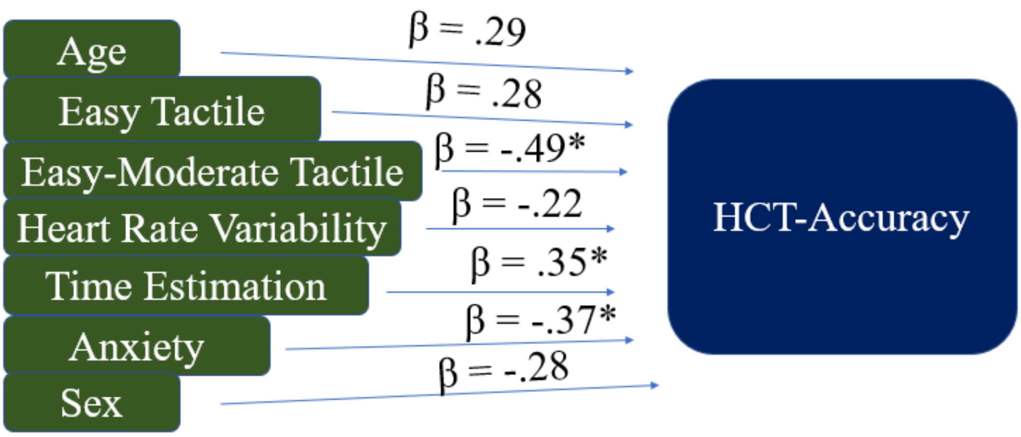

Figure 5. The significant regression model predicting HCT-Accuracy, with standardised beta coefficients. * indicates $p < .05$; ** indicates $p < .01$.

Table 7

*Beta coefficients for each variable in the significant regression model. * indicates p < .05; ** indicates p < .01.*

Variable	***β***	***β*(std. Err.)**	**Standardised *β***	***t***	***p***
Easy-Moderate Tactile	-.45	.21	-.49	-2.17	.040*
Anxiety	-.31	.15	-.37	-2.08	.049*
Time Estimation	.30	.14	.35	2.08	.048*
Age	.35	.20	.29	1.76	.092
Sex	-.27	.20	-.28	-1.35	.191
Easy Tactile	.25	.24	.28	1.05	.304
Heart Rate Variability	-.18	.14	-.22	-1.34	.191

Easy-Moderate Tactile was found to be a significant predictor of HCT-Accuracy: β = -.49, t = -2.17, p = .040). A hierarchical regression showed that Easy-Moderate Tactile accounted for an additional 11% of variance in HCT-Accuracy (R^2 change = .11, F(1,24) = 4.72, p = .040).

2.3.4 Interim Discussion

Our planned replication analyses failed to find the same results as in Experiment 1. In fact, no significant models were found to predict HCT-Accuracy from these initial analyses. Whilst it could be considered positive that none of the non-interoceptive variables predicted HCT-Accuracy, it contradicts a wide literature demonstrating that interoceptive accuracy is affected by these factors. It is therefore important to question why the finding was not replicated in this second sample.

The group demographic differences between Experiments 1 and 2 were analysed to reveal a number of significant differences in means and variances. It is possible that the lack of replication can be attributed to these differences. Due to the limited sample size, we were unable to test this theory by analysing a subset of participants from Experiment 2 whose group demographics matched those of Experiment 1. Therefore, more data are needed to verify this hypothesis.

Further explorative analyses were conducted in an attempt to understand the lack of replication. Due to different task instructions whereby participants in Experiment 2 were explicitly told to put zero if they felt no heartbeats, the data were analysed again after removing data from participants who answered with zero on at least one of the 4 trials. This analysis failed to produce any significant prediction models, suggesting that these instructions were not responsible for the differences in the dataset that led to the lack of replication. However, removing these participants reduced the sample size from 44 to 28 participants, which may mean that the inability to detect a significant predictor model in this case was due to the insufficient power of the sample. It would have been desirable if the sample size of participants not answering zero had been sufficient to run reliable analyses. It is therefore difficult to conclude from this dataset that the differing instructions did not impact the results of the study.

Additional exploration of the data attempted to reveal why there were no significant predictors of HCT-Accuracy in this sample. The findings by Zamariola et al. (2018) that scores on the HCT can be influenced by time interval duration led us to explore participants' gradients between time interval duration and score. It was rationalised that a participant adhering to the instruction should have a gradient close to zero as time interval should not severely impact their performance. We therefore interpreted a steep gradient as an indicator that the task was not performed correctly. Rerunning the regression analysis having removing participants with a gradient of 0.85 or greater revealed a significant prediction of HCT-Accuracy by a model containing Easy-Moderate Tactile, anxiety, time estimation, age, sex, Easy Tactile and heart rate variability. Within this model, Easy-Moderate Tactile, anxiety and time estimation were all significant predictors. As expected, anxiety had a negative relationship with HCT-Accuracy and Time Estimation had a positive relationship with HCT-Accuracy. However, the significant tactile perception control task in this model was a negative predictor of HCT-Accuracy. We would typically expect from the literature that tactile sensitivity is should be positive predictor of heartbeat perception (Knapp et al., 1997). The finding from this experiment opposes that of Experiment 1 in which tactile perception had a positive relationship with HCT-Accuracy. However, an inverse relationship between interoceptive and exteroceptive body awareness has previously been noted in the literature (Valenzuela-Moguillansky, Reyes-Reyes & Gaete, 2017). It is possible to rationalise this inverse relationship by considering that there may be increased reliance on exteroceptive cues and ability if interoceptive ability is low, and vice versa. Whilst this inverse relationship can be justified, it is unclear why different difficulty levels of the same tactile task would exhibit opposite relationships with the same interoceptive measure. Future directions and improvements for this task are discussed at the end of the chapter.

The above analysis should be taken with caution due to its exploratory nature. More in depth analysis of the gradient between time interval duration and score is needed in order to validate it as a method for participant exclusion. In addition, this exclusion led to the sample size of the analysis falling short of the required 44 participants as indicated by the power analysis from Experiment 1. Overall, the lack of replication is indicative of the current problems in this research field and emphasises the importance of not generalising findings across all tasks and populations. It is clear that control variables are not able to consistently predict heartbeat perception across all samples.

2.4 EXPERIMENT 3 – HEARTBEAT DISCRIMINATION TASK CONTROL MEASURES

2.4.1 Methods

2.4.1.1 Participants

The participants tested in Experiment 3 were the same as those detailed in Chapter 1 and Experiment 2.

2.4.1.2 Design

Experiment 3 followed the same design as Experiment 2, except in this experiment the dependent variable was HDT-Accuracy.

2.4.1.3 Materials

The same materials were used as in Experiment 2.

2.4.1.4 Procedure

The procedure for this experiment was the same as the procedure set out in Experiment 2.

2.4.2 Data Analysis

2.4.2.1 Score Calculations

Scores for the HDT, tactile perception control task and time estimation control task were calculated as set out in Chapter 1, Experiment 1 and Experiment 2.

2.4.2.2 Exclusions

As in Chapter 1, heartbeat data from 3 participants were lost and HDT data from 8 participants were removed. Therefore, data from 36 participants were analysed.

2.4.2.3 Descriptive Statistics

The descriptive statistics for each variable for all participants in presented in Table 4 (see Experiment 2). The same transformations were applied to the control variable data as in Experiment 2 (log transforms to anxiety and knowledge of resting heart rate; a reciprocal transform to age; a cube transform to Easy-Moderate Tactile). Table 8 presents the descriptive statistics for participants analysed in this experiment. Z-scores were computed for all variables before the analysis.

Table 8

Descriptive statistics for HDT-Accuracy and control variables (untransformed and transformed data)

Variable	**Mean**	**SD**
HDT-Accuracy	0.18	0.50
Age	20.94	2.51
Age (reciprocal transform)	0.05	<0.01
Sex	1.80	0.41
BMI	22.02	1.99
Systolic Blood Pressure	108.56	11.44
Knowledge of Resting Heart Rate	12.74	11.36
Knowledge of Resting Heart Rate (log transform)	0.90	0.48
Anxiety	4.22	4.00
Anxiety (log transform)	0.57	0.39
Depression	3.42	3.31
Easy Tactile	365.69	50.79
Easy-Moderate Tactile	312.15	115.35
Easy-Moderate Tactile (cube transform)	40462886.85	23379038.18
Time Estimation	311.29	54.13
Resting Heart Rate	75.26	9.14
Heart Rate Variability	0.08	0.05

2.4.2.4 Analyses

As in Experiment 1, a stepwise backwards method regression was run to identify which combination of control measures were able to predict HDT-Accuracy. A hierarchical regression was then employed to determine whether the tactile perception control task significantly improved the prediction of HDT-Accuracy. As before, the R^2 change following the addition of this variable to the model was taken as a measure of model improvement.

2.4.3 Results

A stepwise backwards regression was run with the control variables as predictors of HDT-Accuracy. A model containing Easy Tactile, age, depression and resting heart rate was found to significantly predict HDT-Accuracy: $R^2 = .34$, $F(4, 29) = 5.21$, $p = .003$. This model is displayed in Figure 6 and Table 9 reports the beta coefficients for the four variables in the model.

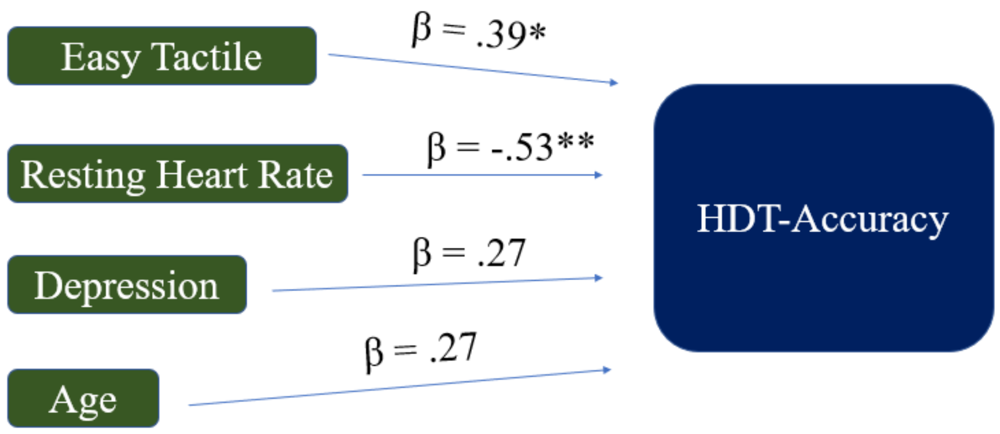

Figure 6. The significant regression model predicting HDT-Accuracy, with standardised beta coefficients. * indicates $p < .05$; ** indicates $p < .01$.

Table 9

*Beta coefficients for each variable in the significant regression model. * indicates p < .05; ** indicates p < .01.*

Variable	β	β**(std. Err.)**	**Standardised** β	t	p
Resting Heart Rate	-.58	.16	-.53	-3.55	.001**
Easy Tactile	.39	.15	.39	2.71	.011*
Depression	.26	.14	.27	1.87	.071
Age	.38	.21	.27	1.83	.078

In the above analysis, performance on the tactile perception control task (Easy condition) was a significant predictor of HDT-Accuracy: $\beta = .39$, $t = 2.71$, $p = .011$. A hierarchical regression showed that Easy Tactile accounted for an additional 11% of variance in HDT-Accuracy (R-squared change = .11).

2.4.4 Interim Discussion

In this experiment we successfully predicted HDT-Accuracy with a variety of non-interoceptive control variables: Easy tactile, resting heart rate, depression and age. This emphasises the importance of controlling for these variables when implementing the HDT as a measure of interoceptive ability. It is interesting to note that within the same sample of participants we were unable to predict HCT-Accuracy with these variables. Therefore, it is clear that the effects found in this chapter should not be generalised to all heartbeat perception tasks. In addition, the variables in this significant prediction model differed to those that successfully predicted HCT-Accuracy in Experiment 1, thus further emphasising this point.

Of the variables in the significant prediction model, resting heart rate and Easy tactile were significant predictors of HDT-Accuracy. The significant negative relationship between HDT-Accuracy and resting heart rate supports the aforementioned finding by Knapp-Kline and Kline (2005). Further, the significant positive relationship between HDT-Accuracy and Easy Tactile replicates the findings in Experiment 1 whilst extending the relationship to an alternative measure of interoceptive accuracy. Despite being non-significant predictors, the inclusion of age and depression in the model is consistent with literature that reports an influence of these factors on heartbeat perception (Murphy, Geary, Millgate, Catmur & Bird, 2017b; Pollatos, Traut-Mattausch & Schandry, 2009).

Whilst the two heartbeat perception tasks share multiple variables of importance, it should be noted that time estimation was not a significant predictor of HDT as it was for HCT. This strengthens the distinction made between the task demands of the HCT and HDT. Indeed, the differing prediction models imply that the non-interoceptive variables should not be assumed to apply to all heartbeat perception tasks regardless of their design. Further attention to the specific variables of importance for the HCT and HDT separately is required, something which is addressed in the chapter discussion.

2.5 EXPERIMENT 4 – CONTROLLING FOR NON-INTEROCEPTIVE VARIABLES

2.5.1 Methods

2.5.1.1 Participants

The participants tested in Experiment 4 were the same as those detailed in Chapter 1, Experiment 2 and Experiment 3.

2.5.1.2 Design

Experiment 3 followed the same methodological design as Chapter 1, but with the addition of the control variables detailed in Experiments 2 and 3.

2.5.1.3 Materials

The same materials were used as in Experiments 2 and 3.

2.5.1.4 Procedure

Experiment 4 analysed the HCT, HDT and control variable data from Experiments 2 and 3, thus the previously set out procedure applies to this experiment.

2.5.2 Data Analysis

2.5.2.1 Score Calculations

Scores for each variable were calculated as set out in Chapter 1 and Experiments 1-3 of Chapter 2.

2.5.2.2 Exclusions

The number of participants in these analyses as opposed to those in Chapter 1 differs by 2 because we did not have complete data for all of the control variables for 2 of the participants.

2.5.2.3 Descriptive Statistics

The dependent variable data for this experiment is the same as in Chapter 1, descriptive statistics for which are presented in Table 1. The control variable data used is the same as in Experiments 2 and 3, with Tables 4, 5 and 8 presenting the descriptive statistics.

2.5.2.4 Analyses

The correlation analyses conducted in Chapter 1 were repeated as partial correlation analyses using all of the control variables that were explored in Experiments 2 and 3 (resting heart rate, heart rate variability, BMI, depression, sex, age, time estimation, tactile perception (Easy and Easy-Moderate conditions) anxiety, knowledge of resting heart rate, systolic blood pressure). We ran additional partial correlations controlling for the variables found to significantly predict HDT-Accuracy in this sample: Easy Tactile, age, depression and heart rate (see Experiment 2). These were only run for correlations in which HDT-Accuracy was one of the variables.

2.5.3 Results

The results of the partial correlations are presented in Table 10. Controlling for the aforementioned non-interoceptive variables failed to reveal any additional significant relationships between the different interoceptive abilities. It did, however, remove significant correlations observed in Chapter 1 between IAS Score and HDT-Sensibility, and HCT-Sensibility and HCT-Awareness. The significant relationships observed in Chapter 1 between HDT-Sensibility and HCT-Sensibility, HCT-Accuracy and HCT-Sensibility, and HDT-Sensibility and HDT-Awareness, remained even after controlling for the non-interoceptive variables. The relationship between HDT-Accuracy and HDT-Awareness remained marginally significant at $p = .005$.

Table 10

*Partial correlations between different measures of interoception controlling for age, sex, BMI, systolic blood pressure, resting heart rate, heart rate variability, knowledge of resting heart rate, depression, anxiety, time estimation, and tactile perception (Easy and Easy-Moderate). * indicates p < .05; ** indicates p < .01.*

Variable 1	**Variable 2**	**N**	**Pearson's Correlation (*r*)**	**Degrees of Freedom**	***p***
HCT-Accuracy	HDT-Accuracy	34	.06	20	.806
HCT-Sensibility	HDT-Sensibility	34	.73	20	<.001**
IAS	HCT-Sensibility	42	.19	28	.325
IAS	HDT-Sensibility	34	.33	20	.139
HCT-Awareness	HDT-Awareness	31	-.12	17	.631
HCT-Accuracy	HCT-Sensibility	42	.37	28	.046*
HCT-Accuracy	HCT-Awareness	40	-.13	26	.509
HCT-Sensibility	HCT-Awareness	40	-.35	26	.070
HDT-Accuracy	HDT-Sensibility	34	.09	20	.703
HDT-Accuracy	HDT-Awareness	32	.44	18	.050
HDT-Sensibility	HDT-Awareness	32	.64	18	.003*

Partial correlations were run between the pairs in Chapter 1 containing HDT-Accuracy as a variable, controlling for Easy Tactile, age, depression and resting heart rate. The correlation between HDT-Accuracy and HDT-Awareness remained significant (r(28) = .51, p

= .004), and non-significant relationships were again found for the correlations between HDT-Accuracy and HDT-Sensibility ($r(30) = .06$, $p = .736$) and HDT-Accuracy and HCT-Accuracy ($r(30) = .15$, $p = .428$).

2.5.4 Interim Discussion

This chapter aimed to investigate whether controlling for non-interoceptive factors would alter the relationships observed in Chapter 1 between measures of interoceptive ability within and between the HCT and HDT. Controlling for these variables failed to reveal any additional significant relationships. This suggests that the absence of significant relationships in Chapter 1 was not due to the influence of the non-interoceptive factors we investigated: HDT-Accuracy and HDT-Sensibility; HCT-Accuracy and HCT-Awareness; HCT-Accuracy and HDT-Accuracy; HCT-Awareness and HDT-Awareness. If these factors were responsible for masking an underlying relationship between the variables, we would have expected that controlling for these factors would reveal a significant relationship. For the former two pairs, this strengthens the proposal that accuracy is distinct from sensibility and awareness. For the latter two pairs, it leads us to conclude that the defining differences of abilities underlying performance on the HCT and HDT are not made up of the non-interoceptive variables we tested.

Further to this, there were a number of significant relationships that were not affected by controlling for the non-interoceptive variables: HDT-Sensibility and HCT-Sensibility; HCT-Accuracy and HCT-Sensibility; HDT-Sensibility and HDT-Awareness. The relationship between HDT-Accuracy and HDT-Awareness remained marginally significant. This further strengthens the idea that these abilities are related, as the significant relationships remain in spite of controlling for a variety of other potentially influencing factors.

We did, however, reveal a non-significant relationship between HCT-Sensibility and HCT-Awareness by controlling for these factors, despite a significant correlation being found in Chapter 1 in the absence of control variables. This leads to support for Garfinkel et al.'s (2015) proposal that these are separate abilities. However, this is still confounded by the fact that the same result is not found in data from the HDT meaning that conflicting conclusions can be drawn from the two tasks.

The partial correlations also revealed that the previously significant relationship between IAS and HDT-Sensibility was found to be non-significant after controlling for these non-interoceptive factors. Therefore, we are now unable to conclude that the IAS is significantly related to either HDT-Sensibility or HCT-Sensibility, which is problematic for its use as a measure of interoceptive sensibility.

2.6 DISCUSSION

In this chapter we explored the role of non-interoceptive variables in heartbeat task performance and applied these as control factors for analyses between performance on the tasks. Experiments 1-3 attempted to significantly predict HCT-Accuracy or HDT-Accuracy using the non-interoceptive control variables measured. Experiment 4 tested whether controlling for these variables would alter the relationships between interoceptive measures observed in Chapter 1.

In Experiments 1 and 3 we were able to show that, with a combination of control measures, HCT-Accuracy and HDT-Accuracy could be significantly predicted. Interestingly, both of these models included Easy Tactile as a significant positive predictor. This indicates that it is important to consider the effect of tactile sensitivity when implementing the heartbeat perception tasks, as individuals who had better tactile perception were also more successful at the HCT and HDT. Other similarities between the models include the inclusion of resting heart rate and age as predictors, with resting heart rate acting as a significant predictor for HDT-Accuracy but not HCT-Accuracy.

It should be noted that the significant prediction models for HCT-Accuracy and HDT-Accuracy contained a different combination of variables. For example, time estimation was not included in the prediction model of HDT-Accuracy, whereas it was a significant predictor of HCT-Accuracy. This supports the idea that, whilst some variables are common to both prediction models, there are differing task demands between the HCT and HDT meaning that a different combination of variables need to be controlled for. Therefore, the combination of variables should not be generalised across heartbeat perception tasks, but instead individually determined for both the HCT and HDT. Future studies should investigate this further, specifically by implementing well matched control tasks for the non-interoceptive requirements of the heartbeat perception tasks. HCT performance relies on sustained attention and working memory, something which is well paralleled in the time estimation control task. Contrastingly, the requirement of multisensory integration for the HDT is not addressed in any of the control variables we employed. This would be a useful development for studies utilising the HDT.

Experiment 2 has further demonstrated that the non-interoceptive control variables differ in their ability to predict heartbeat perception tasks across population samples. Here, we were unable to predict HCT-Accuracy with a combination of control variables despite being able to do so in Experiment 1. This highlights that it may not always be possible to significantly predict heartbeat perception using the same combination of control variables. A number of explanations were explored such as the participants' approach to the task including answering zero to the number of heartbeats they felt and having a steep gradient between time interval and score. In these approaches, individuals were excluded, and the analyses were run again. However, no concrete conclusions could be drawn due to the reduced sample size of the subsets that were analysed. It seems feasible that the lack of replication may be due to differences in group demographics and thus the inability to demonstrate the effects of the variables, but there were not enough data to verify this.

The results of Experiment 2 are also problematic with respect to the finding that the tactile perception control task positively predicts the heartbeat perception tasks. Once participants were excluded on the basis of their time interval to score gradient, a significant prediction model emerged in which a higher vibration intensity condition of the tactile perception control task negatively predicted HCT-Accuracy. This significant negative relationship opposes the findings of Experiments 1 and 3 and the generally accepted literature that tactile sensitivity is positively related to heartbeat perception (Knapp et al., 1997). Whilst there is evidence in the literature for a negative relationship between exteroceptive and interoceptive abilities (Valenzuela-Moguillansky et al., 2017), it is problematic that the opposite pattern has been observed from a weaker vibration intensity condition of the same task in Experiments 1 and 3. One of the key problems here is knowing which intensity to rely on for determining the true relationship between tactile perception and heartbeat perception. This difficulty arises due to the fact that the vibration intensities were fixed. This is a limitation of the task as the different intensity levels may have related to different levels of difficulty for each participant. This could be improved by setting the intensity level of the task to each participant's individual tactile sensitivity threshold in order to avoid trialling multiple predetermined intensities for each participant. With one intensity of vibration set to each participant's personal sensitivity, a clearer impression of the effect of the tactile task on interoceptive accuracy could be obtained. Thus, it is clear that our tactile perception control task requires development before being further investigated and potentially utilised in the future.

Experiment 4 demonstrated the effect of controlling for the non-interoceptive variables when exploring relationships between different interoceptive measures as seen in Chapter 1. The majority of relationships remained unchanged after controlling for these factors which indicates that the unexpected relationships observed in Chapter 1 were not due to the influence of non-interoceptive factors. This adds strength to the findings of Chapter 1 and validates the discussions of inconsistency between interoceptive measures. Controlling for these factors did remove the significant relationship between HCT-Sensibility and HCT-Awareness which supports Garfinkel et al.'s (2015) distinction between different interoceptive abilities. However, it also removed the significant relationship between the IAS and HDT-Sensibility which brings into question the use of the IAS as a measure of interoceptive sensibility.

This chapter indicates that the heartbeat perception tasks do not index purely interoceptive abilities as they can be predicted by a number of non-interoceptive factors. However, the factors which predict task performance were seen to differ depending on the heartbeat perception task employed. Therefore, the importance of each variable should be assessed for each task. The tactile perception control task seems to be an important predictor of both the HCT and HDT and should be developed further in order to be employed in conjunction with these tasks. Moving forward, relevant non-interoceptive variables should be controlled for in order to obtain a more valid index of interoceptive accuracy. Finally, our implementation of these control variables to the correlations between different interoceptive measures indicated that the relationships were generally not altered by controlling for non-interoceptive factors. This validates the discussions within Chapter 1 where these correlations were reported without the implementation of control variables.

CHAPTER 3 – THE RELATIONSHIP BETWEEN INTEROCEPTION AND PROPRIOCEPTION

3.1 INTRODUCTION

The final consideration of this thesis is whether or not accuracy in the interoceptive domain is related to accuracy in the proprioceptive domain. Interoceptive accuracy, as previously discussed, is typically indexed via the HCT and HDT. A commonly used measure of proprioceptive accuracy is the position matching task (Goble, 2010), in which participants must match the position of their arms in the absence of visual information. This task can either be ipsilateral, where participants are asked to reproduce the previously experienced target position using the same arm, or contralateral, which involves participants matching one arm to the position of the other arm. In order to index proprioceptive accuracy, we have developed an ipsilateral version of this task in which participants are first moved to a location under a grid and then asked which target point they think they have been moved to. We refer to this task as a location matching task due to its reliance on a grid of locations. Here, we employ this task in addition to two measures of interoceptive accuracy (the HCT and HDT) in an attempt to reveal a relationship between proprioceptive accuracy and interoceptive accuracy.

At present, there is conflicting opinion in the literature as to whether proprioception is a form of interoception. While some definitions have classified interoception and proprioception as separate abilities (Sherrington, 1906), others have defined interoception as "a general concept, which includes two different forms of perception: proprioception and visceroception" (Vaitl, 1996), or "the afferent information that arises from anywhere and everywhere within the body – the skin and all that is underneath the skin, e.g., labyrinthine and proprioceptive functions – not just the visceral organs" (Cameron, 2001). There is no clear consensus opinion as to whether these abilities are distinct or related.

The limited studies exploring the relationship between interoception and proprioception have reported contrasting findings. Murphy et al. (2017a) investigated this relationship using a task of muscular effort widely thought of as proprioceptive and a common proxy measure for interoception, the TAS. In the proprioception task, participants arms were fixed, and they were given a reference bucket of a certain weight to hold. This was then replaced with an empty bucket and they were asked to match the force exerted to hold the first bucket by adding weights to the empty bucket. This required them to accurately perceive the muscular effort required to hold the reference bucket and determine when they had matched this effort in the test phase. A significant correlation was found between this task and the TAS; therefore, this study seems to suggest that interoceptive and proprioceptive abilities are related. We extend these findings by using common measures of interoceptive accuracy (HCT and HDT) as opposed to a proxy measure of interoception (the TAS).

By contrast, Ferentzi et al. (2018) investigated whether sensitivity to a particular interoceptive modality can be generalised to other modalities. Of interest to this chapter, they employed the HCT, a common measure of interoceptive accuracy, in addition to an elbow joint task to index proprioceptive sensitivity. The elbow joint task had two parts: first, participants were asked to reproduce the position that their forearm had previously been moved into by moving their elbow; second, participants were asked to match the position of the opposite forearm by moving their elbow. Correlation analyses failed to reveal any significant associations between the versions of the proprioception task and the HCT. This suggests that these are two separate abilities. However, the study employs the HCT, a commonly known 'noisy' measure of interoception, and fails to consider the impact of non-interoceptive factors on the relationship. In fact, it should be noted that no studies at present have investigated this relationship whilst controlling for the number of known factors found to affect performance on heartbeat perception tasks (Murphy et al., 2018). Further, it may be that these factors are also applicable to proprioception as there are a number of known predicting factors of proprioceptive ability including age (Skinner et al., 1984).

This chapter hypothesises that, in line with Ferentzi et al. (2018), a relationship will not be found between interoceptive accuracy and proprioceptive accuracy in the absence of control variables, but that this relationship will emerge when these variables are controlled for. If, despite the presence of these control variables, no relationship is found, this would bring into question the proposal that interoception and proprioception are in some way related.

3.2 METHODS

3.2.1 Participants

The participants recruited for this study came from the same pool of participants as in Chapter 1. This task specifically was run on 25 of these participants, 5 male and 20 female, in the age range 18-32 (M = 20.72, SD = 2.73).

3.2.2 Design

Participants completed all of the heartbeat tasks and controls as set out in Chapter 2 (Experiments 2-4), in addition to a location matching task. The dependent variables were HCT-Accuracy, HDT-Accuracy and Proprioception Error Score (PES). The control variables used were those set out in Chapter 2 (Experiments 2-4) and are displayed alongside all other variables used in this chapter in Figure 7.

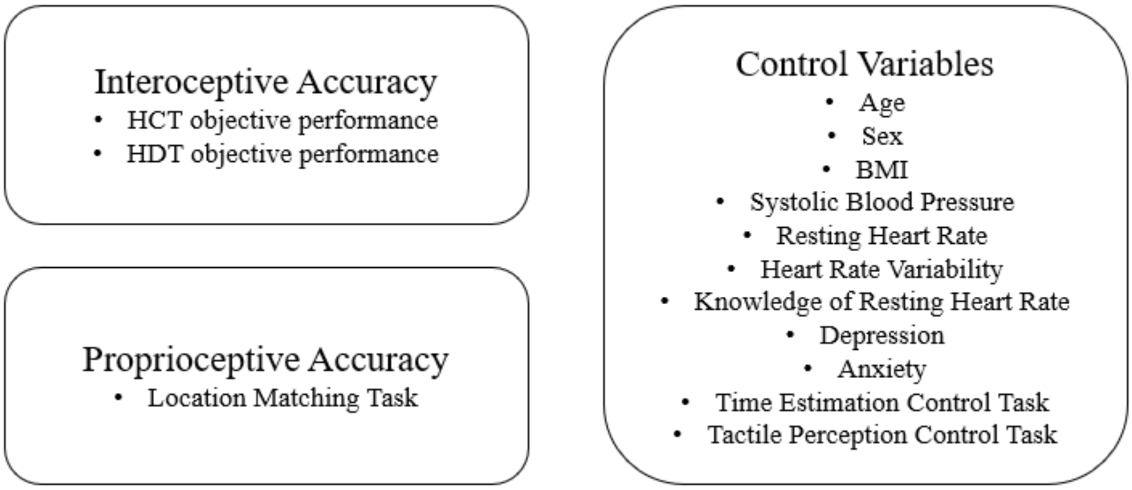

Figure 7. A list of the variables used in Chapter 3 and the tasks used to index them.

3.2.3 Materials

The location matching task was performed with a KINARM (BKIN Technology, London, Ontario; sampling rate: 1000Hz) and was run using Simulink (The Mathworks, Natwick, MA) and Dexterit-E (BKIN Technology).

3.2.4 Procedure

Participants were sat in a fixed chair in front of the KINARM so that their body was centrally located in front of the screen. They were asked to rest their head on the head rest of the KINARM which ensured that they were facing down towards the screen in a fixed position. A bib was attached from around the participant's neck to the KINARM so that they were unable to see the position of their arms during the task.

Participants completed a practice phase followed by a test phase using each arm, the order of which was counterbalanced with half of participants starting with their dominant arm and the other with their non-dominant arm. For each arm, they first practiced using the KINARM by holding onto the handle under the screen and moving from a centre location to the location of targets that appeared on the screen. Targets appeared individually on the screen in red on a black background and a white dot on the screen tracked their current location. The visual feedback of their position allowed participants to become familiarised with the 1:1 mapping between the screen and their own position in space. This was deemed necessary as pilot testing revealed that without these practice trials participants found it difficult to understand that the movements of the KINARM could be mapped to screen coordinates. Once the participant had successfully reached the location, the target turned green and the centre target reappeared for participants to move back to. The targets comprised 10 cm reaches to 8 positions on a circle with a radius of 10cm, in addition to the 4 corners of a 10cm by 10cm square surrounding the circle (Figure 8). This made a total of 12 trials.

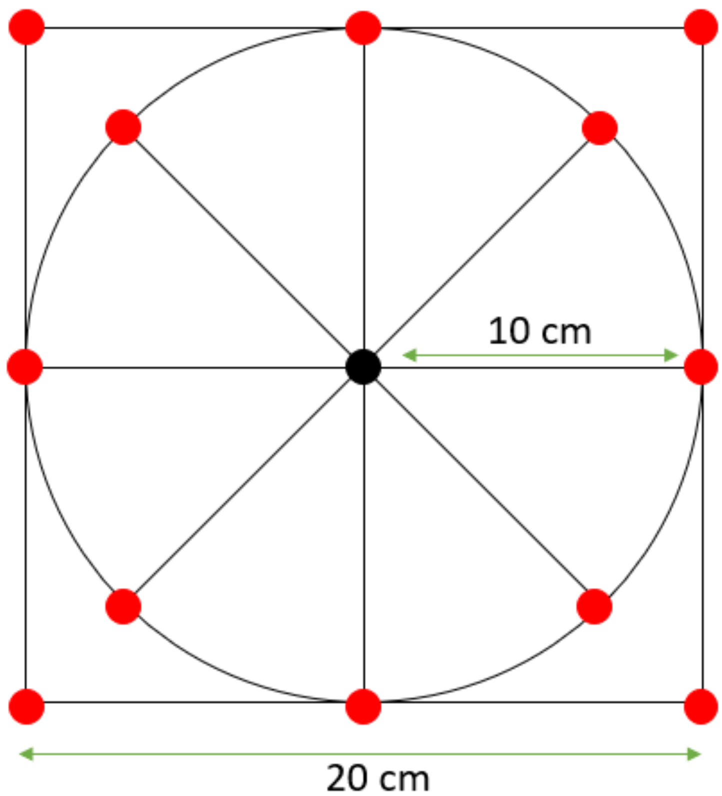

Figure 8. Specifications for the distance between the targets in the practice phase of the location matching task. The figure shows targets in red and the centre location in black.

Following the practice stage, participants took part in the test phase. A 20cm by 20cm grid appeared on the screen containing a red central location and 396 possible target locations with a 1cm distance between them (see Figure 9). The targets were coloured green and labelled with a letter and a number. The grid was not visible during the practice phase so participants had no experience of linking specific grid locations to the position of their arm. None of the target positions overlapped with the red locations used in the practice phase.

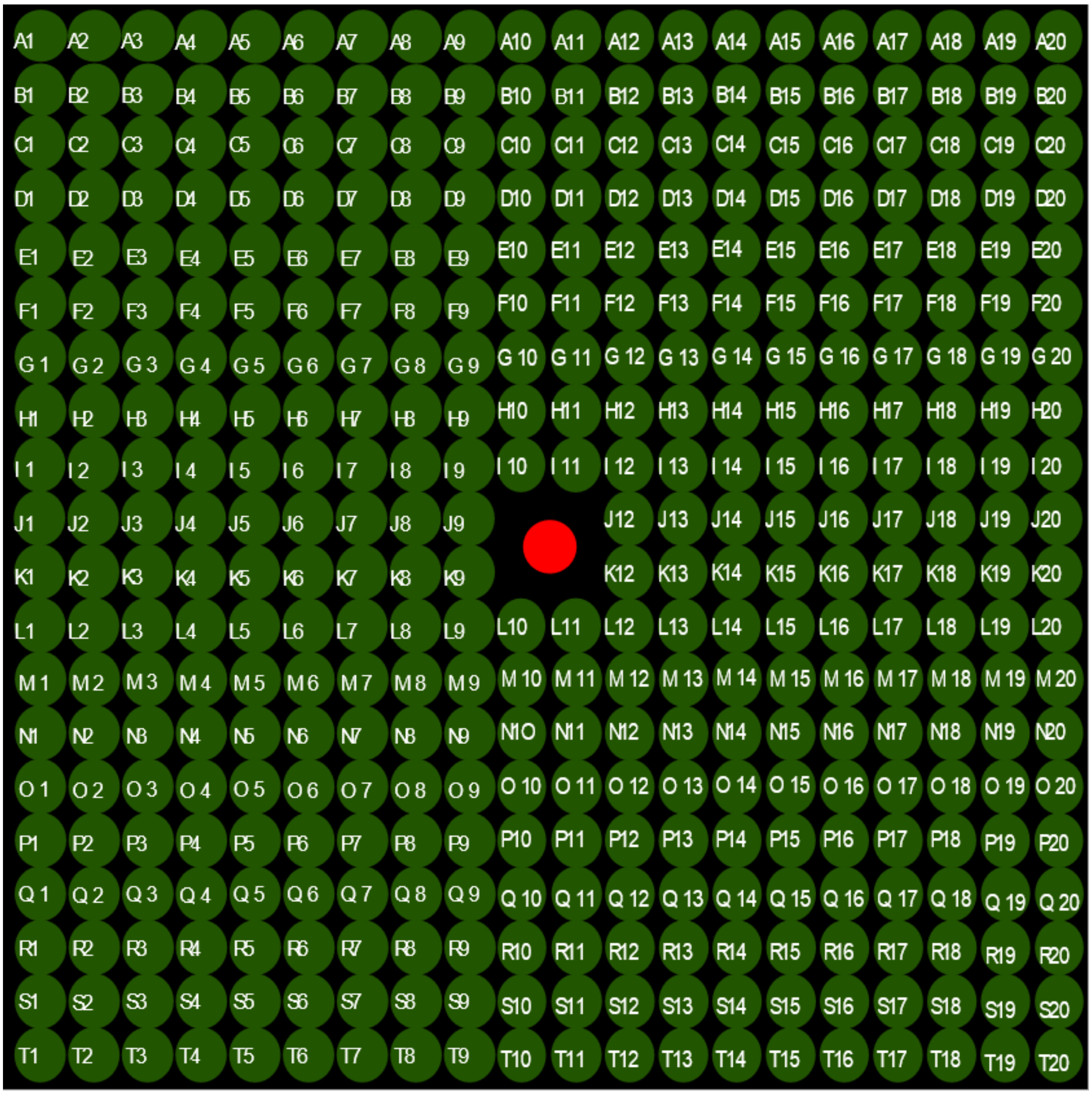

Figure 9. The view of the grid as seen by participants on the screen during the test phase of the location matching task.

In the task, participants held onto the handle and were moved in a straight line from the centre point to one of the target locations. The locations of the targets, which were the same for both arms, are displayed in Figure 10. The duration of the movement was randomised between 1000 ms and 1500 ms seconds to remove speed as a cue for distance. They were then asked to read out the label of the target location at which they thought they had been moved to. The participant was moved back to the centre point after each trial to ensure that their beliefs about their current location did not interfere with their performance on the subsequent trial. The duration of this movement back to the centre was fixed at 1000 ms, and participants were held at the centre for 2000 ms before being taken to the next target. The task consisted of 18 trials with targets appearing in a random order. During this task they received no visual feedback of their current location or information regarding their performance.

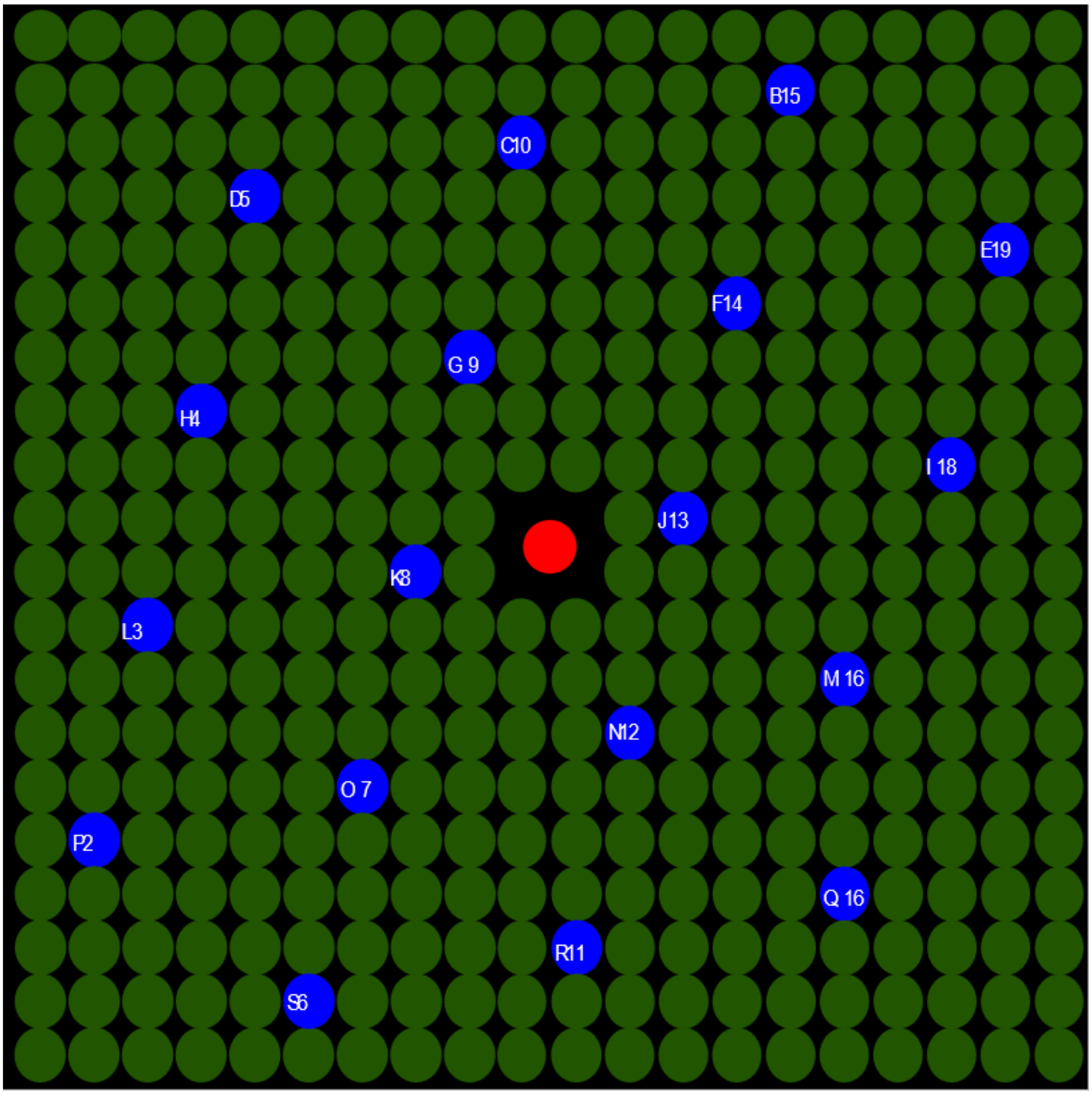

Figure 10. The locations of the targets used within the test phase of the location matching task. Blue circles indicate the targets used.

3.3 DATA ANALYSIS

3.3.1 Score Calculations

Proprioception Error Scores (PES) from the location matching task were calculated as the average error across trials, with error measured as the distance in centimetres between the target location and the location specified by the participant. Overall PESs, in addition to separate scores for the dominant and non-dominant arm, were recorded. For the HCT, HDT, tactile perception control task and time estimation control task, scores were calculated as set out in the previous chapters.

3.3.2 Exclusions

Due to time constraints, the location matching task was only run with 25 participants. Of these participants, 3 had no HCT or HDT data due to a malfunction with the pulse oximeter, and a further 2 had their HDT data removed due to the incorrect timing of tones during the task. Therefore, 23 participants were tested on the HCT and the location matching task task, and 20 on the HDT and the location matching task. One participant did not complete the full set of control variables, therefore was also excluded from the analysis. Thus, the total sample sizes were 22 and 19 for the HCT and HDT subsets respectively.

3.3.3 Descriptive Statistics

Descriptive statistics for the PESs can be found in Table 11. Log transformations were applied to these scores. The same transformations were applied to the HCT, HDT and control variable data as set out in Chapter 2 (Table 4). Tables 12 and 13 present the descriptive statistics for all data used in the analyses between PESs and HCT, and PESs and HDT respectively. Z-scores were computed for all variables before analysis.

Table 11

Descriptive statistics for Proprioception Error Scores (untransformed and transformed data)

Variable	N	Mean	SD	Skew	Kurtosis
Dominant Arm PES	25	2.03	0.52	1.07	1.43
Dominant Arm PES (log transform)	25	0.29	0.10	0.44	-0.07
Non-Dominant Arm PES	25	2.17	0.75	1.36	1.55
Non-Dominant Arm PES (log transform)	25	0.32	0.13	0.69	0.14
Overall PES	25	2.10	0.59	1.52	2.28
Overall PES (log transform)	25	0.31	0.11	0.99	0.42

Table 12

Descriptive statistics for HCT-Accuracy and Proprioception Error Scores (untransformed and transformed data)

Variable	**Mean**	**SD**
Overall PES	2.12	0.61
Overall PES (log transform)	0.30	0.11
Dominant Arm PES	2.05	0.53
Dominant Arm PES (log transform)	0.30	0.11
Non-Dominant Arm PES	2.18	0.77
Non-Dominant Arm PES (log transform)	0.32	0.14
HCT-Accuracy	182.57	117.89
Age	20.87	2.80
Age (reciprocal transform)	0.05	0.01
Sex	1.74	0.45
BMI	21.60	1.92
Systolic Blood Pressure	109.29	10.38
Knowledge of Resting Heart Rate	15.95	13.26
Knowledge of Resting Heart Rate (log transform)	0.98	0.55
Anxiety	3.65	4.05
Anxiety (log transform)	0.51	0.39
Depression	3.39	3.74
Easy Tactile	356.78	53.49
Easy-Moderate Tactile	307.95	123.36
Easy-Moderate Tactile (cube transform)	40128682.89	23568911.50
Time Estimation	300.33	70.60
Resting Heart Rate	75.99	9.70
Heart Rate Variability	0.07	0.05

Table 13

Descriptive statistics for HDT-Accuracy and Proprioception Error Scores (untransformed and transformed data)

Variable	**Mean**	**SD**
Overall PES	2.09	0.61
Overall PES (log transform)	0.29	0.10
Dominant Arm PES	2.02	0.50
Dominant Arm PES (log transform)	0.29	0.10
Non-Dominant Arm PES	2.15	0.80
Non-Dominant Arm PES (log transform)	0.31	0.14
HDT-Accuracy	0.17	0.49
Age	21.15	2.91
Age (reciprocal transform)	0.05	0.01
Sex	1.75	0.44
BMI	21.68	1.91
Systolic Blood Pressure	109.65	10.95
Knowledge of Resting Heart Rate	14.95	13.47
Knowledge of Resting Heart Rate (log transform)	0.93	0.56
Anxiety	3.60	4.12
Anxiety (log transform)	0.49	0.41
Depression	3.45	3.65
Easy Tactile	358.21	56.17
Easy-Moderate Tactile	301.65	131.41
Easy-Moderate Tactile (cube transform)	39689578.41	25248637.76
Time Estimation	308.94	60.56
Resting Heart Rate	73.98	8.08
Heart Rate Variability	0.08	0.05

3.3.4 Analyses

Pearson's correlations and partial correlations controlling for the control variables (BMI, systolic blood pressure, resting heart rate, heart rate variability, knowledge of resting heart rate, time estimation, age, sex, depression, anxiety, and tactile perception) were conducted to investigate the relationships between PESs (Total, Dominant and Non-Dominant) and HCT-Accuracy, and PESs (Total, Dominant and Non-Dominant) and HDT-Accuracy.

Follow up analyses were employed to further investigate the effects of the control variables in the above relationships found to be significant. Regression analyses were run for both variables in the correlation in which all the control variables acted as predictors. The residuals for each participant were then calculated in order to create new scores reflecting the value that remained after the control variables had been controlled for. Correlations were run between the residuals and original scores in order to determine which score it was necessary for the control variables to act upon to reveal a significant relationship. Finally, stepwise backwards method regressions were run on the relevant scores to determine which control variables significantly predicted them.

3.4 RESULTS

No significant correlations were found between PES (Total, Dominant and Non-Dominant) and HCT-Accuracy and HDT-Accuracy, statistics for which are displayed in Table 14. When these relationships were reanalysed as partial correlations, controlling for the aforementioned control variables, a significant relationship was found between Dominant PES and HCT-Accuracy (p = .032), and a marginally significant relationship between Total PES and HCT-Accuracy (p = .051). No other significant relationships emerged. Full statistics for the partial correlations are displayed in Table 15. It should be noted that a significant correlation was found between Dominant PES and Non-Dominant PES, with all participants tested on the task included in the analysis: $r(25) = 0.65$, $p < .001$.

Table 14

Pearson's correlations between Proprioception Error Scores and both the HCT and HDT.

	Dominant PES	Non-Dominant PES	Total PES
HCT-Accuracy	$r(22) = -.29$, p = .175	$r(22) = .08$, p = .741	$r(22) = -.08$, p = .710
HDT-Accuracy	$r(19) = .10$, p = .678	$r(19) = -.15$, p = .531	$r(19) = -.06$, p = .796

Table 15

*Partial correlations between Proprioception Error Scores and both the HCT and HDT controlling for age, sex, BMI, systolic blood pressure, resting heart rate, heart rate variability, knowledge of resting heart rate, depression, anxiety, time estimation, and tactile perception (Easy and Easy-Moderate). * indicates p < .05.*

	Dominant PES	Non-Dominant PES	Total PES
HCT-Accuracy	$r(22) = -.68$, p = .032*	$r(22) = -.38$, p = .283	$r(22) = -.63$, p = .051
HDT-Accuracy	$r(19) = .06$, p = .899	$r(19) = -.31$, p = .494	$r(19) = -.19$, p = .677

Analyses were conducted to further explore the significant and marginally significant relationships between HCT-Accuracy and Dominant PES, and HCT-Accuracy and Total PES respectively. Separate regression analyses were run with HCT-Accuracy and the PES as respective dependent variables and the non-interoceptive control measures as predictors. From these regressions, the residuals that remained after controlling for the non-interoceptive variables were calculated for HCT-Accuracy and PES respectively. This allowed us to obtain participants' scores for each variable after accounting for the impact of the control variables. Correlations were then run between the original variables and newly calculated residuals in order to determine which score the control variables acted upon to reveal a significant relationship.

For Dominant PES, a significant correlation was found between the HCT-Accuracy residuals and PES residuals ($r(21) = -.57$, $p = .006$) and HCT-Accuracy and PES residuals ($r(21) = -.50$, $p = .017$), but not between HCT-Accuracy residuals and PES ($r(21) = -.35$, $p = .109$). Thus, removing variance associated with the control variables from the PES revealed a significant relationship with HCT-Accuracy, however removing variance associated with the control variables from the HCT-Accuracy score did not reveal a significant relationship with PES. Similarly for Total PES, significant correlations were found between both residuals ($r(21) = -.53$, $p = .011$), and HCT-Accuracy and PES residuals ($r(21) = -.47$, $p = .027$) but not between HCT-Accuracy residuals and PES ($r(21) = -.17$, $p = .462$).

Due to the above results, a stepwise backwards method regression was run to explore which variables were important for predicting PES and thus had the greatest impact as control variables. For the Dominant PES, a model containing age, sex, BMI, depression, time estimation, resting heart rate and heart rate variability was found to be significant ($R^2 = .40$, $F(7, 14) = 2.99$, $p = .038$). Age, time estimation, resting heart rate and depression were found to be significant predictors. The regression model is displayed in Figure 11 and Table 16 reports the beta coefficient for each variable.

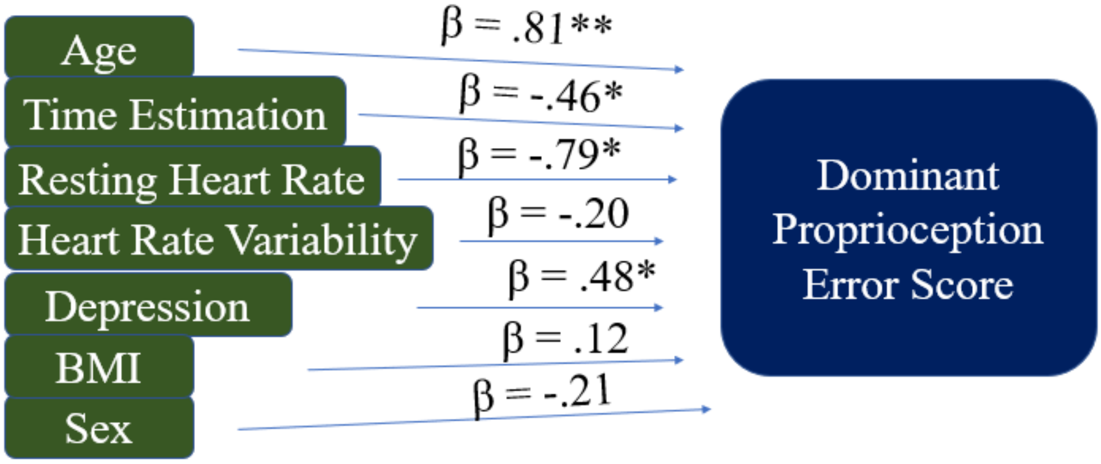

Figure 11. The significant regression model predicting Dominant Proprioception Error Score, with standardised beta coefficients. * indicates p < .05; ** indicates p < .01.

Table 16

*Beta coefficients for each variable in the significant regression model. * indicates p < .05; ** indicates p < .01.*

Variable	***β***	***β*(std. Err.)**	**Standardised *β***	***t***	***p***
Age	1.16	.35	.81	3.32	.005**
Resting Heart Rate	-.85	.30	-.79	-2.87	.012*
Depression	.43	.16	.48	2.73	.016*
Time Estimation	-.42	.18	-.46	-2.38	.032*
Sex	-.22	.19	-.21	-1.17	.263
Heart Rate Variability	-.20	.20	-.20	-0.96	.351
BMI	.16	.23	.12	0.69	.499

When a stepwise backwards method regression was run for Total PES, a significant model containing age, sex, systolic blood pressure, anxiety, depression, Easy Tactile, Easy-Moderate Tactile, time estimation, resting heart rate and heart rate variability emerged (R^2 = .50, $F(10, 11) = 3.08$, $p = .039$). Age, time estimation and resting heart rate were significant predictors. The model and standardised beta coefficients are displayed in Figure 12 and Table 17.

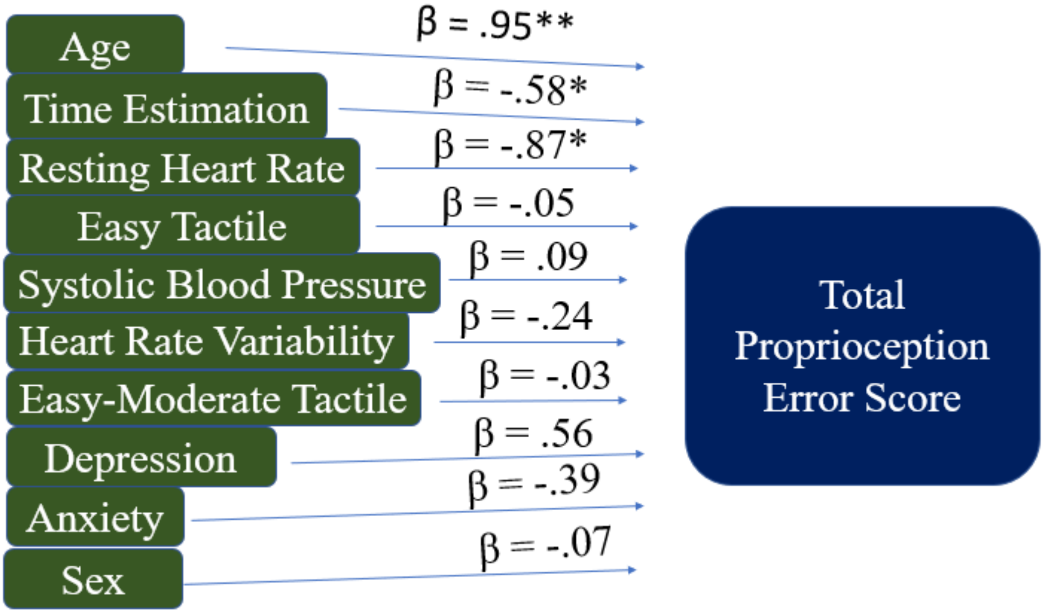

Figure 12. The significant regression model predicting Total Proprioception Error Score, with standardised beta coefficients. * indicates $p < .05$; ** indicates $p < .01$.

Table 17

*Beta coefficients for each variable in the significant regression model. * indicates p < .05; ** indicates p < .01.*

Variable	***β***	***β*(std. Err.)**	**Standardised *β***	***t***	***p***
Age	1.37	.35	.95	3.92	.002**
Resting Heart Rate	-.94	.33	-.87	-2.87	.015*
Time Estimation	-.53	.21	-.58	-2.53	.028*
Depression	.50	.25	.56	2.01	.070
Anxiety	-.39	.33	-.39	-1.17	.267
Heart Rate Variability	-.23	.21	-.24	-1.13	.284
Systolic Blood Pressure	.10	.29	.09	0.33	.752
Sex	-.07	.44	-.07	-0.16	.874
Easy Tactile	-.05	.38	-.05	-0.12	.905
Easy-Moderate Tactile	-.04	.33	-.03	-0.11	.916

3.5 DISCUSSION

Through conducting partial correlations whilst controlling for a variety of control variables, this chapter has revealed a significant relationship between HCT-Accuracy and PES (Dominant and Total). The negative relationship indicates that a higher score on HCT-Accuracy is associated with a lower proprioception error score, thus interoceptive and proprioceptive task performance have a positive relationship with one another. Note that this relationship was only found when non-interoceptive factors were controlled for using a partial correlation analysis. Consequently, these results highlight control variables as important considerations in the exploration of this relationship. Failure to implement these controls would have resulted in the conclusion that interoceptive and proprioceptive abilities were not related, thus our analysis allowed us to gain an understanding of which variables act upon the relationship between these two abilities. The significant relationships found point to this as an area for future research in which other measures of interoception and proprioception should be analysed whilst controlling for control variables. This may lead us to draw significant conclusions where previous research has failed to indicate a relationship.

However, it is important to note that a significant relationship was not found between Non-Dominant PES and HCT-Accuracy by controlling for control measures as it was for Dominant PES and HCT-Accuracy. This demonstrates that Dominant PES was related to performance on the HCT, but Non-Dominant PES was not. Thus, there must be a difference between the abilities relied on when completing the task with the dominant arm as opposed to the non-dominant arm. Previous studies have shown that proprioceptive ability differs between the dominant and non-dominant arm, with interesting findings that the non-dominant arm has a proprioceptive advantage (Goble & Brown, 2007; Goble, Lewis & Brown, 2006). Goble and Brown (2008) concluded that the performance advantage of the non-dominant arm was specific to a purely proprioceptive task in which an individual’s elbow was held at a particular angle for 3 seconds and they were then asked to match this angle with their arm. By contrast, they found that in a visual version of the task, in which participants were asked to point a laser to the same location as a previously presented visual target, the dominant arm was seen to have an advantage. This suggests that dominant and non-dominant arms rely on visual and proprioceptive information to a different extent. Goble & Brown (2008) theorised that the dominant arm is more likely to utilise visual information in preference to proprioceptive information due to the fact it is commonly used in the visual field for tasks such as object manipulation. By contrast, the non-dominant arm is more commonly held outside of the visual field so it is more likely to rely on proprioceptive information as opposed to visual information. Considering both the proprioceptive and visual demands of our task, it could be considered that individuals perform differently between arms due to the relative ease of the proprioceptive and visual requirements. For example, when using their dominant arm, participants may be more successful at making a visual transform between their physical location and the coordinates on the screen. Conversely, when the task is conducted with their non-dominant arm, they may be more successful at perceiving the physical location of their arm due to the stronger proprioceptive ability of that arm. Further clarification of this hypothesis is needed but, if true, it emphasises the importance of implementing proprioception tasks that do not have any visual demands. It should also be noted that combining both dominant and non-dominant performance in the total score strongly reduced the clarity of the relationship observed between interoceptive accuracy and proprioceptive accuracy in the dominant arm alone. Future research concerning proprioception should therefore consider both dominant and non-dominant performance separately to check for differential effects.

It is necessary to critically consider what the observed relationship between PES and HCT-Accuracy implies. A correlation between these two tasks does not necessarily indicate that the two underlying abilities can be conflated to one combined factor. They may instead be distinct abilities that are able to influence one another. Indeed, Evrard's (2019) organisation of the primate insular cortex defines a location for the integration of "interoceptive activity with inputs from cortical and subcortical regions involved in the proprioceptive control of movements". This pathway for the integration of interoceptive and proprioceptive input supports the idea that the two abilities can influence one another. Further investigation into the overlap of pathways between interoception and proprioception will extend our understanding of whether these abilities are in fact distinct.

The residual correlation analyses indicate that the emergence of a significant relationship was due to the removal of variance associated with the control variables from the PES rather than HCT-Accuracy. The findings regarding HCT-Accuracy are unsurprising due to the results of Chapter 2 Experiment 2 which reported an inability to predict HCT-Accuracy with the control variables. However, they are unexpected in light of the literature as a whole which suggests that many non-interoceptive factors are associated with HCT-Accuracy (Murphy et al., 2018). Chapter 2 has explored why this may be the case. The finding that the control factors relate to proprioception leads to a suggestion that these factors should be considered in studies investigating this ability and its relationships with other abilities.

In particular, the stepwise backwards method regression indicates that performance on the proprioception task can be predicted by a model containing age, resting heart rate, depression, time estimation, sex, heart rate variability and BMI. Of these factors, age, heart rate, depression and time estimation significantly predict performance. Age and depression positively predicted PES, and therefore negatively predicted proprioceptive ability. The former seems intuitive as proprioceptive ability has been reported to decline as age increases (Skinner et al., 1984). The latter can be understood by the finding that increased depression relates to reduced physical exercise (Cassidy et al., 2004), and regular physical exercise is known to be associated with improved proprioceptive ability (Petrella, Lattanzio, & Nelson, 1997; Tsang & Hui-Chan, 2003). Contrastingly, resting heart rate and time estimation were found to negatively predict PES and therefore positively predict proprioceptive ability. It is not possible that participants were using time as a cue in the task as the duration of each movement was randomised. However, it may be that time estimation indexes domain-general abilities including sustained attention and working memory and that it is these abilities which are important with respect to the proprioceptive location matching task that we have employed. Future studies could test this hypothesis by implementing other control tasks specifically designed to index sustained attention and working memory and attempt to correlate performance on these tasks to both PES and the time estimation control task. The relationship with resting heart rate is more questionable and would need further investigation to understand why this occurs. It may be that an additional factor, such as physical exercise, relates to both resting heart rate (Reimers, Knapp, & Reimers, 2018) and PES (Petrella et al., 1997; Tsang & Hui-Chan, 2003). This would explain why a relationship would be observed between resting heart rate and proprioceptive ability.

It is important to note that no relationship was found between HDT-Accuracy and proprioceptive ability. It is unsurprising that HCT-Accuracy and HDT-Accuracy had different relationships with other abilities as they were not found to correlate with one another to form a related index of interoceptive accuracy (see Chapter 1). However, it is important to question why HDT-Accuracy's correlation with proprioception was non-significant. It may be due to the fact that rather than simply perceiving heartbeat, the HDT requires participants to also integrate the sensation with a simultaneous auditory cue. In other words, HDT performance requires multisensory integration. This requirement for sensory integration would not be controlled for by our current control variables. As a result, this task requirement may mask an underlying relationship between heartbeat perception and proprioceptive ability, thus preventing us from concluding that these two abilities are related. Future studies should test the idea that the multisensory integration demands of the HDT are preventing the emergence of a relationship with proprioception by creating a control task which would account for this ability.

Overall, these results demonstrated that a relationship between interceptive accuracy and proprioceptive accuracy can be observed when control measures are implemented, which highlights this relationship as an important area for future research. However, the different relationships proprioceptive accuracy exhibited with the HCT and HDT should be further assessed, in addition to differing relationships exhibited by the dominant and non-dominant arms. Finally, we conclude that the impact of control variables for both interoceptive and proprioceptive performance is especially relevant for this research and should be considered further in order to determine the factors of significant importance for each ability.

GENERAL DISCUSSION

4.1 FINDINGS

This thesis has aimed to address the issues of whether different interoceptive abilities are distinguishable, how non-interoceptive factors relate to heartbeat perception, and whether or not interoceptive and proprioceptive abilities are related. Chapter 1 tested the hypothesis that the different measures of interoceptive ability as proposed by Garfinkel et al. (2015) are in fact distinct, and that these measures correlate across tasks. Chapter 2 aimed to reveal the role of various non-interoceptive factors in predicting interoceptive accuracy and expected to find that controlling for these factors would alter relationships previously observed in Chapter 1. Finally, Chapter 3 addressed the relationship between interoception and proprioception, in addition to the utility of controlling for the aforementioned non-interoceptive factors in analyses between these abilities.

The results of Chapter 1 presented mixed findings relating to the independence of interoceptive abilities. It is not clear from this chapter that accuracy, sensibility and awareness are distinct aspects of interoceptive ability. Across both the HCT and HDT, mixed results indicated that there is some difficulty in identifying the exact nature of the relationships between these abilities. For example, there was no correlation between accuracy and sensibility in the HDT, but a significant positive relationship was found between them in the HCT. The opposite is true for the relationship between accuracy and awareness, whereby a non-significant relationship was found from the HCT data but a significant positive relationship from the HDT data. Finally, for the relationship between sensibility and awareness, a significant positive relationship was found from the HDT data and a significant negative relationship from the HDT data. These discrepancies highlight the caution that should be taken when indexing interoceptive abilities as the abilities exhibit different relationships with one another when indexed by different tasks. However, it should be noted that controlling for non-interoceptive factors in Experiment 4 of Chapter 2 removed the significant relationship between HCT-Sensibility and HCT-Awareness.

Chapter 1 also investigated the links between specific interoceptive abilities across tasks. No relationship was found between the measures of accuracy from the HCT and HDT, nor for the measures of awareness. This implies that accuracy and awareness in the HCT do not index the same abilities as accuracy and awareness in the HDT. This seems likely as the task demands differ, with the HCT relying more greatly on sustained attention and working memory and the HDT relying on multisensory integration. It is therefore understandable why no relationship would be found between both the accuracy scores and awareness scores for these tasks. However, a relationship was found between the confidence ratings in the HCT and HDT as a measure of interoceptive sensibility which seems intuitive as in both tasks this is indexed as the average confidence rating across all trials. This suggests that these ratings could be generalised across tasks to index interoceptive sensibility. However, no relationship was found between HCT-Sensibility and the IAS, and the significant relationship found between HDT-Sensibility and the IAS was removed after controlling for non-interoceptive factors in Experiment 4 of Chapter 2. This brings into question the validity of these measures of interoceptive sensibility.

Experiments 1-3 in Chapter 2 showed that non-interoceptive factors can affect performance on heartbeat perception tasks which emphasises the importance of control variables in future studies. In this chapter we were able to show that HCT-Accuracy and HDT-Accuracy can be significantly predicted with a combination of non-interoceptive control measures. However, a different combination of control measures was found to predict accuracy across the two tasks, indicating that heartbeat perception cannot be predicted across tasks with the same factors. In addition, Experiment 2 demonstrated that this prediction ability is not present for all samples, emphasising that these control factors are not consistently effective in all analyses. Interestingly, our tactile perception control task was found to significantly predict HCT-Accuracy in Experiment 1 and HDT-Accuracy in Experiment 3 in a positive direction. However, Experiment 2 complicated this finding by showing a negative significant relationship in an explorative analysis of the data.

As previously highlighted, Experiment 4 of Chapter 2 demonstrated that a number of relationships from Chapter 1 were affected when non-interoceptive factors were controlled for. However, the majority of the relationships remained unchanged by this analysis, thus strengthening these findings and validating the discussions of inconsistency between interoceptive measures.

The analyses conducted in Chapter 3 revealed that there was a significant relationship between HCT-Accuracy and PES (Dominant and Total) when controlling for the variety of control factors addressed in previous chapters. The results indicated that higher HCT-Accuracy is associated with lower PES, thereby suggesting that these interoceptive and proprioceptive abilities are positively linked. However, it should be noted that this relationship was not found between Non-Dominant PES and HCT-Accuracy, suggesting that dominant and non-dominant PES differ in their relationships with interoceptive ability. Further analysis of the significant relationship between HCT-Accuracy and PES indicated that the control factors related to proprioception and not interoception in this case. We observed that age, resting heart rate, depression and time estimation significantly predicted proprioceptive performance. It should be noted that a relationship was not found between HDT-Accuracy and PES. It is unsurprising that this sample showed different relationships with PES for HCT-Accuracy and HDT-Accuracy as previous chapters have indicated that these tasks may not index the same abilities.

4.2 THEORETICAL IMPLICATIONS

The relationships observed in Chapter 1 bring into question the proposal by Garfinkel et al. (2015) that accuracy, sensibility and awareness are distinct aspects of interoceptive ability, and finds evidence in support of proposals that the abilities are in fact related (e.g. Forkmann et al., 2016). For the model to be applied to all measures of interoceptive ability, the distinctions should be observed regardless of the tasks employed. We demonstrate that this is not always the case. It may be that particular tasks and participant samples find evidence in support of the model, but without consistent evidence it is not possible to conclude that this applies in all circumstances. This leads us to question attempts to reveal a relationship between clinical conditions and a specific interoceptive ability (e.g. Garfinkel et al., 2016b), as the different abilities are found to relate to one another. The chapter also supports findings that interoceptive accuracy indexed by the HCT and HDT are not related (Phillips et al., 2003; Schulz et al., 2013), emphasising the problem of conflating the two measurements into one form of interoceptive accuracy. Finally, the absence of a significant relationship between the IAS and HCT-Sensibility brings into question the use of the IAS for indexing interoceptive sensibility, especially as an inconsistent relationship between these abilities has previously been documented (Murphy et al., in press-a).

Chapter 2 demonstrates that a number of non-interoceptive factors influence heartbeat perception, thereby supporting the literature that these measures are not purely interoceptive (Brener & Ring, 2016; Knapp-Kline & Kline, 2005; Murphy et al., 2018; O'Brien et al., 1998; Rouse et al., 1988). Whilst non-interoceptive control variables are found to be important, their effect differs based on the heartbeat perception task. Therefore, it should be noted that it cannot be assumed that the same combination of control factors can predict performance on all heartbeat perception tasks. The chapter also re-emphasises the importance of tactile perception in heartbeat perception tasks as previously indicated by Knapp et al. (1997) but raises the question of how they are related as both positive and negative relationships were found.

Chapter 3 supports the existence of a significant relationship between interoceptive accuracy and proprioceptive accuracy (Murphy et al., 2017a). This has implications for the development of models of interoceptive and proprioceptive abilities and may lead researchers to consider relationships between clinical conditions and proprioception where focus has previously been placed on interoception (e.g. Garfinkel et al., 2016b). The difference in the relationship with interoception for dominant and non-dominant arms supports a distinction previously made that performance on proprioceptive tasks differs between arms (Goble & Brown, 2007; Goble, Lewis & Brown, 2006) and suggests that different strategies are adopted by the dominant and non-dominant arm. This highlights the relevance of considering both dominant and non-dominant performance separately to check for differential effects. In addition, this chapter adds an important contribution to the literature by revealing that a number of control factors can predict proprioception task performance. This suggests that these factors should be considered in future studies attempting to relate proprioceptive ability to task performance in other domains. Specifically, age and depression positively predicted proprioceptive error, the former of which replicates Skinner et al. (1984) and the latter of which can be understood by Cassidy et al.'s (2004) finding that depression relates to reduced physical exercise combined with the fact that regular physical exercise is known to be associated with improved proprioceptive ability (Petrella, Lattanzio, & Nelson, 1997; Tsang

& Hui-Chan, 2003). However, we also found that resting heart rate and time estimation negatively predicted proprioceptive error, something which requires further verification.

4.3 FUTURE DIRECTIONS

The findings of Chapter 1 are in conflict with literature that assumes that there are three distinct aspects of interoceptive ability. The inconsistency in their relationships with one another highlights the difficulty in interoception research for generalising across tasks. Future studies with increased sample size would be useful for clarifying these relationships in order to avoid reliance on the model of interoceptive ability. In addition, these supposedly distinct abilities fail to relate to the corresponding ability indexed by a different task. Therefore, researchers should be discouraged from selecting one of the measurements and using it as an indicator of that specific interoceptive ability. Future studies should also investigate the validity of both the IAS and confidence ratings as measures of interoceptive sensibility, as this study found that they did not relate to one another. This could be achieved by determining their respective relationships with alternative self-report methods of interoceptive sensibility in order to clarify which method best reflects this ability.

Chapter 2 highlights a variety of areas for future study. One area of importance is the use of the tactile perception control task, which requires further development before its utilisation in future research. Due to discrepancies in the relationship between tactile perception and heartbeat perception at different intensity levels, subsequent studies should personalise the intensity level to the participant's individual tactile sensitivity threshold. As a result, a clearer analysis outcome may be obtained as the difficulty level would be matched across participants. More generally, future studies should consider the use of control variables when investigating heartbeat perception to obtain a more accurate measure of interoceptive ability. However, the combination of variables should not be generalised to future studies as they have been found to differ in their predictive ability across tasks. Instead, each study should determine the variables of importance for their sample.

The findings from Chapter 3 lead to the requirement of a number of future studies. First, the significant relationship between proprioceptive and interoceptive abilities should be further verified using alternative measures of the two abilities. This would allow us to conclude whether the relationship observed can be generalised to all forms of interoceptive and proprioceptive ability as opposed to the specific tasks used in the study. In terms of proprioception and predicting factors, further investigation is needed to understand the relationships of proprioception and control variables such as resting heart rate. Specifically, it should be determined whether these variables directly relate to one another or whether a third factor, such a physical exercise, relates to them both individually. More generally, future studies investigating proprioceptive abilities should consider which control factors are necessary in order to ensure they are indexing purely proprioceptive abilities with their tasks.

4.4 CONCLUDING REMARKS

This thesis has demonstrated that it is problematic to conflate the variety of interoceptive tasks to one combined measure of interoceptive ability. We have presented correlations conflicting the concept of three distinct measures of interoceptive ability and have further shown that these three measures fail to consistently correlate across tasks. This has important implications for studies of interoceptive ability in which single measures of interoception are selected to reflect interoceptive ability as a whole. We have further highlighted the importance of control variables when studying heartbeat perception, as task performance can be predicted by a number of non-interoceptive factors. This suggests that these heartbeat perception tasks fail to selectively index interoceptive accuracy, and thus caution should be taken when using them to attempt to do so. We encourage all future research employing heartbeat perception tasks as a measure of interoception to consider and utilise the control variables set out in this thesis to obtain a more accurate index of interoceptive ability. Finally, we have presented evidence for a link between interoception and proprioception but suggest that more research is required to clarify this relationship. This investigation also revealed an important finding that proprioceptive tasks are limited by similar control factors as heartbeat perception tasks. We therefore further emphasise the importance of these control variables in proprioceptive research in addition to studies of interoception.

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Appendices

6.1 Appendix A - Interoceptive Accuracy Scale

Below are several statements regarding how accurately you can perceive specific bodily sensations. Please rate on the scale how well you believe you can perceive each specific signal. For example, if you often feel you need to urinate and then realise you do not need to when you go to the toilet you would rate your accuracy perceiving this bodily signal as low.

Please only rate how well you can perceive these signals without using external cues, for example, if you can only perceive how fast your heart is beating when you measure it by taking your pulse this would not count as accurate internal perception.

1. I can always accurately perceive when my heart is beating fast
2. I can always accurately perceive when I am hungry
3. I can always accurately perceive when I am breathing fast
4. I can always accurately perceive when I am thirsty
5. I can always accurately perceive when I need to urinate
6. I can always accurately perceive when I need to defecate
7. I can always accurately perceive when I encounter different tastes
8. I can always accurately perceive when I am going to vomit
9. I can always accurately perceive when I am going to sneeze
10. I can always accurately perceive when I am going to cough
11. I can always accurately perceive when I am hot/cold

12. I can always accurately perceive when I am sexually aroused

13. I can always accurately perceive when I am going to pass wind

14. I can always accurately perceive when I am going to burp

15. I can always accurately perceive when my muscles are tired/sore

16. I can always accurately perceive when I am going to get a bruise

17. I can always accurately perceive when I am in pain

18. I can always accurately perceive when my blood sugar is low

19. I can always accurately perceive when someone is touching me affectionately rather than nonaffectionately

20. I can always accurately perceive when something is going to be ticklish

21. I can always accurately perceive when something is going to be itchy

Scale: Strongly Agree (5), Agree (4), Neither agree nor disagree (3), Disagree (2), Disagree Strongly (1).

6.2 Appendix B – Intensity Calculations for the Tactile Perception Control Task

Diameter of tactile speaker (d) = 1.3 cm

Radius of tactile speaker (r) = d/2 = 1.3/2 = 0.605 cm

Area of tactile speaker (A) $= \pi r^2$ = 3.14*0.605^2 = 1.15cm^2 = 1.15x10^{-4} m^2

Voltage of tactile speaker (V) = 3.3 V

Easy Tactile Resistance (R_1) = 2.7 kΩ

Easy-Moderate Tactile Resistance (R_2) = 4.76 kΩ

Moderate Tactile Resistance (R_3) = 6.8 kΩ

Difficult Tactile Resistance (R_4) = 3.9 kΩ

Voltage = Current * Resistance (V=IR) → Current = Voltage / Resistance (I=V/R)

Easy Tactile Current (I_1) = V/R_1 = 3.3/2.7 = 1.22*10^{-3} amp

Easy-Moderate Tactile Current (I_2) = V/R_2 = 3.3/4.76 = 6.9*10^{-4} amp

Moderate Tactile Current (I_3) = V/R_3 = 3.3/6.8 = 4.9*10^{-4} amp

Difficult Tactile Current (I_4) = V/R_4 = 3.3/3.9 = 8.5*10^{-4} amp

Power = Current * Voltage (P = IV)

Easy Tactile Power (P_1) = I_1*V = 1.22 mA * 3.3V = 4.0*10^{-3} W

Easy-Moderate Tactile Power (P_2) = I_2*V = 0.69 * 3.3 = $2.3*10^{-3}$ W

Moderate Tactile Power (P_3) = I_3*V = 0.49 * 3.3 = $1.6*10^{-3}$ W

Difficult Tactile Power (P_4) = I_4*V = 0.85 * 3.3 = $2.8*10^{-3}$ W

Intensity = Power/Diameter (N=P/D)

Easy Tactile Intensity (N_1) = P_1/D = $4.0*10^{-3}$/ $1.15*10^{-4}$= **34.8 W/m²**

Easy-Moderate Tactile Intensity (N_2) = P_2/D = $2.3*10^{-3}$/ $1.15*10^{-4}$= **20.0 W/m²**

Moderate Tactile Intensity (N_3) = P_3/D = $1.6*10^{-3}$/ $1.15*10^{-4}$= **13.9 W/m²**

Difficult Tactile Intensity (N_4) = P_4/D = $2.8*10^{-3}$/ $1.15*10^{-4}$= **24.3 W/m²**

6.3 Appendix C – Stepwise Backwards Regression Output (Chapter 2 Experiment 2 – HCT)

Model	Predictors	Adjusted R Square	*F*	*p*	Degrees of Freedom
1	Heart Rate Variability, BMI, Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Moderate Tactile, Easy Tactile, Systolic Blood Pressure, Resting Heart Rate	-0.09	0.73	.713	12, 29
2	Heart Rate Variability, BMI, Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Moderate Tactile, Systolic Blood Pressure, Resting Heart Rate	-0.05	0.82	.619	11, 30
3	Heart Rate Variability Estimation, Anxiety, Moderate Tactile, Systolic Blood Pressure, Resting Heart Rate	-0.02	0.93	.517	10, 31
4	Heart Rate Variability, BMI, Depression, Sex, Age, Time Estimation, Anxiety, Moderate Tactile, Resting Heart Rate	0.01	1.04	.431	9, 32
5	Heart Rate Variability, BMI, Depression, Age, Time Estimation, Anxiety, Moderate Tactile, Resting Heart Rate	0.03	1.17	.349	8, 33
6	BMI, Depression, Age, Time Estimation, Anxiety, Moderate Tactile, Resting Heart Rate	0.05	1.29	.284	7, 34
7	BMI, Depression, Age, Time Estimation, Anxiety, Moderate Tactile	0.07	1.48	.214	6, 35
8	BMI, Age, Time Estimation, Anxiety, Moderate Tactile	0.08	1.69	.162	5, 36
9	Age, Time Estimation, Anxiety, Moderate Tactile	0.07	1.80	.149	4, 37
10	Time Estimation, Anxiety, Moderate Tactile	0.06	1.86	.153	3, 38
11	Time Estimation, Anxiety	0.05	1.98	.152	2, 39
12	Time Estimation	0.02	1.81	.186	1, 40

6.4 Appendix D – Stepwise Backwards Regression Output (Chapter 2 Experiment 2 – HCT after removing zero scores)

Model	Predictors	Adjusted R Square	*F*	*p*	Degrees of Freedom
1	Heart Rate Variability, BMI, Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Easy-Moderate Tactile, Easy Tactile, Systolic Blood Pressure, Resting Heart Rate	-0.45	0.33	0.971	12, 14
2	Heart Rate Variability, Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Easy-Moderate Tactile, Easy Tactile, Systolic Blood Pressure, Resting Heart Rate	-0.36	0.38	0.944	11, 15
3	Heart Rate Variability, Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	-0.27	0.45	0.901	10, 16
4	Depression, Sex, Age, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	-0.20	0.52	0.837	9, 17
5	Depression, Sex, Time Estimation, Anxiety, Knowledge of Resting Heart Rate, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	-0.13	0.62	0.75	8, 18
6	Depression, Sex, Time Estimation, Anxiety, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	-0.08	0.74	0.645	7, 19
7	Depression, Time Estimation, Anxiety, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	-0.03	0.89	0.519	6, 20
8	Time Estimation, Anxiety, Easy-Moderate Tactile, Easy Tactile, Resting Heart Rate	0.02	1.10	0.392	5, 21
9	Time Estimation, Anxiety, Easy Tactile, Resting Heart Rate	0.06	1.39	0.269	4, 22
10	Time Estimation, Anxiety, Easy Tactile	0.08	1.77	0.181	3, 23
11	Time Estimation, Easy Tactile	0.09	2.28	0.124	2, 24
12	Time Estimation	0.07	2.96	0.098	1, 25