The relationship between interoception and processing of others' interoceptive expressions

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Declaration of Authorship

I, Lara Carr, hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others, this is always clearly stated.

Signed: 

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Abstract

Interoception refers to the perception of, attention to, and propensity to use internal bodily signals. Whilst previous research has investigated the processing of these signals in one's own body, little research has investigated processing of these states in others, beyond the emotional domain. Where emotion is concerned, evidence suggests that an understanding of one's own emotions is central to the processing of others' emotions. Given the close relationship between emotional and interoceptive experience, it is likely that the processing of one's own interoceptive states is also associated with the processing of others' interoceptive expressions. This thesis used novel photographic stimuli to investigate the processing of others' interoceptive expressions and its relationship with one's own self-reported interoceptive abilities, in adolescence and throughout adulthood. Separate studies assessed recognition accuracy, the propensity to interpret others' expressions as interoceptive, and attention to and memory for others' interoceptive expressions. Although self-reported interoceptive abilities were related to the propensity to interpret expressions as interoceptive, they were unrelated to the accurate recognition of, attention to, and memory for others' interoceptive expressions. Results, therefore, partially supported the assertion that the processing of interoceptive expressions is related to the processing of one's own interoceptive states. This thesis also presents evidence of altered interoceptive and emotional processing in children with Medically Unexplained Symptoms and Tourette syndrome, making future research on potentially related processes, including the processing of others' interoceptive expressions, in these groups a priority. Overall, this thesis presents the first investigation into the processing of others' interoceptive expressions and its relationship with one's own interoceptive abilities. The current findings have implications for social relationships and the ability to provide care to others, and pave the way for future research aiming to reduce the potential impact of interoceptive atypicalities on social cognition.

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Finally, Dad, this one’s for you. I wish you were here to see this, but I know, without question, you would be, as you always were, full of pride.

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Introduction

Interoception is a broad term referring to the sensing, interpretation, and integration of signals originating from within the body, including the accurate perception of, attention to, and propensity to utilise internal signals, such as one's heartbeat or breathing (Murphy, 2022; Murphy et al., 2019a; Murphy et al., 2020a; Suksasilp & Garfinkel, 2022). Whilst interoception is concerned with the processing of non-emotional internal states, it is also thought to be a core component of emotion processing, with almost every model of emotion ascribing some role for physiological change in emotional experience (e.g., James, 1984; Lange, 1885; Schater & Singer, 1962; Barrett, 2014). In line with this, interoceptive atypicalities appear closely related to alexithymia (a sub-clinical construct characterised by difficulties identifying and describing one's own emotions; Apfel & Sifneos, 1979; Nemiah et al., 1976), suggesting that those with difficulties perceiving or attending to internal bodily signals may also struggle to identify and explain their emotions (Brewer et al., 2016; Murphy, et al., 2018a).

While alexithymia is typically defined as difficulties identifying or describing one's own emotions, it is also associated with a deficit in the processing of others' emotions across a range of cognitive domains (Luminet et al., 2021). For example, alexithymia is associated with difficulties recognising others' emotions from facial (Grynberg et al., 2010) or vocal (Heaton et al., 2012) expressions. Beyond recognition accuracy, alexithymia also appears to be associated with a deficit in attention to (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013), memory for (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout, 2021.; Vermeulen et al., 2006; Vermeulen & Luminet, 2009) and appraisal of (Luminet et al., 2021) others' emotional expressions. This suggests that an understanding of one's own emotions is crucial for understanding others' emotions, with a failure to categorise an emotion in oneself hampering the learning of cues associated with that emotion in others. Research is yet to investigate, however, the processing of others' interoceptive expressions[1].

The hypotheses presented in this thesis are based on the theory that similar mechanisms may be used to learn about others' interoceptive expressions as they are to learn about others' emotional expressions and, in turn, an understanding of one's own interoceptive states may be

[1] The term 'interoceptive expressions' is used throughout this thesis to refer to the facial and postural cues associated with, or used to convey, one's interoceptive states (e.g., nausea, fatigue, breathlessness, temperature, and pain), equivalent to emotional expressions in the context of emotion.

crucial in learning to understand others'. One way which we might learn about the expressions associated with inteoceptive states is through experiencing the bodily state ourselves. Whilst experiencing a bodily sensation, we tend to spontaneously produce the interoceptive expression, arising in proprioceptive feedback regarding the behavioural response to the internal state. Beyond proprioceptive feedback, we might also observe the associated visual feedback whilst expressing our own interoceptive states. For example, we might observe ourselves feeling hot in a mirror or video recording. If an association can be formed between the expression, what is felt proprioceptively or observed visually, and the feeling of the internal state, then this may be instructive in recognising similar internal bodily states in others. Evidently, having precise representations of one's own internal states will facilitate this process.

Others' expressions are also instructive. For example, it is a well-known phenomenon that people tend to immitate others' behaviours, including facial mimicry of emotional displays and body postures (Hess & Fisher, 2014). It seems likely that in certain circumstances, the same is true of interoceptive expressions. On observing a nauseated individual, for example, one may produce subtle expressions of nausea oneself. Beyond direct immitation, it is also the case that within a shared environment, individuals are likely to be experiencing similar states (e.g., similarities in temperature or hunger), and in these instances one's own interoceptive state may be associated with others' interoceptive expressions. Alternatively, throughout development, caregivers are likely to explicitly immitate children's interoceptive states whilst providing verbal feedback. To recognise the immitated interoceptive expressions in others, however, one must be able to clearly interpret one's own internal state. If an individual does not recognise that they are feeling hot, for example, observations of others immitation their expression, or verbal labels of 'hot' are less likely to become strongly associated with the internal state. Finally, we may learn about the expressions associated with internal bodily feelings when others use a verbal label to describe individuals that we are both observing e.g., 'that person looks cold'. Here, rather than associating the expression with one's own internal state, it is necessary to associate the observed expression with the verbal label provided. Crucially, having a precise representation of the verbal label is presumably influenced by having a clearly defined concept of the internal state itself, again leading to improved associative learning between the label and observed expression. According to Conceptual Act Theory (Barrett, 2014), if you have a good understanding of what it means to feel "cold", you should have a better understanding of the verbal label itself and, in turn, an individual equipped with a better understanding of the label will likely find it easier to link the label to the interoceptive expression. Overall, through each or all of these mechanisms, an understanding of one's own internal bodily states appears crucial in learning to recognise these expressions in others. Indeed, whether we learn about others' inteoceptive expressions as we do emotional expressions remains to be seen. Nontheless, given the relationship between interoceptive and emotional processing (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013; Gendron & Barrett, 2009; James, 1894; Lange, 1885; Schachter & Singer, 1962), and the processing of one's own and others' emotions (Luminet et al., 2021), it seems likely that those who struggle to recognise interoceptive signals in themselves may also struggle to recognise these interoceptive states in others. This thesis investigates the relationship between the perception of and attention to interoceptive states in one's own body and the processing of others' interoceptive expressions.

Beyond one's own interoceptive abilities, it is also possible that age and gender play a role in one's processing of others' interoceptive states. Although research into the processing of others' interoceptive expressions is scarce, the impact of age and gender on interoceptive processing in the self has been explored. Indeed, age appears inversely related to interoceptive processing, such that as age increases, both accuracy perceiving and self-reported attention to one's own interoceptive signals decreases (Khalsa et al., 2009; Murphy et al., 2018c). Where gender is concerned, women tend to self-report higher attention to interoceptive signals (Grabauskaite et al., 2017), but display decreased recognition accuracy for their own interoceptive states, at least when measured in a laboratory and in the cardiac domain (Prentice & Murphy, 2022). See sections 1.5 and 1.6 for a more detailed discussion of the effects of age and gender on interoception. Given the role of age and gender in predicting processing of one's own interoceptive states, age and gender may also affect the processing of others' interoceptive expressions. Notably, this effect might be independent of, or interact with, individual differences in one's own interoceptive abilities when predicting processing of others' interoceptive expressions.

The current thesis therefore aims to examine the relationship between perception of and attention to interoceptive states in oneself and the processing of others' interoceptive expressions in adolescence and throughout adulthood. This thesis also examines whether age and gender are associated with processing of others' interoceptive expressions, including the extent to which these variables interact with one's own interoceptive abilities when predicting processing of others' interoceptive states.

Chapter 1. Literature Review

1.1 Definitions of interoception

Interoception refers to the perception of, attention to, and propensity to use internal bodily signals (e.g. heartbeat), across both conscious and unconscious levels (Gabriele et al., 2022; Garfinkel et al., 2015; Murphy et al., 2019a; Murphy et al., 2020a; Murphy, 2022; Suksasilp & Garfinkel, 2022). It differs from proprioception, which is the processing of skeletomotor and vestibular information about positioning or movement of the body, and is generally differentiated from exteroception, which refers to the processing of external information such as visual, auditory, olfactory, tactile, and gustatory stimuli. Sherrington (1948) proposed the first definition of interoception which was restrictive, only referring to states that originated in the viscera, such as heart rate, breathing, and hunger. A proliferation of interoceptive research (Ceunen et al., 2016), however, has led to various nuanced definitions which can be distinguished in part by the number of internal states that interoception is proposed to encompass (Khalsa & Lapidus, 2016). As research has demonstrated no clear distinction between an interoceptive and exteroceptive signal *per se* (Cameron, 2001; Critchley & Garfinkel, 2017; Plailly et al., 2007; Small, 2010) this thesis will adopt the broadest definition of interoception, proposed by Craig (2003a). This broad definition is based on the neural underpinnings of interoception, suggesting that for a signal to be interoceptive it must be processed by a common neural pathway either via lamina 1 of the spinal and trigeminal dorsal horn to the anterior insular cortex (AIC) or anterior cingulate cortex (ACC) (Craig, 2003a), or by cranial nerves to the nucleus of the solitary tract (Critchley & Harrison, 2013). According to this definition, interoception includes signals relating to temperature, itch, pain, sensual/affective touch, and muscular effort, as well as visceral sensations, such as hunger, thirst, and breathlessness (Craig, 2003a). The perception of each of these interoceptive signals is informed by various classes and channels of interoceptive information. These different classes can be distinguished by how the signal is generated, which varies from chemoreception to mechanoreceptive organ-stretching, and by the afferent pathway, which varies from neural to humoral (Critchley & Garfinkel, 2017). See Section 1.3. for more detail on the neural basis of interoception.

With the increased interest in and evident importance of interoceptive research, the need for an agreed-upon model of interoception has become imperative. A successful model should outline how individual differences, across the breadth of interoceptive abilities, can be quantified. A recently proposed and widely utilised model of interoception suggested that individual differences in interoceptive ability can be measured across three dissociable dimensions: interoceptive sensitivity (objective precision with which internal bodily signals can be detected), sensibility (beliefs concerning one's interoceptive processing), and awareness (a metacognitive dimension referring to the extent to which one's objective ability is aligned with their subjective beliefs; Garfinkel et al., 2015; Garfinkel & Critchley, 2013). Before this division, these terms had often been used interchangeably, or broad terms such as 'awareness' were used to refer to different aspects of interoception (Furman et al., 2013a; Krautwurst et al., 2014; Pollatos et al., 2007), hindering comparisons across studies. Whilst evidence from the cardiac and respiratory domains initially indicated that these three aspects of interoception were distinct, with no correlation between dimensions (Garfinkel et al., 2016), common variance has since been reported (Forkmann et al., 2016), with inconsistencies in findings potentially being explained by the dimension of interoception being assessed, rather than measurement type itself.

More recent models have proposed a further dissociation between interoceptive accuracy and interoceptive attention, outlining a 2 x 2 factorial structure of interoception (Murphy et al., 2019a, 2020). The first factor is concerned with the facet of interoception being measured itself (either interoceptive attention or interoceptive accuracy), with the second factor distinguishing between measurement approaches, namely whether measurement assesses the individual's performance on objective tasks or their subjective beliefs about their performance. Here, interoceptive accuracy refers to the more commonly discussed dimension, namely an individual's ability to perceive their interoceptive signals precisely. Interoceptive attention, on the other hand, refers to how much attention one typically pays to these signals. These are conceptually distinct, for example, an individual may attend highly to their interoceptive signals, but not necessarily perceive these signals accurately. Interoceptive abilities can therefore be divided into objective interoceptive accuracy, self-reported beliefs about one's interoceptive accuracy, objective interoceptive attention, and self-reported beliefs about one's interoceptive attention. Further to this, interoceptive awareness (using Garfinkel and colleagues' definition (Garfinkel et al., 2015; Garfinkel & Critchley, 2013)) can be quantified as the correlation between objective and subjective measures, separately for interoceptive attention and interoceptive accuracy. This metacognitive ability is also often referred to as interoceptive insight (Khalsa & Lapidus, 2016). In support of the importance of distinguishing between interoceptive domain and measurement type, it has been demonstrated that objectively measured interoceptive accuracy (at least in the cardiac domain) correlates with self-reported interoceptive accuracy (scores on the Interoceptive Accuracy Scale) but not with self-reported interoceptive attention (scores on the Porges Body Perception Questionnaire; Murphy et al., 2020a). It is worth noting that recent research has also outlined an additional dimension of interoception, namely the propensity to use interoceptive signals (Murphy, 2022), referring to an individual's tendency to utilise internal signals to gauge their internal states and make decisions, in laboratory tasks or daily life. Overall, contemporary conceptualisations make a crucial distinction between different performance dimensions of interoception (accuracy, attention, propensity to use internal signals) as well as between the different measurement types, and research should aim to incorporate as many of these as possible to gain a full understanding of interoceptive abilities (Suksasilp & Garfinkel, 2022).

1.2 Measurement of interoception

As described in Section 1.1, a distinction between interoceptive accuracy and attention has recently been proposed (Murphy et al., 2019a) with both objective and subjective measures of both accuracy and attention across multiple interoceptive signals being recommended (Suksasilp & Garfinkel, 2022). To date, however, the vast majority of research has investigated interoceptive accuracy, particularly using objective measures. In contrast, interoceptive attention has almost exclusively been assessed using self-report.

The most commonly utilised measures of objective interoceptive accuracy are heartbeat perception tasks. The most prolific of these is the heartbeat counting task (HCT; Dale & Anderson, 1978; Schandry, 1981). Here, participants are instructed to count the number of heartbeats they feel in various specified time periods, typically between 25 and 103 seconds (Murphy et al., 2018a). For each trial, accuracy is calculated as the extent to which performance is error-free, with mean scores across trials taken as an estimate of interoceptive accuracy. The heartbeat counting task is frequently utilised due to its ease of implementation, its ability to tap into a precisely measurable physiological signal, and the absence of any potentially problematic ethical concerns i.e., being invasive. It is also not limited by debate surrounding the conceptualisation of interoception, as cardiac signals are included in all definitions of interoception. Despite this, multiple methodological issues relating to the HCT have been highlighted (for thorough reviews see Brener et al., 2016; Corneille et al., 2020; Zamariola, Maurage, et al., 2018).

To begin, there are several types of error which can contribute to the accuracy score, one of which is underreporting. Indeed, participants appear to consistently underestimate the number of heartbeats, across several contexts, including at rest (36% under - reporting), before public speaking (32% under-reporting), and after exercise (23% under-reporting; Schandry & Specht, 1981). Ring & Brener (1996) reported similar results whilst sitting, standing, and after exercise, suggesting that even in situations when the intensity of the cardiac signal is increased (e.g. after exercise or before public speaking), participants still do not detect every heartbeat that has occurred. The reliability and magnitude of these errors suggest that most adults struggle to detect heartbeat sensations, with only around one third of participants thought to be accurate detectors of their own heartbeats (Khalsa & Lapidus, 2016), and less than 5% of participants making overestimation errors (Zamariola et al., 2018). Nonetheless, the fact that some individuals do report non-existent heartbeats suggests that even good performance on this task may be driven in part by poor discrimination of cardiac signals. Perhaps even more concerning, the typically derived accuracy score does not distinguish between those who underreport and overreport heartbeats, despite the fact that abilities involved in not perceiving an existing heartbeat are likely to be fundamentally different to those involved in reporting a heartbeat that does not exist. It is worth noting that a subsequent formula (Garfinkel et al., 2015) exists which mitigates against overestimating accuracy in individuals with high variance, particularly for those who report more heartbeats than occur, however this formula still faces many of the issues described here. Taken together, these findings suggest that the HCT is not an appropriately sensitive test of interoceptive accuracy for the vast majority of participants (Khalsa & Lapidus, 2016).

Further to this, if HCT scores do reflect an individual's ability to perceive heartbeats, there should be a correlation between actual and estimated number of heartbeats, and this should increase linearly with HCT scores. In fact, it is average scorers on the HCT who exhibit the strongest correlation between actual and reported score (Zamariola et al., 2018). A weak positive correlation was found between reported and actual number of heartbeats, but there was no significant difference between the high (4^{th} quintile) and highest perceivers (5^{th} quintile), suggesting that the HCT scores fail to distinguish those with the most accurate perception.

As outlined previously, a higher accuracy score on the HCT is assumed to equate to higher interoceptive accuracy in the cardiac domain, but this assumes that the individual counts the number of heartbeats they can feel, rather than basing their response on existing beliefs about their heart rate. Research has demonstrated that although actual heart rate is related to counted heart rate, there is a closer relationship between believed heart rate and actual heart rate. This suggests that HCT estimates may be based on beliefs rather than the processing of cardiac sensations (Ring & Brener, 1996). Furthermore, equivalent accuracy improvements have been reported in groups who received auditory feedback which was synchronous or asynchronous with their heartbeat (Ring et al., 2015). As receiving feedback in synchrony with heartbeats did not appear to benefit performance any more than hearing one's heart rate, this suggests that feedback-mediated improvements in accuracy are not due to training individuals to detect individual heartbeat sensations. Additionally, when heart rate was manipulated in participants with cardiac pacemakers, participants' heart rate estimates did not follow the heart rate shifts, with significantly reduced accuracy in the highest pace rate condition (Windmann et al., 1999). Perhaps most pertinently, when participants are explicitly instructed to only report the heartbeats that they feel and not to guess, their accuracy is dramatically reduced, by up to 50% (Desmedt et al., 2018). Indeed, this also serves to highlight the lack of standardisation in delivering the HCT, as instructions have varied across studies, making comparisons between findings which appear to utilise similar methods unreliable. These findings demonstrate a reliance on heart rate belief, rather than the sensory processing of heartbeats, challenging the validity of the heartbeat counting task as a measure of interoceptive accuracy, as this implies that high performers on heartbeat counting tasks may simply possess good knowledge of heart rate, potentially alongside poor cardiac perception. It should be noted that a time estimation task is sometimes included to partially control for this (Ainley et al., 2014). Nonetheless, whilst some studies report a correlation between time estimation and HCT performance, the majority report low or non-significant associations (Ainley et al., 2014; Dunn et al., 2007; Dunn et al., 2010; Murphy et al., 2018a; Shah et al., 2016), suggesting that time estimation, HCT performance, and potentially knowledge of heartbeats, are separate abilities. Findings on the importance of heart rate knowledge have recently been extended, whereby the relationship between intelligence and HCT performance appears to be mediated by heart rate beliefs (Murphy et al., 2018d). This demonstrates that when assessing the relationship between the HCT and other psychological variables, the influence of heart rate beliefs must be accounted for.

Overall, the limitations described above challenge interpretation of the HCT, making it difficult to draw conclusions from studies relying exclusively on this measure of interoceptive accuracy. Alternative measures of cardiac perception have also been utilised, such as the Heartbeat Discrimination Task (HDT; Whitehead et al., 1977) and the Phase Adjustment Task (PAT; Plans et al., 2021), and are free of many of these limitations, although it is worth noting that alternative challenges to these tasks have also been noted. During the HDT, participants are presented with an external stimulus, commonly a series of tones or flashing lights, which are either synchronous or asynchronous with their own heartbeats. Participants are then asked to judge whether the stimuli are in synchrony with their heartbeats. In both conditions, the stimuli are presented at the same rate, usually dependent on participants' own heart rate, so that frequency or existing heart rate knowledge cannot be used to guide responses. Whilst this task controls for the role of beliefs, criticisms suggest that as participants are required to match two stimuli in time to complete the task, it may be too difficult for many, particularly when examining interoceptive accuracy at the lower range of ability (Brener & Ring, 2016). Ring & Brener (2018), however, subsequently argued that humans can judge whether two stimuli are synchronous very easily, even across modalities (Zampini et al., 2005). Nonetheless, there is also disagreement over the most appropriate methodology of the HDT. Two-alternative-forced choice procedures are most common, but these are based on the flawed assumption that heartbeat sensations appear at the same temporal location in relation to the R-wave in all individuals (Brener et al., 1993; Brener & Ring, 2016; Clemens, 1984). When only using two time intervals, therefore, with one labelled as contingent and the other as non-contingent, it is not possible to determine whether an incorrect response reflects an inability to detect heartbeat sensations, or whether contingent and non-contingent conditions are equally coincidental with heartbeat sensations in the given individual. With this in mind, recent advancements have seen the implementation of the HDT with multiple intervals from the R wave, which span the cardiac cycle, commonly referred to as the method of constant stimuli (Brener et al., 2016). Whilst these overcome issues associated with two-alternative forced choice designs, they require a large number of stimulus presentations to compute reliable accuracy scores. The newly developed PAT addresses this, presenting tones at participants' heart rate but misaligned with heartbeat, with participants required to adjust the phase until the tones are synchronous with their heartbeats (Plans et al., 2021). Participants are then classified as "interoceptive", "non-interoceptive," or "unclassified", if there is not enough evidence to inform a decision. It is worth noting that unlike the HDT, there is no correct or incorrect response; participants can perceive their heartbeat at any one of a range of delays, with accuracy in the PAT indexed as the consistency of the delays selected across trials. As selecting a similar delay across trials suggests that participants are responding to heartbeats that they can feel, these participants are classified as interoceptive, whereas those select highly variable delays are considered to have less precise interoceptive accuracy. As the PAT only requires 20 trials to obtain a reliable classification, this overcomes issues with the HDT method of constant stimuli.

Despite the HDT and PAT overcoming many of the issues with traditional heartbeat perception tasks, perhaps the most pertinent issue overall is the suggestion that performance may be facilitated by exteroceptive information (Khalsa et al., 2009). When asked to report the location of heartbeat sensations, overlap maps demonstrate that participants often report these in locations with close proximity to major arteries, such as the neck, arms, and abdomen. This suggests that the perception of heartbeat sensations may be informed by receptors in the skin rather than deeper signals from the viscera. Evidence that heartbeat perception is negatively correlated with body mass index (BMI; Herbert & Pollatos, 2014), and body fat (Rouse et al., 1988) supports this assertion, as a lower BMI and body fat percentage will equip these individuals with an increased capability to utilise exteroceptive cues. Moreover, in comparing individuals with elevated systolic blood pressure to those with normotensive systolic blood pressure, participants with elevated systolic blood pressure were more able to perceive heartbeat sensations before and after feedback training (O'Brien et al., 1998). It is reasonable to assume that these individuals experience increased input from touch receptors in the chest wall, again highlighting the potentially exteroceptive nature of heartbeat perception. When coupled, these findings demonstrate that the very nature of heartbeat perception casts doubts on the validity of cardiac perception tasks as measures of interoceptive accuracy.

Beyond methodological issues with heartbeat perception tasks, relying on tasks assessing accuracy in the cardiac domain is also problematic as cardiac perception accuracy does not appear to be a reliable predictor of perception accuracy in other interoceptive domains (Ferentzi et al., 2018). There have been attempts, albeit far fewer than in the cardiac domain, to objectively measure interoceptive accuracy in the respiratory domain (Garfinkel et al., 2016; Nikolova et al., 2022). These tasks attempt to quantify individual differences by finding the smallest respiratory resistance that participants can identify. During one task, participants are required to breathe through an open breathing circuit with varying amounts of resistance presented on inhalation, manipulated with filters (Garfinkel et al., 2016; Harrison et al., 2021). After each trial, participants are asked if resistance was present, and the lowest resistance an individual could detect is taken as their interoceptive accuracy index in the respiratory domain, with lower values indicating higher accuracy. Alternatively a two-alternative forced choice paradigm has been employed, in which participants take two in-breaths and are asked to report which was more difficult, again with breathing resistance being manipulated with filters (Nikolova et al., 2022). Although these two tasks seem to yield similar findings (Nikolova et al., 2022), both are limited as they do not include objective measurement of respiratory experience across individuals, such as lung capacity or variations in respiratory patterns. If it is the case that these substantially vary between participants, this may lead to differences in airflow and subsequent differences in the level of respiratory resistance felt at the same level of obstruction. Without these objective measurements, findings from respiratory tasks of interoceptive accuracy are difficult to interpret.

Tasks assessing interoceptive accuracy in the gastric domain are limited by similar issues. The predominant task to measure gastric interoceptive accuracy is the Water Load Test (WLT – II; Van Dyck et al., 2016). This updated version of the original task (Herbert et al., 2012; Koch et al., 2000) involves two successive five-minute testing sessions. In the first, participants are instructed to drink non-carbonated water until they reach a point of satiation. They are then instructed to drink until they reach a point of complete fullness. It is assumed that gastric interoceptive accuracy is negatively related to the proportion of water consumed in the first step relative to the total volume of water consumed, however, similar to the respiratory task, the WLT – II is limited by a lack of objective measurement of stomach size. Whilst this task attempts to index this by including a step asking participants to drink to a point of complete fullness, presumably individuals with poor interoceptive accuracy would struggle to accurately determine their point of complete fullness. Additionally, "complete fullness" is subjective and, therefore, likely interpreted differently by each individual. Finally, the stomach empties relatively rapidly (Horowitz et al., 1989), again causing difficulties estimating stomach fullness during this task. Gastric distention has also been utilised to assess interoceptive accuracy in this domain, whereby participants' interoceptive accuracy is indexed by the threshold for initial detection, intensity, and pain ratings (Hölzl et al., 1996; Zaman et al., 2016). Whitehead & Drescher (1980), have also utilised a similar paradigm to the HDT, asking participants to indicate whether stomach contractions were in or out of sync with a flashing light. Due to the invasive nature of these tests, however, they have been used infrequently.

Beyond the cardiac, respiratory, and gastric domains, investigations into objective interoceptive accuracy have been sparse. Notably, tasks do exist which measure participants' accuracy detecting a vast array of sensations which were previously not considered interoceptive but are under more recent definitions, such as taste (Murphy et al., 2018b), muscular effort (Herbert et al., 2007b; Murphy et al., 2018b), hunger, thirst, and satiety (Harshaw, 2008), and pain (e.g., de Zwaan et al., 1996; Pollatos et al., 2015). There is also limited work which has assessed neural activity during the processing of interoceptive sensations. fMRI, for example, has been used to assess activity in the interoceptive cortex (AIC and ACC) during stimulation of the proximal and distal oesophagus (Aziz et al., 2000) and the anal and rectal canal (Hobday et al., 2001), as well as whilst participants attempted to regulate their gut activity in response to a virtual rollercoaster (Li et al., 2017). Whilst these tasks implicate cortical areas such as the AIC and ACC in interoceptive processing, they fail to provide an objective measurement of interoceptive accuracy.

In line with the distinction between interoceptive accuracy and attention (Gabriele et al., 2022; Murphy et al., 2019a; Murphy et al., 2020a) separate objective measurements are needed to index one's tendency to attend to internal bodily signals. As the importance of this distinction has only been emphasised recently, however, there are currently very few tasks designed to specifically assess this. Nonetheless, experience sampling methods have recently been proposed as an appropriate method to capture objective interoceptive attention (Murphy et al., 2020b). These methods involve asking participants to report on their attention to internal signals at frequent intervals over a period of around two weeks, thereby providing an objective measurement of one's tendency to attend to interoceptive signals. It is worth noting, however, that the feasibility of this method is yet to be determined. Alternatively, the heartbeat-evoked potential (thought to represent the cortical processing of heartbeats; Coll et al., 2021) also serves as a promising avenue for future research, as increased attentional allocation to one's heartbeats appears to be associated with a greater heartbeat-evoked potentials (although see Coll et al. (2021) for a recent meta-analysis which highlights the need for standardisation in the measurement of heartbeat-evoked potentials before firm conclusions can be drawn). Given the potential implications of atypical interoceptive attention (Khalsa & Lapidus, 2016), designing and trialling new methods to capture objective interoceptive attention should be a priority for future research.

Beyond objective measurements of interoception, there is also a need to assess self-reported interoceptive processing. Participants' perception of their own interoceptive accuracy can be obtained by asking how well they feel they performed during any objective task of interoception, however, it is worth noting that confidence ratings are domain-specific and provide a moment by moment, rather than a trait measure, of perceived accuracy. Further measures are therefore needed that provide a trait belief measure of interoceptive abilities. Accordingly, a number of questionnaires assess self-reported interoceptive processing, including the Body Perception Questionnaire (BPQ; Porges, 1993), the Body Consciousness Questionnaire (Miller et al., 1981), the Multidimensional Assessment of Interoceptive Awareness (MAIA; Mehling et al., 2012), the Body Awareness Questionnaire (Shields et al., 1989), the Interoception Sensory Questionnaire (Fiene et al., 2018), the Eating Disorder Inventory-3 (Garner, 2004), and the Self Awareness Questionnaire (Longarzo et al., 2015). Whilst these measures have been utilised widely in the literature, they are limited as they do not distinguish between interoceptive accuracy, attention, and the frequency with which internal bodily signals occur (see Desmendt et al., 2022 for a review). Encouragingly, however, the recently introduced Interoceptive Accuracy Scale (IAS; Murphy et al., 2019a, 2020) and Interoceptive Attention Scale (IATS; Gabriele et al., 2022) appear to overcome these issues by asking participants to report on the accuracy with which they can perceive, or the amount of attention they pay to, interoceptive signals in isolation. The IAS and IATS ask participants to report on an identical set of 21 physical sensations that have either been described as interoceptive in nature or involve activation of the AIC, which has been identified as an interoceptive hub (See Section 1.3 for a review of the neural bases of interoception). Scores on the IAS do not appear to correlate with scores on the IATS (Gabriele et al., 2022), and whilst self-reported interoceptive attention remains uncorrelated with objectively measured interoceptive accuracy, self-reported interoceptive accuracy appears to correlate with performance on the HCT (Murphy et al., 2019a). These findings provide further support for the distinction between interoceptive accuracy and attention as outlined in Section 1.1, and suggest that, in contrast to previous self-report measures of interoception, the IAS and IATS are useful tools for assessing perceived interoceptive accuracy and attention separately.

Of course, self-report measures are limited by participants' degree of insight into their interoceptive abilities, and it should be noted that although associations have been seen between the IAS and HCT, the correlation appears to be relatively small (Murphy et al., 2019a). Despite this, self-report measures are useful as they are likely to capture many of the day-to-day difficulties that are missed in the objective assessment of interoceptive accuracy or attention. Self-report measures also enable participants to report on a wide range of interoceptive sensations, whereas objective measurements are limited as they focus on interoceptive processing within a single interoceptive channel. As there is evidence that interoceptive ability is not unitary, and instead differs across interoceptive signals (Ferentzi et al., 2018), self-report measures are also useful for capturing interoceptive abilities more broadly.

When self-report measures are administered alongside objective measurements this also allows for analysis of 'interoceptive insight' (Khalsa & Lapidus, 2016), or metacognitive 'awareness' (Garfinkel et al., 2015), referring to the correlation between one's self-reported interoceptive processing and performance on objective tests. Individual differences in interoceptive insight exist, and insight may be weakly associated with objective accuracy in the cardiac domain (Forkmann et al., 2016; Garfinkel et al., 2015; Murphy et al., 2019a), although differences have been observed across heartbeat perception tasks. Nonetheless, without reliable measures of interoceptive accuracy and attention, it is impossible to determine whether a low interoceptive insight score is truly indicative of reduced insight, or is instead reflective of flawed objective or self-report measures, or the measurement of different interoceptive dimensions (accuracy versus attention) or domains (e.g., objective cardiac accuracy versus self-reporting on multiple states). Given that objective performance on the two most common tests of cardiac interoceptive do not relate to each other (Hickman et al., 2020) it is likely that differences in interoceptive insight are reflective, at least partially, of methodological issues with these tasks. Overall, these findings demonstrate that further work is needed to allow for the reliable indexing of interoceptive processing across a variety of bodily axes, using both objective and self-report measures.

1.3. Neurobiological basis of interoception

The anterior insular cortex (AIC) and anterior cingulate cortex (ACC) are commonly referred to as the "interoceptive cortex", due to consistent evidence for their involvement in the processing of interoceptive sensations (Craig, 2002, 2003, 2009; Critchley & Harrison, 2013; Garfinkel & Critchley, 2013). In fact, some contemporary definitions of interoception stipulate that for a sensation to be interoceptive it must be processed by one of these brain regions (See Section 1.1). The AIC and ACC are where the highest levels of processing of internal bodily signals take place, allowing for the conscious representation of the interoceptive state. Interoceptive processing also involves, of course, the afferent signalling which preceeds this high level processing. Interoceptive signals are first processed by small-diameter Aδ and C afferent fibres, which innervate the entire human body, before projecting to lamina 1 of the spinal and trigeminal dorsal horn (the most dorsal section of the spinal cord; Panneton, 1991; Woolf & Fitzgerald, 1983).The neurons of lamina 1 can be distinguished by the feelings that they communicate, which each have distinct physiological, morphological and chemical characteristics. Each class of lamina 1 neurons exclusively conveys messages associated with different physical sensations, including, but not limited to, sharp prickling pain, innocuous cool and burning pain, itch, warmth, affective touch, muscle ache, and burn (Andrew & Craig, 2001; Craig et al., 2001; Han et al., 1998; Yu et al., 1999). Interoceptive signals are also processed by parasympathetic afferents, projecting to the nucleus of the solitary tract (NTS), which innervate the tongue, pharynx, and viscera. NTS neurons also fall into distinct categories, which can be distinguished by the activity they convey. NTS neurons have been shown to exclusively convey activity associated with the five different tastes, as well as other visceral feelings such as hunger, nausea, and thirst.

Both lamina 1 and NTS subsequently project to the parabrachial nucleus (either directly or via A1 catecholamine cell groups), which is the main integration site of various interoceptive cues (Craig, 2002; Craig, 1995). From here, the parabrachial nucleus projects to the medial and basal ventral medial nuclei of the thalamus (VMb), the periaqueductal grey (PAG) and the hypothalamus. Direct projections also occur from lamina 1 neurons to the hypothalamus, via A1 cell groups, and from the NTS to the PAG and hypothalamus. Both the PAG and hypothalamus are considered homeostatic centres, guiding goal-directed activity to maintain homeostasis (Canteras & Swanson, 1992; Saper, 2002). Direct thalamic connections from the NTS and lamina 1 neurons also exist. More specifically, the NTS projects to ventral caudal part of the medial dorsal nucleus of the thalamus (MDvc), and lamina 1 neurons to the MDvc, the posterior part of the ventral medial nucleus of the thalamus (VMpo) and the basal part of the ventral medial nucleus of the thalamus (VMb). Finally, these nuclei project to the cerebral cortex. Specifically, neurons from the VMpo and VMB terminate in the dorsal posterior insula, which is bi-directionally connected to the ACC, whereas the MDvc projects directly to the ACC.

The AIC and ACC are typically stimulated simultaneously (Medford & Critchley, 2010), but it is in the AIC where bodily states are thought to be re-represented, eliciting the subjective interoceptive experience (Craig, 2002, 2003, 2009; Craig, 2011). The ACC, however, allows for the relevant motor response to the bodily feeling re-represented in the AIC (Craig, 2002). Activation in both the AIC and ACC have consistently been associated with change in autonomic activity (Critchley, 2009), heat rate (Critchley et al., 2000), respiration (Pattinson et al., 2009), blood pressure (Harper et al., 2000), and glucose levels (Allport et al., 2004). These regions are also activated in the processing of pain (Apkarian et al., 2005; Peyron et al., 2000), temperature (Craig et al., 2000; Eisenblätter et al., 2017), visceral stimulation (Aziz, Schnitzler, & Enck, 2000), hunger and satiety (Del Parigi et al., 2002), itch (Ikoma et al., 2006; Mochizuki et al., 2007), affective touch (Francis et al., 1999; Gordon et al., 2013), and tiredness (Caseras et al., 2008).

Studies of patients with insula lesions also typically report interoceptive difficulties (Ibañez et al., 2010), although there are some reports that perception of itch, tickle, pain, temperature, and one's heartbeat are relatively spared (Damasio et al., 2013; Khalsa et al., 2009), highlighting the role of thalamic, somatosensory, and hypothalamic regions in the perception of interoceptive states alongside the AIC and ACC. Nonetheless, stimulation of the insula results in changes in heart rate (Oppenheimer et al., 1992), inhibition of respiration, abdominal sensation, and nausea (Penfield and Faulk, 1955), and unpleasant sensations in the mouth, nose, and throat (Krolak-Salmon et al., 2003). Neural activation in the insula also correlates with subjective awareness of interoceptive states including subjective unpleasantness of dyspnea (Von Leupoldt et al., 2008), subjective orgasm quality in females (Ortigue et al., 2007), subjective fullness (Stephan et al., 2003), and bladder distention (Jarrahi et al., 2015). AIC activity is also associated with the ability to perceive heartbeats accurately (Critchley et al., 2004), and Transcranial Magnetic Stimulation (TMS) of the right insula results in decreased interoceptive accuracy across both cardiac and respiratory domains (Pollatos et al., 2016). Overall, the evidence suggests that the AIC and ACC are crucial in the perception of interoceptive states, with somatosensory, thalamic, and hypothalamic regions also playing a role.

1.4. Interoception and emotion

Emotions involve experiential, behavioural, and physiological elements. They are thought to draw upon interoceptive signals, with the psychological expression of emotional feelings resulting from physiological changes in the body, driven by autonomic reflexes (Tsakiris & Critchley, 2016). Many individuals have championed this idea, perhaps the most seminal of these being William James (James, 1894) and Carl Lange (Lange, 1885) who, with the James – Lange theory of emotion, proposed that for an emotional feeling to occur, the perception of bodily changes are both necessary and sufficient. Predicated by the Schacter and Singer (1966) model, which argued for a role of both interoceptive and contextual elements in the interpretation of emotion, almost every model of emotion now ascribes some role of physiological change in the experience of emotion (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Gendron & Feldman Barrett, 2009; James, 1894; Lange, 1885; Schater & Singer, 1962; Seth, 2013).

There is a plethora of evidence which demonstrates the close relationship between interoceptive and emotional experience. Behaviourally, individuals appear to consistently associate statistically separate and culturally universal bodily sensation maps with similar emotional states, such as decreased activation of extremities in depression, or increased activation of the upper half of the body in anger (Nummenmaa et al., 2014). Further research has also reported that perceived similarities between particular interoceptive and emotional signals tend to be consistent across neurotypical individuals (Brewer et al., 2016). This pairing of physiological changes with emotional experience is central to the argument that interoceptive sensations form the basis of emotion. Since there are individual differences in the perception of bodily signals (Cameron, 2001), these theories of emotion suggest that affective experience should also be proliferated with such variation. Accordingly, research reports associations between interoceptive abilities and emotional lability (Schandry, 1981), emotion regulation (Füstös et al., 2013; Kever et al., 2005) and intensity of one’s emotional experience (Füstös et al., 2013; Herbert et al., 2007a; Pollatos et al., 2007). Interoception therefore appears key in the ability to accurately identify emotions, and for judgements of intensity, both of which are necessary to perceive one’s own emotional state (Naqvi & Bechara, 2010).

Those with an increased ability to detect their own interoceptive signals also appear to display increased neural activity during the processing of emotional stimuli, as measured using EEG

(Herbert et al., 2007a). When participants viewed pleasant and unpleasant images, heartbeat perception scores, assessed with the HCT, were positively associated with P300 deflection and positive slow wave range amplitude. Prior research has demonstrated that an increased P300 event-related potential and a sustained later positive slow wave amplitude are associated with the viewing of emotional, compared to neutral, images (Keil et al., 2001, 2002). These findings support the hypothesis that interoceptive accuracy is positively related to the central processing of emotional stimuli and intensity of emotional experience. This is further supported by fMRI data, which demonstrate that heartbeat perception and emotional content tasks (e.g., the explicit recognition of others' emotions from faces and voices or watching emotional videos) lead to activation in the same insula areas, pointing to similar neural regions and processes employed in both affective and non-affective interoception (Adolphs, 2002; Cohen et al., 2001; Gu et al., 2013; Zaki et al., 2012).

Notably, these findings all relate to interoceptive accuracy in the cardiac domain, with the limitations described in Section 1.2 making interpretation of results challenging. Encouragingly, however, these results have also been replicated in a mixed-methods paradigm. Zamariola & Colleagues (2019) administered the HCT, a range of self-reported questionnaires (BPQ & MAIA), and a semi-structured interview. Findings demonstrated that those who report having low interoceptive ability (albeit across a combination of attention and accuracy items) also appear to have deficits in emotion regulation, extending the findings from objective interoceptive assessments. Interestingly, one of the themes that emerged during the interview was the alexithymic tendencies of participants with poorer interoceptive abilities (difficulties recognising and describe one's own emotions, and an externally orientated cognitive style; Apfel & Sifneos, 1979; Nemiah et al., 1976). Perhaps this relationship between alexithymia and interoception is most convincing of the importance of physiological awareness in emotion processing. Research has suggested that alexithymia is associated with deficits in both affective and non-affective interoceptive processes (Brewer et al., 2016; Murphy et al., 2018b). As outlined in Section 1.3, both the AIC and ACC appear integral in interoceptive processing, and both structural and functional atypicalities have been observed in these areas in alexithymia (Goerlich-Dobre et al., 2014; Gu et al., 2013; Wingbermühle et al., 2012). Alexithymia, therefore, appears to be associated with abnormalities in the same neurological structures as implicated in both affective and non-affective interoception. As alexithymia and interoception appear to rely on similar structures, it is reasonable to expect that individuals with alexithymia, who struggle to identify emotions, may also struggle to identify non-affective internal states.

In line with the suggestion that alexithymia is associated with impaired interoception, those with elevated levels of alexithymia have also been shown to display deficits in interoceptive ability across a range of domains including cardiac perception (Herbert et al., 2011; Murphy, et al., 2018a), taste, and muscular effort (Murphy et al., 2018b), although note that findings have been mixed (Trevisan et al., 2019). Nonetheless, once several common confounds on the heartbeat counting task are controlled for, the negative relationship between alexithymia and interoceptive accuracy seems to prevail (Murphy et al., 2018a). Individuals with alexithymia also appear to self-report more difficulties recognising their internal states, and are more likely to confuse affective and non-affective states, across both typical and clinical populations (Brewer et al., 2016a). Individuals with elevated alexithymia also appear to self-report higher interoceptive attention than those with low alexithymia (Gaggero et al., 2021; Zamariola, et al., 2018), although again findings have been inconsistent (Trevisan et al., 2019). It is worth noting that another route to alexithymia through language has been outlined (Hobson et al., 2018, 2019), meaning that whilst alexithymia is likely to be present in all individuals displaying interoceptive deficits, not all individuals with alexithymia necessarily possess interoceptive deficits. Indeed, this alternate route to alexithymia may partially explain the mixed findings in the field.

Interestingly, alexithymia often co-occurs with clinical disorders characterised by interoceptive atypicalities. Alexithymia is often high, for example, in those with eating disorders (Nowakowski et al., 2013), where interoceptive deficits are common, and often thought of as a contributing factor to the characteristically reduced perception of hunger in those with eating disorders (Pollatos et al., 2008). Atypical interoception has also been implicated in the development and maintenance of substance abuse disorders (Verdejo-garcia et al., 2012), which are again often accompanied by elevated levels of alexithymia (Mann et al., 1995). A similar pattern of high alexithymia, alongside interoceptive difficulties, has been identified across a wide range of psychological and neurodevelopmental disorders (see Brewer et al., 2021 for a review). Whilst this evidence is indirect, taken together, the aforementioned findings provide compelling support for the proposition that visceral awareness is critical in emotion processing.

Not only do interoceptive and emotional processing share many similarities, the processing of one's own emotions also seems strongly associated with one's perception of others' emotions (see Section 1.7). Given the apparent similarities between interoceptive and emotional processing and the processing of one's own and others' emotions, much of the current body of work is based on extending investigation from the emotional domain into the domain of more basic interoceptive processing.

1.5 Interoception across development

In adults, interoception is thought to play a role in a range of cognitive abilities, including emotion processing (Barrett, 2014; Critchley & Nagai, 2012; Damasio, 1994; Damasio et al., 1991; Gendron & Feldman Barrett, 2009; Seth, 2013), learning and decision making (Dunn et al., 2010; Kandasamy et al., 2016; Werner et al., 2009), advantageous risk taking (Kandasamy et al., 2016), attention (Matthias et al., 2009) and memory (Garfinkel et al., 2013a; Pollatos & Schandry, 2008; Werner et al., 2010). Nonetheless, despite the potential impact of interoceptive atypicalities across these domains, research on interoception throughout development is limited.

As discussed in Section 1.2, interoceptive research is saturated with studies which measure objective interoceptive accuracy, in particular using heartbeat perception tasks (Ainley et al., 2014; Dunn et al., 2007; Herbert et al., 2007b). Despite the faults associated with these tasks, the reliance on assessment of cardiac perception in adults makes changes in cardiac interoceptive accuracy throughout development relevant. Koch & Pollatos (2014) conducted the largest assessment of cardiac interoceptive accuracy in children, recruiting 1350 participants ranging in age from 6 to 11 years. Participants completed the HCT, with findings suggesting a distribution of heartbeat perception scores with a slight left skew, comparable to that of a healthy adult sample (Herbert et al., 2007a), demonstrating that children, aged 6 to 11 years, differ substantially in their ability to feel their heart beat. Heartbeat perception scores were found to be unrelated to age, suggesting that cardiac interoceptive accuracy is not sensitive to developmental change after the age of six. It is worth noting that in this study participants were not explicitly instructed to only rely on heartbeats that they can feel, rather than providing an estimate. In adults, however, employing these adapted instructions are reported to result in HCT performance that is reduced by up to 50% (Desmedt et al., 2018). It is reasonable to assume that the same may be true for children, therefore, these findings should be interpreted with caution.

Nonetheless as the evidence suggests there is no relationship between age and cardiac interoceptive accuracy in children aged 6 – 11 years, further investigations have assessed cardiac sensitivity in preschool children, aged 4 – 6 years (Schaan et al., 2019). It seems reasonable to assume that children may undergo vast improvements in interoception during this period, as they experience profound increases in cognitive and behavioural processes related to interoception, such as language, allowing them to report bodily signals (e.g., pain; von Baeyer et al., 2017), and factual knowledge of the human body (Jaakkola & Slaughter, 2002). An adjusted paradigm was utilised, whereby children were required to report the how quickly their heart was beating (using a pictorial four point Likert scale) on two occasions, once before and once after completing 10 seconds of jumping jacks. The difference in z-standardised change scores for both the objective heart rate recording and self-reported heart rate was taken as an index of cardiac perception accuracy, with scores closer to 0 indicating higher interoceptive accuracy. Positive scores indicate greater self-reported change in heart rate than objectively occurred, while negative scores indicate a greater objective change than was self-reported. The authors reported a marginally significant effect of age, with scores increasing with age. Notably, however, an increased score is not necessarily reflective of increased accuracy, but instead demonstrates that older children tend to self-report more change in heart rate than was objectively recorded. Furthermore, while the perturbation task (jumping jacks) resulted in a significant change in objective heart rate, participants' self-reported heart rate did not differ significantly pre- and post-exercise. While these findings imply that children aged 4 – 6 years have little insight into their own cardiac changes, the non-significant difference may also be reflective of the limited response options. Indeed, 60% of children reported a change of 0 or 1, suggesting the response options were not sensitive enough to index cardiac change. With this in mind, there is an evident need for further development and subsequent administration of appropriate paradigms in a pre-school sample.

Not only do children appear to perform similarly to adults on behavioural tests of interoception, but also appear to recruit similar neurological areas in the processing of interoceptive sensations (Klabunde et al., 2019). In a pilot study of 11 6- to 17-year-olds, children appear to activate similar brain regions to adults during a heartbeat detection task compared to tone detection tasks, such as the left insula, left medial prefrontal cortex, and bilateral inferior parietal lobe. Furthermore, there was a positive association between ACC activity, during interoceptive processing, and age, suggesting neurodevelopmental changes occur in interoceptive processing. It is worth noting, however, that due to the small sample and crosssectional design, further research is needed to investigate precise developmental trajectories at the neural level.

As children and adults appear to perform comparably on behavioural measures of interoceptive accuracy and recruit similar neurological areas in interoceptive processing, it seems likely that the ability to perceive internal bodily signals is linked to a range of cognitive abilities and mental health outcomes in children, as it is in adults (Barrett, 2014; Damasio, 1998; Dunn et al., 2010; Garfinkel et al., 2013a; Gendron & Feldman Barrett, 2009; Kandasamy et al., 2016; Matthias et al., 2009; Pollatos & Schandry, 2008; Seth, 2013; Werner et al., 2009; Werner et al., 2010). As in adults (Herbert et al., 2007b), interoceptive accuracy appears to be related to physical activity in children, such that as physical activity increases so does objective interoceptive accuracy (Georgiou et al., 2015). Beyond physical health, there here have been a small number of investigations into the relationship between heartbeat perception, anxiety, and childhood panic/somatic symptoms. In a sample of 8- to 11-year-olds, those with good heartbeat perception had significantly higher anxiety sensitivity (AS) and panic/somatic symptoms than those with poor heartbeat perception, with those with high panic/somatic symptoms seven times more likely to have good heartbeat perception (Eley et al., 2004). These findings demonstrate that in children as young as 8 years, panic/somatic ratings were correlated significantly with heartbeat perception scores. Notably, this study utilised the HCT. The HCT has come under scrutiny, as outlined in Section 1.2, and of course, these limitations still apply, demonstrated for example by the low proportion of the sample (9%) who were classified as "good perceivers," and this proportion being even lower (5.4%) when the sample consisted of only 8-year olds, rather than those ranging from 8 – 11 years. It is also worth noting that in a subsequent investigation into heartbeat perception and anxiety in children with tic disorders and matched control participants, a positive relationship only pertained for the clinical group with no relationship reported between heartbeat perception and anxiety in the control group (Pile et al., 2018). These inconsistencies are similar to those in the literature on anxiety and heartbeat perception in adults, with a recent meta-analysis reporting no relationship between anxiety and cardiac interoceptive accuracy across different interoceptive tasks and anxiety measures (Adams et al., 2022). Nonetheless, as investigations in children remain sparse, future research is needed to fully quantify the relationship between interoceptive abilities, panic/somatic symptoms, and anxiety, as well as other mental health and physical outcomes, throughout development.

The period of development that follows childhood is that of adolescence. Whilst adolescence was previously defined as the period from 10 – 19 years of age, recent definitions propose that it is better characterised as the period between the ages of 10 and 24 years (Sawyer et al., 2018). Adolescence is accompanied by many physical, neurological, and psychological changes (Blakemore et al., 2010; Blakemore & Choudhury, 2006; Colemean & Hendry, 1990; Crone et al., 2016; Rutter & Rutter, 1993). Research explicitly investigating interoception in adolescence is limited (Murphy et al., 2017), however, high rates of alexithymia have been reported; while the prevalence of alexithymia in adults is 8-10% (Linden et al., 1995; Salminen et al., 1999), approximately 18% of 11–18-year-olds exhibit high levels of alexithymia (Gatta et al., 2014; Sakkinen et al., 2007). As elevated alexithymia also appears closely related to atypical interoception (Brewer et al., 2016; Murphy et al., 2018b), this suggests that adolescence might also be associated with disrupted interoceptive processing. Adolescence has also been associated with factors that have been linked to atypical interoception such as increased risk-taking (Steinberg, 2007), and the onset of psychopathology (Brewer et al., 2021; Kessler et al., 2005; Khalsa et al., 2018; Murphy et al., 2017; Paus et al., 2008). It is possible that disrupted interoceptive processing may explain these findings.

Beyond this, there is work that has explored interoception in adolescence more explicitly, albeit limited. One recent study investigated the relationship between the heartbeat-evoked potential (HEP), thought to represent the cortical processing of heartbeats in adults (Coll et al., 2021), performance on the HCT, and self-reported interoceptive processing, indexed by score on the MAIA (Mai et al., 2018). As in adults (Coll et al., 2021; Schulz et al., 2015), significantly greater HEP positivity was observed whilst participants completed the HCT, rather than at rest. Furthermore, HEP positivity during the HCT was positively associated with interoceptive accuracy, in line with findings in adults, where increased HEP activity has been seen in individuals with higher interoceptive accuracy (Coll et al., 2021; Montoya et al., 1993; Pollatos et al., 2005; Pollatos & Schandry, 2004). Despite this, self-reported interoceptive processing was unrelated to both objective interoceptive accuracy and HEP, a finding which is replicated in the adult literature (Baranauskas et al., 2017; Mallorquí-Bagué et al., 2014), likely due to the differing dimensions of interoception measured by the MAIA and the HCT. Together, these findings suggest that the HEP may be a reliable index of interoceptive processing in adolescence, as it is in adulthood (Coll et al., 2021), as well as suggesting that similar distinctions between interoceptive dimensions exist in adolescence as they do in adulthood. Future research should aim to further investigate the HEP as a useful tool to index interoceptive processing in adolescence, in particular, whether individual differences in HEP amplitude are associated with other mental and physical health factors.

Indeed, studies which have investigated self-reported interoceptive processing suggest a similar relationship between mental and physical health and interoceptive as is present in adulthood. In adolescence, self-reported interoceptive processing appears negatively associated with suicidal ideation and eating disorder symptoms (Perkins et al., 2021); self-reported difficulties identifying cues, such as huger and satiety, predicted increased suicidal ideation and eating disorder symptoms at a later time point. On the other hand, body positivity, appreciation, and pride appear positively associated with self-reported interoceptive processing (Todd et al., 2019a, 2019b). Further to this, in a study of objective interoceptive accuracy in adolescence, whilst no relationship was observed between obesity and performance on the HCT, opposite associations were reported between percentage of errors in the heartbeat perception task and insula activation for healthy adolescents and adolescents with excess weight (Mata et al., 2015). A negative correlation between percentage of errors and insula activation was observed in healthy participants, whereas percentage of errors was positively correlated with insula activation in excess weight participants. Adolescents with excess weight, therefore, appear to have an altered association between insula function and processing of interoceptive information, in line with evidence that reports poorer perception of cardiac signals in obese adults (Herbert & Pollatos, 2014). Surprisingly, an investigation into the relationship between emotion recognition and interoceptive accuracy, in adolescents aged 12 to 17 years, reported decreased recognition of sad and fearful faces in those with higher interoceptive accuracy scores, as measured by the HCT (Georgiou et al., 2018). These findings are inconsistent with reports that adults high in interoceptive accuracy possess superior emotion recognition abilities (Mulcahy et al., 2019; Pollatos et al., 2011), suggesting there may be alternate relationships between interoceptive processing and the recognition of others' emotions throughout development. Given the small sample of good heartbeat perceivers (n = 14) in this study, however, future research is needed to fully characterise the relationship between one's own interoceptive processing and the recognition of others' emotions, throughout development.

Whilst these findings provide crucial insight into the impact of individual differences in interoception on other mental and cognitive factors in adolescence, the small number of participants and limited age ranges assessed preclude conclusions concerning developmental changes in interoception throughout the childhood and adolescent period. The sole study which has investigated developmental changes in objective interoceptive accuracy in childhood, adolescence, and adulthood, employed an adaption of the HDT, whereby participants are presented with images of two rabbits, and instructed to look at the rabbit which is flashing in time with their heartbeat (Yang et al., 2022). The authors reported higher objective interoceptive accuracy in adolescence, when compared to pre-schoolers and adults, suggesting that interoception increases throughout childhood and adolescence before decreasing in adulthood. Whilst this supports the relationship between ageing and interoception previously outlined in the literature (Khalsa et al, 2009; Murphy et al., 2018c), it disputes arguments that adolescence may be associated with disrupted interoception. It is worth noting, however, that this study recruited a sample of pre-schoolers with a mean age of 5.33, and a sample of adolescence with a mean age of 13. The lack of participants in late childhood, and spanning the broad adolescent period, means the developmental trajectory throughout childhood and adolescence cannot be determined. As neuroimaging studies suggest that between the ages of 13 and 17 years, adolescents experience increased neural activity in areas involved in interoceptive processing, compared to children and adults (Li et al., 2017; May et al., 2014), it might be that early adolescence is associated with disrupted interoception whereas later adolescence is not. Given the potential impact of atypical interoception in adolescence, in particular on mental health, safety behaviours and cognitive outcomes, further research is clearly needed which investigates interoceptive changes in this age group.

A final developmental period of interest is that of older age. Older age is associated with increased vulnerability to a series of health issues, potentially making the ability to perceive interoceptive states precisely even more important. Despite this, investigations into the effect of advancing age on interoceptive processing are sparse. Khalsa and colleagues employed the HDT across two testing sessions in adults aged 22 to 63 years (Khalsa et al., 2009). The HDT, as outlined in Section 1.2, requires participants to judge whether a series of tones are synchronous or asynchronous with their heartbeat. A negative relationship between interoceptive accuracy and age was reported, suggesting that increasing age is associated with decreased precision in the perception of cardiac signals. Decline in interoceptive accuracy with age was present in individuals aged 40 – 60 years. It is worth noting, however, that this study was limited by the small number of participants below 41 years ($n = 13$) and above 61 years ($n = 6$) of age. Encouragingly, however, the results were replicated in a subsequent investigation employing the HCT, with a sample ranging in age from 20 – 90 years (Murphy, et al., 2018c).

Again, an inverse relationship emerged between age and interoceptive accuracy in the cardiac domain, such that as age increased, ability to detect cardiac signals decreased. This study extended the findings of Khalsa and colleagues (2009), demonstrating that interoceptive accuracy continues to decline into both late and very late adulthood.

Interestingly, the relationship between age and interoceptive accuracy was partially mediated by changes in BMI (Murphy et al., 2018c), which has previously been associated with HCT performance (Herbert & Pollatos, 2014). These findings suggest that increases in BMI with age is one potential cause of age-related decreases in interoceptive accuracy. As age also exerted a direct effect on accuracy, however, other mechanisms are also likely to contribute to interoceptive difficulties in older age. One potentially interesting relationship is that of interoceptive accuracy and attention. Although interoceptive accuracy and attention appear distinct dimensions (See Section 1.1 for a full explanation), it is still plausible that one's attention to interoceptive signals may lead to subsequent changes in interoceptive accuracy, and vice versa. Indeed, Murphy et al. (2018c) also reported a negative relationship between self-reported interoceptive attention (measured with the BPQ) and age in adults aged between 18 and 89 years, suggesting that ageing is not only associated with decreased interoceptive accuracy, but also with decreased attention to internal bodily signals. It is possible that, as ageing is associated with increased vulnerability to numerous health problems, reduced attention to one's interoceptive signals acts as a mechanism to reduce health anxiety. Without longitudinal investigations, the exact nature of the relationship between advancing age and interoceptive attention remains unclear. It is possible, for example, that this relationship is not linear, with interoceptive attention potentially initially increasing with advancing age before reducing in later adulthood. Current understanding of the relationship between age and interoceptive attention is also limited by the use of the BPQ in the only study of interoceptive attention and age thus far (Murphy et al., 2018c). As outlined in Section 1.2 the BPQ has subsequently been found to have interpretation issues, limiting the interpretation of these findings (Gabrielle et al., 2022). Given the importance of appropriately attending to and interpreting internal states with increasing age, further research is clearly needed which separately measures interoceptive accuracy and attention using validated measures.

Overall, these findings demonstrate that interoceptive accuracy is variable in childhood, implying that beyond effects of age itself, individual differences in interoception are likely to influence other cognitive, emotional and health outcomes in childhood, as in adulthood.

Interoception also appears to be associated with mental and physical health outcomes in adolescence. Whilst adolescents have been found to outperform pre-schoolers and adults in an objective interoceptive accuracy task (Yang et al., 2022), thorough exploration of interoceptive change across a broad developmental period is still required. It is possible that early adolescence may be a risk period for atypical interoceptive processing (Murphy et al., 2017), explaining related behaviours, such as risk-taking, as well as the onset of psychopathology, although direct investigations of this theory are required. Finally, it seems that advancing age into later adulthood may be associated with decreases in both interoceptive accuracy and attention. Notably, however, very few studies have directly investigated developmental changes in interoception, or their relationship with other cognitive processes, justifying further investigation into interoception development and its concurrent relationship with other outcome variables.

1.6 Gender

Beyond the developmental changes in interoception outlined in Section 1.5, gender[2] differences have also been observed. Women tend to self-report greater attention to internal bodily signals than men (Grabauskaite et al., 2017), in line with the finding that men tend to self-report fewer somatic symptoms than women (Barsky et al., 2001). Conversely, a recent meta-analysis concluded that females, compared to males, exhibit significantly reduced objective interoceptive accuracy when assessed with the HCT or HDT (Prentice & Murphy, 2022). These findings are in line with previous research that reports reduced performance in females relative to males on the HCT (Desmendt et al., 2020), suggesting a consistent effect of gender on interoceptive accuracy, at least in the cardiac domain. It is worth noting that, in the above meta-analysis, no gender differences were observed in the gastric domain (Prentice & Murphy, 2022). As these findings are limited by the small number of studies conducted in this domain, however, further work is required to determine the effect of gender across a range of interoceptive signal channels.

Interestingly, gender differences in interoception do not appear to be present when assessed in more naturalistic settings, outside of the laboratory. When estimating blood glucose levels,

[2] In this thesis the term ‘gender’ is used throughout as gender identity was explicitly recorded, rather than sex, across all included studies. It is worth noting, however, that in previous research the terms gender and sex have often been used interchangeably.

diabetic men were more accurate when only internal cues were available, whereas there were no gender differences present when both internal and external cues were available (e.g., knowledge about food intake, insulin intake, and physical activity; Cox et al., 1985). Similar findings have also been demonstrated in the perception of blood pressure (Pennebaker & Watson, 1988; Smith et al., 1986), such that males were significantly more accurate than females when levels could only be gauged using internal signals, but no differences were present when both internal and external cues were available. These findings suggest that women and men may use different mechanisms to gauge interoceptive states, with men relying more on interoceptive cues (e.g., gastric sensations to indicate hunger) and women relying more on external cues (e.g., the time of the day to indicate hunger).

One possible explanation for the gender differences in interoceptive ability is the socialisation experiences of males and females (Prentice et al., 2022). For example, girls are more likely to be labelled as emotional by their parents than boys (Fivush et al., 2000.; Kuebli & Fivush, 1992; Mascaro et al., 2017), while distress in infant boys is more likely to be attributed to pain than in infant girls (Cohen et al., 2014). Differences in internal state labelling by others are likely to affect development of the child's interoceptive language and conceptual understanding, potentially leading to better understanding of emotional constructs in females than males (Abbruzzese et al., 2019; Olderbak et al., 2019; Sullivan et al., 2017; Thompson & Voyer, 2014), with the opposite being true of interoceptive constructs. In turn, this may prompt females to rely less on their internal signals to gauge interoceptive states. An alternative explanation is that women come to rely less on internal bodily cues due to the increased amount of physical and hormonal change that they experience across the lifespan, due to events such as menstruation, pregnancy, and menopause (Murphy et al., 2019b). If it is the case that interoceptive cues are more variable, and subject to more noise, in females than males, this might explain the increased reliance on external cues as a compensatory mechanism, eliminating gender differences in naturalistic settings (Cox et al., 1985; Pennebaker & Watson, 1988; Smith et al., 1986). Of course, these explanations are currently speculative and further research is needed to investigate potential gender differences in both interoceptive accuracy and attention. Given the evidence for gender differences in interoceptive abilities, however, it is also necessary to investigate how gender may alter the relationship between interoception and other cognitive abilities. Where the current thesis is concerned, whether the relationship between processing of one's own and others' interoceptive states changes as a function of gender is of interest.

1.7 Social perception

As outlined in Section 1.4, there appears to be a close relationship between interoceptive and emotional experience (James, 1894; Lange, 1885; Schachter & Singer, 1962; Critchley & Nagai, 2012; Damasio, 1994; Damasio et al., 1991; Gendron & Barrett, 2009; Seth, 2013). Within the emotion literature, there is a vast amount of research not only into how we process our own emotions, but also into how we process the emotions of others. The ability to correctly infer another's emotion is a complex process consisting of multiple stages. First, an individual must appropriately attend to another's expressive cues (e.g., facial and vocal expressions, body posture and motion), before perceptually processing these cues. The individual must then compare the observed expression to their perceptual representations of emotional expressions, which involves memory of previously encountered expressions in others, as well as one's own expressions and memory of the contexts in which these have previously occurred, allowing the expression to be categorised alongside similar emotional expressions. Finally, a verbal label can be attributed to the observed emotional expression (Adolphs, 2002; Spunt & Adolphs, 2019). The ability to successfully classify basic emotions typically emerges between 6 and 11 years of age (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012), although sensitivity to changes in emotion continues to develop throughout adolescence (Thomas et al., 2007). Vocal emotion recognition accuracy does not appear to peak until age 20 (Amorim et al., 2021), suggesting that the recognition of emotions continues to develop throughout adolescence.

Given that recognising another's emotion is crucial for a range of cognitive and mental health outcomes (Gross, 2002; Hu et al., 2014; Kret & Ploeger, 2015; Parker et al., 2004; Schutte et al., 2007), research has also investigated potential explanations for individual differences in the processing of other's emotions. As the processing of one's own emotions is thought to be critical in the processing of others' emotions (Bird & Viding, 2014), much research has attempted to quantify the relationship between understanding of one's own emotions and the processing of others' emotions across a range of cognitive domains, often relying on measures of alexithymia (Luminet et al., 2021). Elevated alexithymia is thought to be associated with decreased accuracy in the recognition of others' emotions from vocal and facial expressions, across typical and clinical groups (Brewer et al., 2015; Cook et al., 2013; Grynberg et al., 2012; Heaton et al., 2012). Beyond recognition accuracy, elevated alexithymia is also associated with a deficit in attention to others' emotions (Pfabigan et al., 2014; Suslow et al., 2003; Van der

Velde et al., 2013; Vermeulen et al., 2006) and memory for others' emotional expressions (DiStefanio & Koven, 2012; Donges & Suslow, 2014; Ridout et al., 2021; Takashi et al., 2015). Individuals with elevated alexithymia also tend to appraise emotional stimuli as less emotive than those with reduced alexithymia (Luminet et al., 2021). Combined, these findings suggest that an understanding of one's own emotions is crucial in the processing of others', with difficulties correctly classifying emotions in one's own body hampering the learning of emotional cues in others.

As with emotions (Gross, 2002; Schutte et al., 2007), the processing of others' interoceptive states is presumably important for social cognition and providing appropriate care. If one fails to recognise when another individual is tired, hungry, or unwell, one may struggle to respond appropriately, negatively impacting relationships. Despite this, very little research has explored the processing of others' interoceptive expressions. Previous work has investigated the processing of others' pain, which has been described as both interoceptive and emotional in nature (Craig, 2003b). Gu et al. (2012) reported that individuals with lesions in the AIC, a key interoceptive brain region (See Section 1.3), exhibit decreased discrimination of hands and feet in painful and non-painful situations. These individuals also demonstrated reduced implicit empathy for others' pain, lacking the typically observed interference effect of pain when asked to judge the laterality of hands and feet. Similarly, individuals with alexithymia have been found to assign lower pain ratings to hands and feet in painful situations relative to individuals with low alexithymia (Moriguchi et al., 2007). Lower ratings of pain in this study were also accompanied by reduced activation of the ACC (again, an area strongly implicated in interoception; see Section 1.3) in those with high levels of alexithymia. In combination, these results suggest that individuals with alexithymia may exhibit a deficit in the processing of others' interoceptive states, as well as emotions. As pain is thought to be composed of both sensory and affective components (Fernandez & Turk, 1992), and interoception is unlikely to be a unitary construct (Ferentzi et al., 2018), however, research is needed which explores the processing of a range of interoceptive expressions.

Additional studies have investigated aspects of processing of others' interoceptive states. Research has suggested that we make judgements about a person's health based on their skin colour (Stephen et al., 2009). Whilst this suggests that individuals use visual cues to make consistent inferences regarding others' health, as skin colour is artificially manipulated it is uncelar from these investigations whether these judegments are objectively correct. Beyond this, however, untrained participants were able to identify acute illness in others at above chance levels (Axelsson et al., 2018). Participants were able to distinguish individuals who had been injected with a bacterial stimulus, which induced an immune response, from those who had been injected with a placebo, from facial photographic stimuli. Prior to this, research had demonstrated that humans could successfully identify obviously sick people (Hedman et al., 2016; Schaller et al., 2010), however, due to the implementation of an experimental setting, these findings support the notion that humans can successfully identify illness even in its early stages. The second study reported that participants performed above chance when asked to identify which of two individuals a heartbeat signal belonged to (Galvez-Pol et al., 2022). Participants viewed videos of two individuals and a square which changed in colour in synchrony with the R-peak (contraction of the heart) of one of the individuals, and were asked which of the two individuals the heartbeat belonged to. Galvez-Pol et al. (2022) subsequently utilised altered paradigms to attempt to determine the visual cues being used to correctly assign heartbeats. Participants viewed the same videos inverted, with the removal of any transient redness of the face, and using still images. Although participants performed significantly better in the original paradigm than in the inverted and still image conditions, performance in these conditions was still significantly greater than chance, suggesting that participants may have based decisions on factors such as age, gender, or perceived health, rather than utilising cues that corresponded to the heartbeat in real time. Future research is, therefore, required to disambiguate the type of information needed to perceive others' heartbeats, as well as determining whether the perception of heartbeats is related to the perception of other interoceptive expressions e.g., fatigue, nausea, and breathlessness.

Given the close relationship between the processing of one's own and others' emotions, and between one's own emotional and interoceptive experience, it seems likely that the processing of one's own interoceptive states is also related to the processing of others' interoceptive expressions. As research is yet to investigate the processing of others' interoceptive expressions across a range of states, and no previous study has investigated the relationship between perception of one's own and others' interoceptive states, this currently remains to be seen. As the perception of interoceptive expressions is presumably crucial for social communication, building and maintaining relationships, and providing appropriate care for others, further work is clearly needed which investigates the processing of others' interoceptive expressions and its relationship with the processing of interoceptive states in one's own body.

Chapter 2. Methodology

As outlined in the introduction to this thesis, interoception refers to the perception of, attention to, and propensity to use internal bodily signals (e.g., cardiac, respiratory, and gastric signals; Garfinkel et al., 2015; Garfinkel & Critchley, 2013; Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Interoceptive experience appears closely related to emotional experience, with almost every emotion model ascribing some role for physiological change (e.g., James, 1984; Lange, 1885; Schater & Singer, 1962; Barrett, 2014). Difficulty identifying and explaining one's own emotions (termed alexithymia) is closely associated with a deficit in the processing of others' emotions across various cognitive domains (Luminet et al., 2021). As well as decreased recognition accuracy for emotional expressions (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), individuals with elevated alexithymia display an attentional (Luminet et al., 2021; Pfabigan et al., 2014; Van der Velde et al., 2013) and memory deficit (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout et al., 2021; Vermeulen et al., 2006; Vermeulen & Luminet, 2009) in the processing of emotional expressions, as well as appraising emotional stimuli as less emotive than those with reduced alexithymia (Luminet et al., 2021). Despite this, research is yet to explore the processing of others' interoceptive expressions and its relationship with the processing of interoceptive states in one's own body. Exploring the processing of others' interoceptive expressions is crucial given that correctly recognising, attending, and interpreting others state displays is likely to allow the provision of appropriate care, as well as affecting one's ability to build relationships and empathise. Until recently, however, there were no appropriate stimuli depicting interoceptive states with which to investigate this.

The Interoceptive Static State Images database (ISSI; Biotti et al., 2021) is a set of fully validated static images representing non-affective internal bodily states (e.g., hot, cold, tired, pain) and control actions (e.g., running, jumping, washing hands, walking). All images included in the ISSI went through a two-stage validation procedure. First, a free-labelling task was implemented, such that participants provided a brief description of what each body posture represents (in response to the question 'What is the person feeling or doing?'). Stimuli that were described correctly (as assessed by independent coders) in the first validation stage were then rated using multiple choice labels and quality rating scales. These data were used to create a set of multiple validation indices for each image, each focusing on distinct aspects of stimulus quality or recognisability, allowing for appropriate stimulus selection depending on researcher requirements. Using these novel validated stimuli, this thesis explores the processing of interoceptive states in one's own body and its relationship to the processing of others' interoceptive expressions across various cognitive domains. To emulate the emotion literature, the relationship between self-reported interoceptive processing[3] and the processing of others' interoceptive expressions was assessed with regards to recognition accuracy (Chapter 3), as well as biases in the interpretation of (Chapter 4), attention to (Chapter 5), and memory for (Chapter 6) others' interoceptive expressions. Self-reported interoceptive accuracy and attention were assessed throughout Chapters 3 – 6 using the Interoceptive Accuracy Scale (IAS; Murphy et al., 2019a, 2020) and Interoceptive Attention Scale (IATS; Gabriele et al., 2022), or the Child-Adapted versions where appropriate. The IAS is reported to have good internal consistency (20 items; α = 0.88, 0.90) and test-retest reliability (see Murphy et al., 2020a for a detailed summary of the psychometric properties of the IAS). Similarly, the IATS is reported to have good reliability (α = 0.91; details of the reliabilty and validatiy of the IATS can be found in Gabriele et al., 2022). Beyond psychometric properties, recent research suggests that accuracy and attention are two separate dimensions of interoception (Murphy et al., 2019a; Murphy et al., 2020a; Suksasilp & Garfinkel, 2022), despite the conflation of these in the majority of self-report measures of interoception (Desmendt et al., 2022). Employing the IAS and IATS, therefore, uniquely allowed for the separate analysis of subjective interoceptive accuracy and attention and their relationship with the processing of others' interoceptive expressions.

Given the reported inverse relationship between ageing and the processing of one's own interoceptive states (Khalsa et al., 2009; Murphy et al., 2018c), this thesis also explores how advancing age affects the processing of others' interoceptive expressions, and whether the impact of age can be explained by changes in self-reported interoceptive processing. For instance, Study Two explores the relationship between propensity to assign an interoceptive, over an action, label to others' interoceptive state displays, and its relationship with self-reported interoceptive processing, in participants aged 16 to 90 years. Study Three assesses attentional biases in the processing of interoceptive expressions, and its relationship with self-reported interoceptive processing, in participants aged 15 to 72 years. Together, Studies One

[3]Interoceptive processing is assessed using self-report measures throughout all studies in this thesis. Where findings are discussed without explicit reference to self-report, this is for the sake of brevity.

to Four provide a comprehensive investigation into the processing of others' interoceptive expressions and its relationship with self-reported interoceptive accuracy and attention.

Lastly, Study Five explores self and parent-reported interoceptive and emotional processing in children and adolescents with Medically Unexplained Symptoms (MUS) and Tourette Syndrome (TS), as well as their relationship with symptom severity and quality of life. Interoceptive and emotional atypicalities are common in a range of clinical disorders (Aaronson et al., 2017; Dunn et al., 2010; Furman et al., 2013; Garfinkel et al., 2016; Hatfield et al., 2019; Jakubczyk et al., 2019; Mul et al., 2018; Naqvi & Bechara, 2010; Nicholson et al., 2019; Paulus & Stewart, 2014; Pollatos et al., 2008), yet research in individuals with MUS and TS is limited, particularly in developmental groups. Research on interoceptive abilities in these groups is therefore required, not only to understand whether interoceptive atypicalities exist, but also to pave the way for future research on their relationship with the processing of others' interoceptive states in the same groups.

2.1. Study One. The relationship between recognition of one's own and others' interoceptive states in adolescence and early adulthood

The first study in this thesis investigated the recognition of interoceptive expressions in oneself, and its relationship with self-reported interoceptive accuracy and attention, in a sample of participants aged 16 to 21 years of age. Given that elevated alexithymia is associated with decreased recognition of others' emotions (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), and interoceptive and emotional experience appear closely related (e.g., Barrett, 2014; James, 1894; Lange, 1885; Schachter & Singer, 1962), it was predicted that self-reported interoceptive processing would be positively related to the recognition of others' interoceptive expressions.

2.1.1 Interoceptive processing in oneself

Self-reported interoceptive accuracy and attention were assessed using the Child-Adapted Interoceptive Accuracy (IAS-C) and Attention Scales (IATS-C), respectively. For a detailed discussion on the benefits of using self-report to measure interoceptive processing see Section 1.2. of the Introduction (Chapter 1). Child-Adapted scales were utilised to accommodate for the inclusion of a younger sample, should in-person COVID-19 testing restrictions allow. Unfortunatly, no children were recruited in the final sample, however, these scales are almost identical to the adult versions, although the wording has been modified to ensure understanding by a younger audience; for instance, “I can always accurately perceive when I need to urinate” in the adult questionnaire is substituted with “I am always correct at feeling when I need to have a wee” in the child questionnaire (for the original and child-adapted questionnaires, see appendices A, B, C, D, E, F). The child-adapted versions are also composed of 20 rather than 21 items due the removal of an item which references sexual arousal. Whilst the validation of the Child-Adapted questionnaires is still ongoing, encouragingly, in adults, the IAS (21 items; $\alpha = 0.89, 90$) and IATS (21 items; $\alpha = 0.90$) are reported to have good reliability (Gabriele et al., 2022; Murphy et al., 2020a).

As the Child-Adapted IATS had been recently developed, the Child Adapted Porges Body Perception Questionnaire (BPQ-C; Palser er al., 2018; Porges, 1993) was also included in Study One, as it has been used widely in the literature to assess self-reported interoceptive attention. The inclusion of the BPQ-C also, crucially, allowed for the analysis of relationships between the three self-report measures of interoception. Whilst interpretation issues have been noted with the BPQ (Gabriele et al., 2022), it is also reported to have good reliability (45 items; $\alpha = 0.85$; Palser et al., 2018).

Through studies 1 – 4, no self-report measure of alexithymia was included (e.g., the Toronto Alexithymia Scale (TAS-20; Bagby et al., 1994)), as the relationship between the processing of one’s own emotions and interoceptive states is relatively well established (Brewer et al., 2016; Gaggero et al., 2021; Murphy et al., 2018a, 2018b; Zamariola, et al., 2018). Considering that this is the first investigation of its kind, the omission of a meaure of alexithymia lessens participant burden and allows focus on the relationship between the processing of one’s own and others’ interoceptive states. It is worth noting, that as interoceptive processing is closely linked to emotional processing (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013; Gendron & Barrett, 2009; James, 1894; Lange, 1885; Schachter & Singer, 1962), it is likely to that if a relationship between the processing of one’s own and others’ interoceptive states was found this was also pertain to the processing of one’s emotions.

2.1.2 Pre-testing task

As Study One was initially designed for use across a broad age range, including children and older adults, prior to completing the recognition task, participants completed a pre-testing task, to assess comprehension of the interoceptive states presented in the subsequent recognition task (cold, tired, hot, out of breath, hungry, itch, pain, feeling sick, feeling full of food). Interoceptive expression labels were also adapted to support understanding (e.g., “nausea” was labelled “feeling sick”). To assess comprehension, participants were shown a word (e.g., “cold”) alongside nine images and asked to “select the picture that shows cold”. All images were of objects associated with the interoceptive state, rather than people, to ensure there was no facilitation effect on the subsequent recognition task. For example, cold was paired with an image of an ice cube, hot with a flame, and pyjamas with tired. Orthographic labels were presented alongside an audio button to ensure that reading ability did not prevent participants from completing the task. Participants completed two phases of the task, viewing one of the two images for each label in the first phase and the other in the second. In the first phase, participants received feedback if the incorrect response was selected, providing them with the correct response. Feedback was provided in the first phase to ensure that participants understood the task. In the second phase, no feedback was given so as to not affect accuracy of subsequent trials.

Participants of all ages completed the comprehension task for two main reasons. Firstly, this ensured consistency across participants if COVID-19 policies on in-person testing allowed for the recruitment of a younger sample, who would be more likely to lack understanding of the internal state words. Secondly, given that children can report bodily signals (von Bayer et al., 2017) and functions (Jaakola & Slaughter, 2002) between the ages of 3 and 8 years, meaning older participants were unlikely to struggle to complete the task for any other reason than a lack of attention, this task was also used as an attention check for adolescent and adult participants. Participants were therefore excluded if they selected the incorrect label on more than three trials, achieving a total score of less than fifteen on the pretesting task. This was deemed important as data were collected online, and utilising college and university participants, which are risk factors for participant inattentiveness (Hauser & Schwarz, 2016). Attention checks were, therefore, included where possible throughout this thesis.

2.1.3 Recognition paradigm

An eleven-alternative forced choice paradigm was utilised to assess recognition of a range of interoceptive states. Participants viewed randomly presented photographic stimuli, taken from the Interoceptive States Static Images (ISSI) database (Biotti et al., 2021), depicting six actors (three male, three female) portraying nine internal states (hot, cold, fatigue, satiety, hunger, itch, breathlessness, nausea, and pain), all of which were utilised in Study One. The ISSI is a database of 423 visual stimuli depicting interoceptive states and control actions, which provides a range of validation ratings for each of the included images. All states were required to be portrayed by the same actors, and equal numbers of stimuli per actor and per state were required. For each state and each actor, stimuli with the highest proportion of validation participants selecting the target label to describe the stimulus were selected for this study. These stimuli were selected to ensure that recognition deficits were not the result of poor depictions of the internal state. Selected stimuli were labelled correctly anywhere from 27 to 100% of the time during validation (Biotti et al., 2021), with lower scores typically arising due to the confusion of two similarly depicted states (e.g., satiety and hunger).

Participants also viewed photographic stimuli of the same six actors posing a control action (running) to ensure that individual differences in recognition were specific to the recognition of interoceptive states, rather than domain-general processes, such as face or body processing, or social attention. Running was selected as a control posture as it does not involve social cues (e.g., waving or beckoning), but differed from a neutral body position. Participants viewed the same number of male and female actors depicting the internal states and the control action to ensure that actor gender did not facilitate or inhibit performance. Research suggests that there is an in-group advantage in emotion recognition tasks, whereby individuals are significantly more accurate at recognising emotions posed by similar individuals (Elfenbein et al., 2002; Soto & Levenson, 2009). With this in mind, an increased number of male or female actors may have facilitated the performance of male or female participants, respectively. Beyond postural images, ten photographs of animals were randomly interleaved to ensure participants were attending to the images and could complete the basic forced-choice task. Again, the inclusion of the animals for all participants ensured for consistency amongst participants if in-person testing restrictions allowed for the recruitment of a younger sample.

2.1.4 Sample size

As no previous work has investigated the recognition of others' interoceptive expressions, a minimum sample of 111 participants were recruited, providing 95% power to detect a medium effect size of r = 0.3 (correlation, one-tailed). As individuals with a mental health condition were excluded retrospectively, and given the likely inattentiveness of our sample (Hauser &

Schwarz, 2016), as many participants were recruited as possible in a 17-month time frame to ensure adequate power after exclusions.

2.1.5 Analysis

Prior to main analyses participants were excluded on two criteria. First, as previously outlined in 2.1.2, if they made more than three mistakes in the pre-testing task. Beyond this, as participants were recruited from local colleges and the university student pool and local colleges, departmental policies meant that individuals with mental health conditions could not be excluded from participating. Participants, were asked, however, "Have you ever been diagnosed with any psychological or developmental condition e.g., autism, depression, anxiety etc?" and those who responded "Yes," or "I would prefer not to answer this question," were retrospectively excluded from analyses. The same mental health exclusion criteria were utilised through Studies 1 to 4.

To compute a measure a recognition accuracy, unbiased hit rate was calculated for each internal state (hot, cold, breathlessness, hunger, satiety, itch, pain, nausea, and pain) and action (running; Wagner, 1993). See Chapter 3 for more details. Unbiased hit rate was utilised, rather than percentage of correct responses, to overcome issues with response bias. Response bias refers to a phenomenon whereby if a participant has a bias towards a specific label (e.g., cold), and, as such, exclusively selects this label throughout the experiment a measure of percent correct would incorrectly imply they were accurate at recognising cold, but inaccurate at recognising any other internal state. Of course, this conclusion is incorrect but serves to demonstrate why alternative measures of recognition accuracy are necessary. Since unbiased hit rate expresses accuracy as a proportion of both response and stimulus frequency it is insensitive to these biases.

2.2. Study Two. The processing of interoceptive states in oneself and others in adolescence, adulthood, and older age

The second study in this thesis extended the findings of Study One, investigating the propensity to assign interoceptive, over action, labels to others, as well as the relationship between these and self-reported interoceptive processing in the self. Importantly, Studies One and Two varied in their response methodology; while Study One provided multiple interoceptive labels as response options, requiring participants to differentiate between multiple interoceptive states, Study Two provided two valid labels to describe the image, with one being interoceptive and one simply describing the actor's actions. This allowed for distinction between the ability to distinguish between multiple interoceptive expressions, and the tendency to interpret another's actions as indicative of interoceptive states, which are both likely to contribute to one's accuracy identifying interoceptive signals in others.

Further, as an inverse relationship has been reported between ageing and interoceptive processing in the self (Khalsa, Rudrauf, & Tranel, 2009; Murphy et al., 2018c), Study Two built on Study One by expanding the age range of participants into older adulthood, to assess the impact of age on the processing of interoceptive states in oneself and others. Where basic emotion recognition is concerned, adult level typically emerges between 6 and 11 years of age (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012), with sensitivity to some changes in emotion continuing to develop throughout adolescence (Thomas et al., 2007). Despite the limited previous research investigating the recognition of interoceptive expressions, as no effect of age was observed in Study One, it may be that the perception of interoceptive expressions matures at a similar age. As Study Two aimed to investigate the processing of others' interoceptive expressions throughout adolescence, adulthood, and older adulthood, a basic recognition task (such as that used in Study One) is likely to be limited by ceiling effects, further justifying the use of an alternative paradigm in Study Two, assessing biases towards interoceptive interpretations rather than accuracy distinguishing between interoceptive states.

Due to the inverse relationship reported between ageing and interoceptive accuracy and attention (Khalsa, Rudrauf, & Tranel, 2009; Murphy et al., 2018c), propensity to assign interoceptive, over action, labels to others was predicted to decline with age.

2.2.1 Self-reported interoceptive abilities

Self-reported interoceptive accuracy and attention were assessed using the Interoceptive Accuracy (IAS; Murphy et al., 2019a, 2020) and Attention Scale (IATS; Gabriele et al., 2022) respectively. See Section 1.2 of the Introduction for a justification of using self-report measures of interoception. The IAS (21 items; $\alpha = 0.89, 90$) and IATS (21 items; $\alpha = 0.90$) are reported to have good reliability (Gabriele et al., 2022; Murphy et al., 2020a). See Chapter 4 for more detail. As there was a close relationship reported between the BPQ-C and IATS-C in Chapter

3, the IATS was employed in isolation as a measure of self-reported interoceptive attention through Studies 2 to 4. Importantly, the use of both scales allows for the separate measurement of interoceptive accuracy and attention, but this is only effective if the responder has interpreted the questionnaires in the intended manner. Research has therefore advocated for the inclusion of interpretation questions (Gabriele et al., 2022). To assess interpretation, after completing the IAS and IATS; therefore, participants in Study Two were asked to indicate what they believed the questionnaire was asking them to report on: the accuracy with which they can perceive sensations, the attention they pay to said sensations, the frequency with which these sensations occur in their body, or another construct. If the participant did not correctly interpret the IAS or IATS, their score on that questionnaire was removed from analyses. Encouragingly, the majority of participants appear to interpret the questionnaires correctly (79% and 84.6% for the IAS and IATS, respectively; Gabriele et al., 2022), particularly, compared to other measures such as the BPQ where research has found that only 36.4% of participants interpret as assessing attention (Gabriele et al., 2022). Questionnaires were presented after the labelling propensity task (outlined in 2.3 below) to ensure that their completion did not prime participants to select interoceptive, over action, labels.

2.2.2 Labelling propensity task

Participants' propensity to assign an internal state label to interoceptive stimuli was assessed using a novel paradigm. Stimuli were selected to be identical to those used in Study One, with the exception that stimuli depicting itch were excluded as it was not feasible to create a variety of action and interoceptive descriptors of these stimuli. The internal states portrayed were, therefore, breathlessness, cold, hot, fatigue, hunger, satiety, nausea, and pain. For each image an interoceptive and an action phrase were derived, both of which could be used to describe the images. Phrases were derived by inspecting and describing the actions in each individual image e.g., 'fanning face', 'patting tummy', and deriving various descriptions of each internal state e.g., 'feeling hot', 'needing to eat'. Once generated, four additional raters read each label and were asked to judge whether each label described the image accurately. All four raters judged each label to be an accurate descriptor of the image. Phrases were perfectly matched across the interoceptive and action trials on number of syllables (and presentations, so that no internal state phrase appeared more times than an action phrase and vice versa), and all labels began with a verb. Frequency was also matched across interoceptive and action trials. See Chapter 4 for details. Each stimulus was presented once, yielding a total of 48 trials, with presentation order randomised across participants. Images were alongside the labels in a two-alternative forced-choice paradigm, with participants being required to select the orthographic label that best described the image.

2.2.3 Sample size

A minimum sample of 111 participants was recruited, providing 95% power to detect a medium effect size of $r = 0.3$ (correlation, one-tailed). A medium effect size was selected as there is no previous literature on the labelling of others' interoceptive expressions.
Given that individuals with a mental health condition were excluded retrospectively (conducted in the same way as in Study One), and 20% of participants answer the IAS and IATS interpretation question incorrectly (Gabriele et al., 2022), as many participants as possible were recruited within a 10-month time frame to ensure adequate power after exclusions, as well as a sufficient number of participants spanning the broad age range in this study (16 to 90 years).

2.3. Study Three. Attention to others' interoceptive expressions and its relationship with the processing of interoceptive states in one's own body

The third study in this thesis investigated the processing of interoceptive states in oneself, attention to others' interoceptive expressions, and the relationship between these. In the emotion literature, alexithymia (difficulties identifying and describing one's own emotions) appears to be related to reduced attention to others' emotional expressions (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013). It was therefore predicted that attention to others' interoceptive expressions would be positively related to self-reported interoceptive attention. As interoceptive accuracy and attention are thought to be two distinct dimensions of interoception (Murphy et al., 2019a; Murphy et al., 2020a; Suksasilp & Garfinkel, 2022), self-reported interoceptive accuracy was predicted to be a less good predictor of attention to others' interoceptive expressions. Further, given the inverse relationship reported between ageing and self-reported interoceptive attention found in Study Two, Study Three aimed to replicate this, as well as extending findings by assessing the impact of ageing on attention to others' interoceptive expressions.

2.3.1 Self-reported interoceptive abilities

As in Study Two, self-reported interoceptive accuracy and attention were assessed using the Interoceptive Accuracy (IAS; Murphy et al., 2019a, 2020) and Attention Scale (IATS; Gabriele et al., 2022) respectively. The IAS (21 items; α = 0.89, 90) and IATS (21 items; α = 0.90) are reported to have good reliability (Gabriele et al., 2022; Murphy et al., 2020a). See Chapter 5 for more detail. Questionnaires were presented after the dot-probe attention orienting task (outlined in 3.3. below) to ensure that their completion did not prime participants to attend more to interoceptive expressions than action postures.

2.3.2 Dot-Probe attentional orienting task

To assess attentional orienting a dot-probe paradigm was developed, piloted, and employed in Study Three. Dot-probe paradigms are used widely throughout the emotion literature to capture attentional biases in the processing of emotional expressions. In studies of emotion, participants tend to briefly view an emotional and a neutral stimulus presented simultaneously on either side of a screen, immediately followed by a target on one side of the screen. Participants are instructed to indicate which side the target appeared on as quickly as possible. If attention is directed towards emotional stimuli, at the expense of neutral stimuli, response times should be lower when the target replaces the emotional stimulus than the neutral stimulus (for meta-analyses see Bar-Haim et al., 2007; Frewen et al., 2008). Importantly, as there was a restriction on in-person testing whilst developing this study, dot-probe paradigms rely on reaction time (RT) as their dependent variable and can therefore be employed online. It is worth noting that with online studies it is not possible to control for computer specifics, refresh rate or internet speed, for example, which may impact RT. Despite this, given that analyses relied on an attentional bias between two conditions and the impact of these variables should be consistent across conditions, this should not have systematically altered results. Beyond this, participants with particularly long or short RTs were excluded (see Chapter 5 for more details on exclusion criteria).

2.3.3 Pilot dot-probe attentional orienting task

In the emotion literature, attentional biases appear to be dependent on stimulus presentation time (Bar-Haim et al., 2007). Considering this, and that no previous investigation has utilised a dot-probe paradigm with interoceptive expressions, a pilot study was conducted with 24 participants, ranging in age from 18 to 21 years, to trial three stimulus presentation times (300ms/500ms/800ms). Participants were only permitted to take part on a laptop or computer with a keyboard, to mitigate against any effect of different response actions (e.g., pushing a button compared to touching a screen; van Rooijen et al., 2017). Each trial began with a fixation cross in the centre of the screen, displayed for 500ms. The fixation cross was immediately replaced with two images of the same individual, one positioned on the left side of the screen and the other on the right side of the screen. One of the two images depicted a neutral body position and the other depicted either the actor posing an interoceptive state or an action. Identical stimuli, from the ISSI (Biotti et al., 2021), were selected to those in Studies One and Two, depicting six actors (three male, three female), although seven interoceptive states were selected rather than nine (cold, hot, fatigue, breathlessness, nausea, pain, and itch). The reason for seven states being utilised was that depictions of the same actors posing actions were also utilised, and these were selected from the ISSI such that no images included social cues. This led to the elimination of waving and beckoning images, leaving running, clapping, jumping, lifting, walking, washing hands, and twirling. The two interoceptive states depicted in the ISSI that were eliminated for Study Three were hunger and satiety, these states were selected as they were the most commonly confused in the validation of the ISSI (Biotti et al., 2021). Images of the same actors displaying neutral body postures were also selected. The inclusion of action stimuli ensured that any effect of self-reported interoceptive processing on attention was specific to interoceptive expressions and could not be explained by changes in attention to postural stimuli more generally.

Interoceptive and action trials were randomly interspersed and equally frequent. Stimuli were either presented for 300, 500ms or 800ms, with participants completing all presentation times in separate blocks. Immediately following the offset of the stimuli, a target (an image of a frog) was presented on either the left or right side of the screen, replacing either the neutral stimulus or the interoceptive or action stimulus. An image of the frog was selected to make the task more engaging for child participants if COVID-19 in-person testing restrictions allowed for the recruitment of a younger sample. Participants were instructed to respond with the location of the target as quickly and accurately as possible, pressing “a” on their keyboard if the target appeared on the left and “l” if the target appeared on the right.

Analyses revealed that there was not a significant difference in RT when the target replaced the interoceptive or neutral stimuli, on interoceptive-neutral trials, at a stimulus presentation time of 300ms, 500ms, or 800ms. Similarly, there was no difference in RT between trials when the target replaced the action and neutral stimuli, on action-neutral trials, at a presentation time of 300ms, 500ms or, 800ms (see Chapter 3: Supplementary Materials 1 for all test statistics). Interestingly, pain stimuli appeared to elicit different attentional effects to other internal states.

At a stimulus presentation time of 500ms, for all interoceptive states except pain, RT was numerically lower when the target replaced the interoceptive stimuli than the neutral stimuli. On pain trials, however, RTs were lower when the target replaced the neutral stimulus than the pain stimulus. Interestingly, this replicated recent research which measured the processing of painful facial expressions, reporting initial fixation on painful stimuli, followed by avoidance, across a 500ms presentation time (Mazidi et al., 2021). Considering this, and the fact that pain is a complex interoceptive signal as it includes both emotional and sensory components (Fernandez & Turk, 1992), pain was removed from the set of internal state stimuli. The internal state stimuli then consisted of depictions of cold, hot, fatigue, breathlessness, nausea, and itch. To balance the number of internal states and actions, twirling was also removed from the set of action stimuli. Twirling was selected as depictions included greater spread of the limbs, both vertically and horizontally, from the neutral body posture compared to other internal states and control actions, which is likely to increase attentional capture. The action categories then consisted of running, clapping, jumping, lifting, walking, and washing hands. The removal of twirling ensured that interoceptive and action stimulus sets were well matched on low-level visual properties relating to spread of the limbs, mitigating the impact of this on the salience of images. Analyses were repeated excluding pain and twirling trials to investigate whether the paradigm then yielded significant differences in RT on internal state trials. Indeed, RT's were significantly shorter when the target replaced the interoceptive over the neutral stimuli, on interoceptive-neutral trials, at a stimulus presentation time of 500ms. Due to this finding at 500ms, this was selected as the fastest presentation speed for Study Three.

As outlined in 3.1, this study also aimed to recruit older adults. Ageing is associated with decreased attentional control, indexed through increased variability in RTs (Hultsch et al., 2002; Campbell et al., 2015), and decreased response speed to visual stimuli (Ng & Chan, 2012). As the current task is likely sensitive to response speed and levels of attentional control, and this is the first time this paradigm has been used with interoceptive expressions, a stimulus presentation time of 800ms was also included in Study Three.

To summarise, in the finalised dot-probe paradigm participants viewed static photographic stimuli (Biotti et al., 2021), depicting six actors (3 male, 3 female) posing six internal states: cold, hot, fatigue, breathlessness, nausea, and itch, six actions: running, clapping, jumping, lifting, walking, and washing hands, and neutral body positions. Stimuli were either presented for 500ms or 800ms, with participants completing both presentation times in separate blocks.

Each block consisted of 144 trials (6 interoceptive + 6 action postures x 6 actors x 2 presentations), yielding a total of 288 trials, with one block for each stimulus presentation time (500ms or 800ms).

2.3.4 Sample size

As approximately 20% of participants interpret the IAS and IATS incorrectly (Gabriele et al., 2022), and individuals with a mental health condition were excluded retrospectively, as many participants as possible were recruited in a 9-month time frame, ensuring a minimum sample of 111 participants. A sample of 111 participants, provided 95% power to detect a medium effect size of $r = 0.3$ (correlation, one-tailed). A medium effect size was selected as no previous research has investigated attention to others' interoceptive expressions. The recruitment of a larger sample also allowed for enough participants spanning the broad age range in this study (16 to 72 years).

2.4. Study Four. Memory Bias for interoceptive expressions, over actions, and its relationship with self-reported interoceptive accuracy and attention

The fourth study in this thesis examined memory for interoceptive expressions and action postures, bias towards memory for interoceptive expressions, and its relationship with self-reported interoceptive accuracy and attention. An inverse relationship has been observed between memory for emotional stimuli and alexithymia (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout, 2021; Vermeulen et al., 2006; Vermeulen & Luminet, 2009), such that those who struggle to recognise and explain their own emotions appear to also have reduced memory for emotional stimuli. Given this relationship, and the association between interoceptive and emotional processing (e.g., Barrett, 2014; James, 1894; Lange, 1885; Schachter & Singer, 1962), a positive relationship was predicted between self-reported interoceptive processing and memory for others' interoceptive expressions.

2.4.1 Self-reported interoceptive accuracy and attention

As in Studies Two and Three, self-reported interoceptive accuracy and attention were assessed using the Interoceptive Accuracy (IAS; Murphy et al., 2019a, 2020) and Attention Scale (IATS; Gabriele et al., 2022) respectively. The IAS (21 items; $\alpha = 0.89$, 90) and IATS (21 items; $\alpha = 0.90$) are reported to have good reliability (Gabriele et al., 2022; Murphy et al., 2020a). See Chapter 6 for more detail. Questionnaires were presented following the memory task to ensure the completion of these did not alter participants' encoding of interoceptive, relative to action, expressions.

2.4.2 Memory task

As in Studies One to Three, participants viewed stimuli from the ISSI database (Biotti et al., 2021). Each participant viewed four (two male and two female actors), out of the six exemplars presented in Study One, depicting nine interoceptive states. The number of depictions was reduced to ensure that participants could complete the memory task at a level above chance. The four actors who received the highest proportion of validation participants selecting the target label to describe their internal state depictions overall were selected for this study. These stimuli were selected to ensure that memory deficits were not the result of poor depictions of the internal state. The interoceptive states depicted were breathlessness, cold, fatigue, hot, hunger, nausea, itch, pain, and satiety. Participants also viewed four exemplars (two males, two females) of the nine action postures available in the ISSI, depicted by the same actors. The nine actions depicted were beckoning, clapping, jumping, lifting, running, twirling, walking, washing hands, and waving. An 'old or new' recognition paradigm was selected to assess memory for interoceptive expressions and action postures, as similar assessments have been used to assess memory for emotional faces (Grady et al., 2007; Ridout, 2021). An old/new paradigm first involves a training phase. During the training phase, participants viewed 18 interoceptive (nine states x two actors (one male, one female)) and 18 action postures (nine actions x two actors (one male, one female)) and were required to make a task-irrelevant judgement on each stimulus, without knowing that memory for the stimuli would be assessed subsequently. In this task, participants were asked to make a gender judgement about each the stimulus. A gender decision was selected as the task-irrelevant judgement for two main reasons. Firstly, the gender of all actors was purposefully unambiguous, therefore, all trials where the participant responded incorrectly were removed from later analysis. This judgement therefore served as an important attention check. Secondly, an alternative question that involved instructing participants to attend to any postural cue may have primed participants to pay more attention to interoceptive or action postures, biasing subsequent performance on the memory task. It was thought to be unlikely that judging gender would bias encoding towards either interoceptive or action stimuli.

Following this, participants completed an audio distractor task, in which they were required to listen to a series of tones and then report on how many tones they heard.

Finally, participants proceeded to the test phase of the paradigm. In the test phase, participants viewed 36 interoceptive (nine states x four actors (two male, two female)) and 36 action postures (nine states x four actors (two male, two female)), and were required to respond indicating whether they viewed the image in the training phase or not. Half of the stimuli had been viewed before while half were novel exemplars of the same states, posed by the same actors.

To ensure that participants could perform the task at a level above chance, after 20 participants' data had been collected, d-prime (d') scores for interoceptive (M = 0.683, SD = 0.510) and action postures (M = 0.811, SD = 0.460) were calculated. Both interoceptive, $t(19) = 5.99$, $p < 0.001$, and action postures, $t(19) = 7.89$, $p < 0.001$, were remembered at a level greater than chance (d' = 0). Data collection therefore continued until the full sample size was recruited.

2.4.3 Sample size

As no previous work has investigated memory for others' interoceptive states, a minimum sample of 111 participants was recruited, which would provide 95% power to detect a medium effect size of r = 0.3 (correlation, one-tailed). Given that approximately 20% of participants answer the IAS and IATS interpretation question incorrectly (Gabriele et al., 2022), and individuals with a mental health condition were excluded retrospectively, as many participants as possible were recruited in a 5-month time frame to ensure adequate power after exclusions.

2.5. Study Five. Interoception and alexithymia in children and adolescents with Medically Unexplained Symptoms and Tourette Syndrome

Study Five differed from Studies One to Four, in that it did not investigate the processing of others' interoceptive states. Instead, it investigated self- and parent-reported emotional intelligence, alexithymia, and interoceptive accuracy in two clinical and developmental groups thought to be characterised by interoceptive difficulties. Children and adolescents with Medically Unexplained Symptoms (MUS) and Tourette Syndrome (TS), and their parents, reported on their emotional abilities and interoceptive accuracy, and Study Five compared these to normative samples, and investigated their relationship with symptom severity and quality of life. Parental reports were collected, where possible, alongside child-reports as insight is typically reduced in clinical groups and children (Barbosa et al., 2002; Eiser & Varni, 2013; Garfinkel et al., 2016; Sherifali & Pinelli, 2007; Van Roy et al., 2010). Obtaining parental-reports, therefore, provides complimentary evidence on the potential difficulties faced by these individuals, as well as providing insight into the relationship between parent- and child-report. Importantly, the findings of Study Five can be used in combination with the preceding four studies to inform future studies on the processing of others' interoceptive states in those with MUS and TS.

2.5. Study Five. Interoception and alexithymia in children and adolescents with Medically Unexplained Symptoms and Tourette Syndrome

2.5.1 Self and parent-reported measures of emotional intelligence, alexithymia, quality of life, and symptom severity.

The EQ-i: YV was employed to assess self-reported intrapersonal and interpersonal functioning, stress management, and adaptability of children and adolescents aged 7 to 18 years. The EQ-i:YV was chosen over alternative emotional intelligence questionnaires as its factor structure has been replicated in samples across multiple nationalities (el Hassan & el Sader, 2005; Esnaola et al., 2016; Parker et al., 2005) and the scale shows high external validity, correlating with other child and adolescent trait emotional intelligence measures (Esnaola et al., 2016). As the EQ-i: YV intrapersonal subscale asks specifically about participant's ability to recognise and explain their own feelings, employing the EQ-i: YV also allowed for the measurement of the alexithymia construct, as well as overall emotional intelligence.

The Child Alexithymia Measure (CAM; Way et al., 2010) was employed to measures parent-reported alexithymia. The CAM has been found to have high internal consistency ($\alpha = .92$) and external validity (Way et al., 2010).

Self-reported interoceptive accuracy was assessed using the Child-Adapted Interoceptive Accuracy (IAS-C). The Child-Adapted scale was utilised given the young sample, aged 8 to 17 years. For full details of the IAS-C please see Section 2.1. within this chapter.

The Child Report: Children’s Somatic Symptoms Inventory (CSI; Walker & Green, 1989) and the Children’s Somatic Symptoms Inventory – Parent Version (CSI – P; Walker et al., 2000) were used to measure physical symptoms that the participant may have experienced, such as headaches, sore muscles, and difficulty swallowing, reported by the child and parent respectively. The CSI and CSI–P are composed of identical items and reporting scale. The CSI was selected over other measures of somatisation as it has been shown to have good construct validity with significant correlations with self-reported anxiety (r = .43), depression (r = .37), and perceived competence (r = -.27), as well as possessing good internal consistency (Garber et al., 1991).

The Paediatric Quality of Life Inventory (PEDSQL™) is composed of four scales measuring parent and self-reported functioning across a number of areas (physical functioning, emotional functioning, social functioning, and school functioning. The PEDSQL™ parent-report is composed of identical items and scales, but instead asks parents to report on their child’s psychosocial and physical quality of life. The PEDSQL™ is reported to achieve excellent reliability (α = .89 child; .92 parent report). The PEDSQL™ also displayed good construct validity correlating with indicators of health care access, days missed from school, and days needing care, as well as successfully distinguishing between healthy children and children with chronic health conditions (Varni et al., 2003).

No specific measure of self or parent-reported interoceptive attention was utilised in Study 5 as at the time of data collection the IATS-C was still undergoing validation. Whilst the BPQ-C was available it is very similar to the CSI and CSI-P and has known interpretation issues, therefore, the CSI was included as a more specific measure of symptoms, as well as allowing exploratory analyses into interoceptive attention.

2.5.2. Sample size

All patients who were diagnosed with MUS and TS at Great Ormond Street Hospital in a 12-month time period were invited to take part in the study. This resulted in a total sample of 20 participants with MUS and 32 participants with TS. As data was collected as part of a service evaluation with the Great Ormond Street audit team, ethical constraints meant that no matched control sample was collected. Despite this, comparisons were made with multiple normative groups wherever possible.

2.6. Summary

The current thesis provides the first comprehensive investigation of the processing of others' interoceptive expressions. Recognition accuracy, attention to, and memory for interoceptive expressions are explored, as well as the tendency to assign interoceptive, over action, labels to others' interoceptive states. Individual differences in the processing of others' interoceptive expressions are assessed in the context of age, gender, and the processing of one's own interoceptive states. Interoceptive and emotional processing in the self, and their relationship, are also investigated in children and adolescence with MUS and TS, two novel clinical groups. Together, these investigations will pave the way for future research aimed at improving social communication for those with atypicalities in the processing of their own or others' interoceptive states.

Chapter 3. Study One: The relationship between recognition of one's own and others' interoceptive states in adolescence and early adulthood

The relationship between recognition of one's own and others' interoceptive states in adolescence and early adulthood

Lara Carr, Dawn Watling and Rebecca Brewer

Abstract

Background: Interoception refers to the perception of, attention to, and propensity to use one's internal bodily signals. While previous research has investigated participants' ability to recognise these states in the self accurately, no research thus far has investigated the ability to recognise others' interoceptive states, beyond the emotional domain. Where emotion is concerned, difficulties recognising one's own emotions (alexithymia) are associated with difficulties recognising emotions in others. It is therefore likely that the ability to perceive one's own non-emotional interoceptive states also predicts the ability to recognise interoceptive states in others.

Method: The current study investigated the relationship between the ability to recognise others' interoceptive states and one's own self-reported interoceptive accuracy and attention, in 160 participants, ranging in age from 16 to 21 years.

Results: Individuals were significantly better at recognising interoceptive states than chance, but recognition accuracy was not associated with self-reported interoceptive abilities or age.

Conclusions: These findings suggest that, unlike with emotions, individual differences in attention to or accuracy recognising one's own interoceptive states may not contribute to difficulties recognising these in others. While these results may be explained by the absence of severe interoceptive difficulties in the current sample, it is also possible that multiple processes contribute to the social perception of others' interoceptive signals, and that compensation strategies allow one to recognise others' interoceptive states despite difficulties recognising these states in oneself.

1. Introduction

Interoception can be defined as the perception of, attention to, and propensity to utilise ones' own internal bodily signals (Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Whilst early definitions of interoception were restrictive, only referring to internal states that originated in the viscera (e.g., heart rate, breathlessness, and hunger; Sherrington, 1948), contemporary definitions are broader, encompassing seemingly less internal sensations (e.g., affective touch and itch; Craig, 2003), with interoceptive signals being defined as those processed by common neural pathways that terminate in interoceptive cortex regions, namely the anterior insula cortex (AIC) and anterior cingulate cortex (ACC; Craig, 2009). Although this broad definition is the subject of some debate (Garfinkel & Critchley, 2013), it is the most frequently used in contemporary literature so is adopted throughout the current article. The structure of interoceptive abilities has also been debated, with recent research distinguishing between interoceptive accuracy (the precision with which an individual can correctly perceive their internal bodily signals), interoceptive attention (one's propensity to attend to internal bodily signals), and one's propensity to use internal signals to guide day to day decisions, as well as distinguishing between whether these abilities are measured objectively or subjectively (Garfinkel et al., 2015; Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022)

The recent resurgence in interoceptive research is reflective of its importance in a host of cognitive outcomes (Khalsa & Lapidus, 2016). In adults, interoception has been linked to a vast array of psychological processes, such as emotional experience (Herbert et al., 2007), recognition of others' emotions (Mulcahy et al., 2019; Pollatos et al., 2011), empathy (Garfinkel et al., 2016), learning and decision making (Dunn et al., 2010; Kandasamy et al., 2016; Werner et al., 2009), memory (Garfinkel et al., 2013; Herbert et al., 2007; Werner et al., 2010), attention (Matthias et al., 2009) and advantageous risk-taking (Kandasamy et al., 2016), with interoceptive atypicalities also being implicated in neurodevelopmental and mental health conditions (e.g. Brewer et al., 2021; Khalsa et al., 2018; Murphy et al., 2017). While interoceptive abilities therefore appear to be linked to a range of psychological abilities, their role in social perception has not been investigated outside the domain of emotion.

Within the emotion literature, an understanding of one's own emotions is theorised to be crucial for recognising others' emotions (Bird & Viding, 2014). Empirical evidence supports this conjecture, with those with alexithymia, characterised by difficulties identifying and describing one's own emotions (Apfel & Sifneos, 1979; Nemiah et al., 1976), exhibiting difficulties recognising emotions in others. Individuals with lower levels of alexithymia, for example, tend to perform significantly better on tasks assessing recognition of others' facial emotion (Grynberg et al., 2012). Alexithymia has also been associated with reduced accuracy when recognising emotion from vocalisations (Heaton et al., 2012). Taken together, this evidence suggests that poor categorisation of an emotion in oneself hampers the learning of the visual and auditory cues associated with that emotion in others, negatively affecting recognition accuracy. Interestingly, this relationship has been observed in clinical populations, for example in autistic samples and those with eating disorders, suggesting that difficulties understanding one's own emotions may explain some of the social difficulties observed in clinical groups (Brewer et al., 2015; Cook et al., 2013).

Importantly for the current study, processing of emotions and interoceptive states are closely related. Theories of emotion consistently implicate physiological changes within the body in giving rise to emotion (James, 1894; Lange, 1885; Schachter & Singer, 1962), and the neural regions involved in processing one's own emotion overlap substantially with those regions implicated in processing one's own interoceptive signals, in particular the AIC and ACC (Craig, 2009; Phillips et al., 2003). Indeed, elevated levels of alexithymia are associated with structural and functional abnormalities in the AIC and ACC (Goerlich-Dobre et al., 2014; Moriguchi & Komaki, 2013). Behaviourally, individuals with higher levels of alexithymia are more prone to confusing affective and non-affective states (Brewer et al., 2016), and an inverse relationship between interoceptive accuracy and alexithymia has been observed across several domains of interoception (Herbert et al., 2011; Murphy et al., 2018). Individuals with alexithymia have also been found to be less likely to rely on interoceptive, relative to exteroceptive, cues to gauge respiratory effort (Murphy et al., 2018). While these findings are not always replicated, with a recent meta-analysis reporting no relationship between interoceptive accuracy and alexithymia (Trevisan et al., 2019), inconsistencies in the literature may be explained by limitations with the measurement of interoceptive abilities (Corneille et al., 2020; Gabriele et al., 2022), or alternate routes to alexithymia, for example through language deficits (Hobson et al., 2019). Overall, it is likely that processing of one's interoceptive states is closely related to the processing of one's emotional states, at both the behavioural and neural levels.

Despite the large literature on the recognition of others' emotions, including the relationship with recognition of one's own emotions, very little research has investigated the recognition of others' non-emotional interoceptive states. As with emotion recognition (Gross, 2002; Schutte et al., 2007) the ability to recognise interoceptive changes in others is presumably essential for successful social communication and empathy, as well as for providing appropriate care for others. One recent study investigated the perception of illness in others, finding that participants were able to identify individuals who had been injected with a bacterial stimulus, which induced an immune response, above chance level (Axelsson et al., 2018). Further research has investigated pain perception, demonstrating that individuals with AIC lesions display decreased discrimination accuracy and prolonged reaction times when recognising others' pain (Gu et al., 2012). Individuals with alexithymia, who may exhibit difficulties recognising their own interoceptive signals, have also been found to assign lower pain ratings to human hands and feet in painful situations and have lower ACC activation whilst rating others' pain (Moriguchi et al., 2007). Alongside this, humans have been found to perform above chance at judging which of two individuals a heartbeat belongs to (Galvez-Pol et al., 2022), although the mechanisms underlying these judgements are unclear. Together, these findings provide preliminary evidence suggesting that it is possible to interpret interoceptive cues from others. It is unclear, however, whether this translates to other interoceptive states (e.g., temperature, breathlessness and hunger), and whether, as with emotion, the ability to recognise interoceptive states in others is related to the ability to perceive these states in one's own body. As alexithymia is related to both interoceptive atypicalities and difficulties recognising emotional and painful expressions in others (Heaton et al., 2012; Jongen et al., 2014; Moriguchi et al., 2007), it is likely that one's own interoceptive abilities are also related to the ability to recognise others' interoceptive states. Beyond empirical evidence in the emotional domain, this is also theoretically likely; more precise representations of one's own interoceptive states should facilitate learning associations between one's own expressive actions (such as facial expressions and body posture) and those states in the self, in turn increasing one's ability to infer another's internal state from their actions, if expressions of interoceptive states are consistent across individuals. Beyond theoretical relevance, if this relationship exists it has multiple real-world implications, as increasing individuals' ability to perceive internal states in their own bodies may lead to improvements in recognition of others' interoceptive states, potentially improving social perception, empathy, and the ability to provide care for others.

While the relationship between one's own interoceptive abilities and recognition of others' interoceptive states is of interest in all age groups, adolescence is a developmental period in which interoception research is particularly lacking (Murphy et al., 2017). Adolescence is the period of development following the onset of puberty, characterised by many physical, neurological, and psychological changes (Blakemore et al., 2010; Blakemore & Choudhury, 2006; Coleman & Hendry, 1990; Crone et al., 2016; Rutter & Rutter, 1993). While adolescence was previously defined as 10-19 years of age, recent definitions recognise that adolescence may be more accurately defined as the period between 10 and 24 years of age (Sawyer et al., 2018). While studies explicitly investigating interoception over adolescence have been limited, high rates of alexithymia have been reported in adolescence; whilst the prevalence of alexithymia in adults is 8-10% (Linden et al., 1995; Salminen et al., 1999), approximately 18% of 11–18-year-olds exhibit high levels of alexithymia (Gatta et al., 2014; Sakkinen et al., 2007). As elevated alexithymia also appears closely related to atypical interoception (Brewer et al., 2016; Murphy et al., 2018), this suggests that adolescence might also be associated with disrupted interoceptive processing. Further to this, adolescence is associated with factors that have been linked to atypical interoception, such as increased risk-taking (Kandasamy et al., 2016; Steinberg, 2007), and the onset of psychopathology (Brewer et al., 2021; Kessler et al., 2005; Khalsa et al., 2018; Murphy et al., 2017; Paus et al., 2008). The current study assessed interoceptive abilities in the self during adolescence, as well as the extent to which these relate to recognition of others' interoceptive states, providing crucial insight into interoceptive processing in this age group. Where basic emotion recognition is concerned, adult level typically emerges between 6 and 11 (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012), however, sensitivity to changes in emotion continues to develop throughout adolescence (Thomas et al., 2007). Vocal emotion recognition accuracy does not appear to peak until the age of 20 years (Amorim et al., 2021), and recognition of facial identity does not appear to peak until after 30 years of age (Germine et al., 2011). Together, these findings demonstrate that social perception continues to develop throughout childhood and adolescence, making adolescence a relevant developmental period to investigate individual differences in the recognition of others' interoceptive states.

The current study is the first to examine the recognition of one's own and others' non-emotional internal states using a recently developed stimulus set depicting actors posing interoceptive states (Biotti et al., 2021), throughout late adolescence, as defined by Sawyer et al. (2018). Participants completed an alternative forced choice recognition paradigm alongside self–report measures of interoceptive accuracy and attention, covering a broad range of interoceptive states. In line with research investigating the relationship between alexithymia and emotion recognition, it was predicted that individuals reporting greater accuracy recognising their own internal bodily states would exhibit more accurate recognition of others' interoceptive state displays. As recent models point to a distinction between interoceptive accuracy and attention (Murphy, 2022; Murphy et al., 2019, 2020; Suksaslip & Garfinkel, 2022), it was predicted that self-reported interoceptive attention would not be related to self-reported interoceptive accuracy, or accuracy recognising others' interoceptive states. Given that social perception continues to improve throughout early adulthood (Germine et al., 2011; Amorim et al., 2021), it was predicted that recognition of others' interoceptive states would increase with age. Finally, while self-reported interoceptive accuracy appears relatively stable (*Carr et al., in prep. a; Carr et al., in prep. b*), self-reported interoceptive attention is reported to decrease across the lifespan (*Carr et al., in prep. a; Carr et al., in prep. b*); it was therefore predicted that self-reported interoceptive attention would decrease with age.

2. Method

2.1 Participants

A total of 273 participants were recruited (214 females and 58 males), ranging in age from 16.00 to 21.83 years (*M* = 18.13, *SD* = 13.75). As participants were recruited from the university student pool and local colleges, departmental policies meant that individuals with mental health conditions could not be excluded from participating. In order for findings to be representative of the typical population, and to remove confounding effects of metal illness, individuals with mental health conditions were removed from the sample retrospectively, leading to the exclusion of 66 participants. Whilst main analyses are reported without these participants, exploratory analyses were also run with these participants (reported in Supplementary Materials 5). After the subsequent exclusion of participants who assigned more than 3 labels incorrectly in the pre-testing phase (see 2.2 below) the final sample was composed of 170 participants (131 females and 39 males), ranging in age from 16.17 to 21.58 years (*M* = 18.04, *SD* = 13.40).

Ethical approval was obtained from Royal Holloway, University of London. All participants provided informed consent prior to participation and received a full debrief upon completion of the study. Participants were recruited from social media, local sixth form colleges and the student pool at Royal Holloway, University of London, in exchange for course credit.

2.2 Measures

2.2.1 Self–Reported interoception

The Child Adapted Porges Body Perception Questionnaire (BPQ-C; Palser et al., 2018; Porges, 1993) was used to assess subjective interoceptive attention. The scale is composed of 39 items. Participants are required to rate on a scale, from *Never* to *Always*, how often they believe they are aware of each bodily sensation, with total scores ranging from 39 to 195. Higher scores are indicative of higher self-reported interoceptive 'awareness', which has mostly commonly been interpreted as referring to interoceptive attention (Gabrielle et al., 2022). The BPQ-C was found to have highly reliability in the current study (39 items; α = 0.95).

Due to recent work suggesting that the BPQ-C may be open to interpretation issues (Gabrielle et al., 2022) replication using a more explicit measure of attention, the Child Interoceptive Attention Scale (IATS-C), adapted from the Interoceptive Attention Scale (Murphy et al., 2020), was also included for a subset of participants (*N* = 117). The Child Interoceptive Attention Scale is a measure of subjective interoceptive attention. The scale is composed of 20 items, each relating to a sensation that has been described as interoceptive in nature. For each sensation, participants are required to rate on a scale from 1 (*Strongly Agree*) to 5 (*Strongly Disagree*), the extent to which their attention is focused on that sensation. Total scores range from 20 to 100, with higher scores indicative of higher perceived interoceptive attention. The IATS-C was found to be highly reliable (20 items; α = 0.90).

The Child Interoceptive Accuracy Scale (IAS-C; Barker et al., 2020, adapted from the Interoceptive Accuracy Scale (Murphy et al., 2019), was utilised to assess subjective interoceptive accuracy. This scale measures participants' beliefs in their ability to perceive their internal bodily sensations accurately. The scale is composed of an identical set of 20 interoceptive sensations to those in the IATS-C. Again, for each sensation, participants are required to rate each item on a scale from 1 (*Strongly Agree*) to 5 (*Strongly Disagree*), indicating the extent to which they believe they are correct at sensing each state. Total scores range from 20 to 100, and higher scores are indicative of higher subjective interoceptive accuracy. The IAS-C was found to have high reliability in this sample (20 items; α = 0.97).

Child-Adapted scales were utilised in this study to accommodate for the inclusion of a younger sample, should in-person COVID-19 testing restrictions allow. Unfortunatly, no children were recruited in the final sample, however, these scales are almost identical to the adult versions (see Porges, 1993; Murphy et al., 2019, 2020).

2.2.2 Pre-testing phase

Before completing the interoceptive state recognition task (outlined in 2.3), participants completed a pre-testing task, which assessed their comprehension of each of the nine interoceptive state labels (hot, cold, hunger, satiety, fatigue, nausea, itch, breathlessness, and pain). Each internal state was paired with two related images (e.g., hot paired with a flame and steam, cold with an ice cube and snow scene, fatigue with a bed and pyjamas). Selected images did not contain people, to ensure that this phase did not assist participants in completing the subsequent recognition task. Each image was presented for 2000ms and then replaced by 9 response options (orthographic labels alongside an audio button that played the verbal label when clicked). Participants were instructed to select the corresponding internal state label that "goes with" the image. Participants completed two phases of the task, viewing one of the two images for each label in the first phase and the other in the second. In the first phase, participants received feedback if the incorrect response was selected, providing them with the correct response. Feedback was provided in the first phase to ensure that participants understood the task. In the second phase, no feedback was given so as to not affect accuracy of subsequent items. Presentation order of the state images was randomised within the first phase and second phase. Participants were excluded from the experiment retrospectively if they selected the incorrect label on more than three trials, achieving a total score of less than 15.

2.2.3 Recognition task

Participants' internal state recognition was assessed using a novel paradigm. Participants viewed randomly presented photographic stimuli, taken from the Interoceptive States Static Images (ISSI) database (Biotti et al., 2021), depicting six actors portraying nine internal states. The interoceptive states portrayed were hot, cold, fatigue, satiety, hunger, itch, breathlessness, nausea and pain. Participants also viewed photographic stimuli of the same six actors posing a control action (running) to ensure that individual differences in recognition were specific to the recognition of internal states, rather than domain-general processes, such as face or body processing, or social attention. Additionally, ten photographs of animals were randomly interleaved to ensure participants were attending to the images and could complete the basic forced-choice task.

Images were presented for 2000ms. Participants were then presented with an eleven-alternate forced-choice paradigm (orthographic words with images and an audio button), describing the nine internal states, and the 'running' and 'animal' options. Participants were instructed to select the response option that they believed best described what the individual was feeling or doing, or 'animal' when a non-human animal image was presented.

2.3 Analysis strategy

In order to analyse performance on the recognition task, unbiased hit rate (Wagner, 1993) was computed as a measure of recognition accuracy for each internal state (hot, cold, breathlessness, hunger, satiety, itch, pain, nausea and pain) and action (running). The unbiased hit rate is calculated using the following equation, where *a* is the number of correct responses:

$$H_u = \frac{a^2}{Number\ of\ trials\ \ x\ \ Number\ of\ times\ the\ response\ is\ selected\ across\ all\ trials}$$

In the current study the total number of trials was six for state and action stimuli, and the total uses of the label was summed across all state, action, and animal trials. The mean of the individual unbiased hit rates for each interoceptive state was taken as the mean state recognition score. Unbiased hit rate was selected, over the proportion of stimuli correctly identified, to mitigate the influence of false alarms and bias in the use of response categories.

One sample *t*-tests were conducted to determine whether recognition ability across the whole sample was better than chance performance (mean unbiased hit rate of 0.5). Correlational analyses were employed to assess the relationship between individual state and mean unbiased hit rates, response times on internal state and action trials, IAS-C, BPQ-C, and IATS-C scores, and age.

In order to determine which ineternal states were confused with each other, a confusion matrix was also created. Whereby, each row corresponds to the intended state portrayed by the actor and each column represents the proportion of times each state label was selected.

The normality of each variable was assessed with visual inspection of histograms and Kolmogorov-Smirnov tests with Lilliefors correction (Lilliefors, 1967). Where normality assumptions were violated, the relevant non-parametric test was employed (see Supplementary Materials 1 for all normality statistics). Where hypotheses were directional one-tailed statistics are reported. Bayesian statistics were conducted to further explore results.

3. Results

3.1 Self-reported interoceptive accuracy and attention

IAS-C scores ranged from 36 to 100 (M = 77.73, SD = 10.77), BPQ-C scores ranged from 63 to 193 (M = 125.57, SD = 26.76), and IATS-C (completed by a subsample of 117 participants) scores ranged from 28 to 99 (M = 69.97, SD = 13.3.9). BPQ-C, IATS-C, and IAS-C scores were not normally distributed, so non-parametric analyses were employed.

Correlational analyses were conducted between each of the individual questionnaires. All questionnaires were significantly positively associated with each other (Table 1). Fisher r-to-z analyses indicated, however, that the strength of the relationship was greater between the two questionnaires measuring interoceptive attention (IATS-C and BPQ-C) than between measures assessing different facets of interoception, i.e., attention and accuracy, IAS-C and IATS-C; z = -1.74, p = 0.041; IAS-C and BPQ-C; z = -1.66, p = 0.049. These findings, therefore, support the theoretical distinction between interoceptive accuracy and attention, despite suggesting a weak relationship between the two constructs.

Table 1. Correlations between self-report interoceptive questionnaires (IAS-C, IATS-C, BPQ-C). One-tailed *p* values are reported (uncorrected for multiple comparisons).

	IATS-C			BPQ-C		
	r	*p*	BF_{10}	*r*	*p*	BF_{10}
IAS-C	0.288	0.002	33.524	0.297	<0.001	381.573
IATS-C				0.526	<0.001	311571.88

Age was not significantly correlated with IAS-C scores, $r(167) = -0.95$, $p = 0.219$ one-tailed, $BF_{10} = 0.258$, IATS-C scores, $r(110) = -0.153$, $p = 0.053$ one-tailed, $BF_{10} = 0.492$, or BPQ-C scores, $r(167) = 0.018$, $p = .407$ one-tailed, $BF_{10} = 0.105$. Age does not, therefore, appear to be associated with self-reported interoceptive accuracy or attention, between the ages of 16 and 21 years.

3.2 Confusion across stimulus categories

Among the internal states, some categories were particularly confused with others; breathlessness and fatigue were confused with hot (10%), hunger was confused with satiety (15%) as was satiety with hunger (37%; Figure 1). Nausea was also confused with breathless (10%) and hunger (18%).

Figure 1. Confusion matrix showing the proportion of times each label was used to describe stimuli of each intended state

3.2 Recognition of others' interoceptive states and its relationship with self-reported interoception

Mean state recognition scores were normally distributed, meaning parametric analyses were employed (see Supplementary Materials 1 for all normality statistics). Participants varied in their ability to recognise interoceptive state displays, and ceiling effects were not observed, with mean state recognition scores ranging from 0.314 to 0.869 (M = 0.684, SD = 0.087). A one sample t-test revealed that, as a group, participants could correctly label others' interoceptive states at a level above chance (unbiased hit rate of 0.5), $t(169) = 27.42$, $p < .001$.

Correlational analyses indicated that mean state recognition score was not significantly associated with IAS-C score, $r(168) = 0.035$, $p = 0.327$ one-tailed. There was also no correlation between mean state recognition score and BPQ-C, $r(168) = -0.034$, $p = 0.330$ one-tailed, or IATS-C score, $r(110) = -0.048$, $p = 0.307$ one-tailed. Unsurprisingly, recognition of the control posture, running, was also unrelated to IAS-C, IATS-C, and BPQ-C scores (Table 2). These relationships were also non-significant in those reporting a mental health condition, and in the full sample without exclusion on the basis on mental health (see Supplementary Materials 5). Correlations were also explored between the three questionnaires and unbiased hit rates for each of the individual interoceptive states (Table 2). All correlations were non-significant even before correcting for multiple comparisons. These results suggest that the ability to recognise others' interoceptive states is not related to self-reported interoceptive accuracy or attention. Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 1.177$; see Supplementary Materials 2), providing moderate support for the alterantive hypothesis that mean state recognition was unrealted to self-reproted interoception.

Table 2. Correlations for each stimulus category and IAS-C, IATS-C and BPQ-C scores. One-tailed *p* values are reported in brackets (uncorrected for multiple comparisons).

	Breathlessness	**Cold**	**Tired**	**Hot**	**Hungry**
IAS-C	.149 *(.026)*	.143 *(.031)*	.029 *(.353)*	-.017 *(.412)*	-.087 *(.129)*
IATS-C	-.059 *(.270)*	-.134 *(.080)*	.035 *(.356)*	-.045 *(.320)*	-.081 *(.198)*
BPQ-C	.021 *(.395)*	-.028 *(.358)*	-.045 (*.280)*	.038 *(.313)*	-.065 *(.201)*
	Itch	**Nausea**	**Pain**	**Satiety**	**Running**
IAS-C	.060 *(.219)*	.030 *(.350)*	-.010 *(0.449)*	-.150 *(.026)*	. 069*(.373)*
IATS-C	-.006 *(.476)*	-.053 *(.291)*	.061 *(.263)*	-.104 *(.138)*	-.014 *(.883)*
BPQ-C	.006 *(.467)*	-.053 *(.246)*	-.027 *(.363)*	-.099 *(.098)*	-.008 *(.918)*

Recognition accuracy was significantly negatively associated with response time (RT) on interoceptive state trials, $r(168) = -0.180$, $p = 0.019$ two-sided, such that as RT increased, accuracy decreased. However, RT on control action (running) trials was not correlated with accuracy $r(168) = -.109$, $p = 0.157$ two-sided. There was also no correlation between RT, on either state or action trials, and self-reported interoceptive abilities (Table 3). Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 0.145$; see Supplementary Materials 3).

Table 3. Correlations (*r*) for RT on State and Action trials and IAS, IATS, and BPQ scores. Two-sided *p* values are presented in brackets (uncorrected for multiple comparisons).

	IAS	**IATS**	**BPQ-C**
RT (State trials)	-.030 (*0.695)*	0.048 *(0.613)*	0.025 (*0.743)*
RT (Action trials)	-.027 *(0.723)*	-.026 *(0.784)*	0.038 *(0.620)*

Age was not correlated with mean state recognition score, $r(167) = 0.069$, $p = 0.185$ one-tailed, nor recognition of the control action, running, $r(167) = -0.147$, $p = 0.057$ one-tailed. Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 1.394$; see Supplementary Materials 4).

3.3 Gender[4]

Mann-Whitney U tests revealed no significant differences between males (*Mdn* = 77) and females (*Mdn* = 78*)* in scores on the IAS, $U(N_{Males} = 31, N_{Females} = 131) = 2431$ $p = .648$ two-tailed. Males (*Mdn* = 72.5) and females (*Mdn* = 72) also did not differ on scores on the IATS, $U(N_{Males} = 24, N_{Females} = 88) = 1087.50$, $p = 0.826$ two-tailed, or BPQ-C, $U(N_{Males} = 31, N_{Females} = 131) = 2432$, $p = .651$ two-tailed, $Mdn_{Male} = 122$, $Mdn_{Female} = 128$.

A mixed 2 x 2 ANOVA was conducted with actor gender as a within-participants factor and participant gender as a between-participants factor. The analysis revealed a significant main effect of actor gender on accuracy, $F(1, 167) = 41.960$, $p < .001$, $np^2 = .297$, such that participants were significantly more accurate at recognising interoceptive states when posed by female, than by male, actors. Participant gender also had a significant effect on recognition accuracy, $F(1, 167) = 4.950$, $p = .027$, $np^2 = .070$, such that females were significantly more accurate than males at recognising others' interoceptive state displays. There was no significant interaction effect between participant and actor gender, $F(1, 167) = 1.271$, $p = .261$, $np^2 = .009$. This effect did not extend into the recognition of actions, where there was no main effect of actor gender, $F(1, 167) = 2.47$, p .535, $np^2 = .002$, or participant gender, $F(1, 167) = 2.474$, $p = .118$, $np^2 = .048$, and no significant interaction between participant and actor gender, $F(1, 167) = .047$, $p = .829$, $np^2 < .001$.

[1] In this study, we explicitly recorded gender identity and therefore use the term 'gender' throughout. It is worth noting, however, that in previous research the terms gender and sex have often been used interchangeably.

A Wilcoxon signed-rank test showed that participants were significantly more accurate when judging the internal states of actors who were the same gender as themselves (males judging males or females judging females; *Mdn* = 0.71), compared to when they were judging actors of a different gender (males judging females or females judging males; *Mdn* = 0.69), $Z = 5{,}497$, $p = 0.008$. Separate correlational analyses were then conducted to assess the relationship between self-reported interoceptive accuracy (IAS) and attention (IATS, BPQ) and state recognition when participants were rating actors of their own gender, and when rating actors of a different gender. IAS scores were unrelated to state recognition when judging actors of a different gender, $r(169) = .136$, $p = .0.078$ two-tailed, and when rating actors of one's own gender, $r(169) = -.086$, $p = .266$ two-tailed. IATS scores were also unrelated to state recognition when judging actors of a different actor, $r(111) = .078$, $p = .445$ two-tailed, and the same gender, $r(111)$ -.116, $p = .227$ two-tailed. Similarly BPQ scores were unrelated to state recognition when judging actors of a different actor, $r(169) = -.105$, $p = .176$ two-tailed, and actors of the same gender, $r(169) = -.023$, $p = .765$ two-tailed.

4. Discussion

The current study was the first to investigate the accuracy of recognition of others' interoceptive state displays, using recently developed static visual stimuli (Biotti et al., 2021). Findings indicated that recognition accuracy was significantly greater than chance, demonstrating that individuals can accurately infer others' internal states from static images posed by actors. Participants varied widely in task performance, however, suggesting that individual differences in recognition accuracy exist, and, as with emotion recognition, may be related to other psychosocial and mental health factors (Besel & Yuille, 2010; Wells et al., 2020). Despite this, contrary to predictions, no relationship was observed between self-reported interoceptive accuracy and recognition accuracy. As predicted, findings also provided no evidence for a relationship between self-reported interoceptive attention and recognition accuracy. These findings suggest that self-reported difficulties identifying or attending to interoceptive states in one's own body may not be related to difficulties recognising these states in others.

The current findings imply that, as with others' emotions (Calder & Young, 2005; Calvo & Nummenmaa, 2016; Richoz et al., 2018) individuals can accurately infer a series of interoceptive states in others from static visual images. This is perhaps unsurprising, given that recognising how others feel is essential for positive social interactions (Izard et al., 2001; Wang et al., 2019). Failing to recognise when another person is feeling hungry, tired, or unwell may impede one's ability to empathise, offer assistance, or show concern, negatively affecting relationships. Beyond social communication, recognising how others feel is an essential skill for those providing care, such as those caring for children, or medical professionals. If caregivers struggle to identify when another individual is feeling tired, breathless, unwell, or in pain, this is likely to impede their ability to provide appropriate aid. Recognising internal states from expressions is even more vital when individuals have difficulty verbalising their internal sensations. Research suggests that approximately 10% of the general population have alexithymia, characterised by difficulties communicating their emotions (Linden et al., 1995; Salminen et al., 1999), and alexithymia has been linked to both language (Hobson et al., 2019) and interoceptive (Brewer et al., 2016; Murphy et al., 2018) difficulties. It is therefore likely that these individuals also struggle to verbally communicate their interoceptive states, meaning others must rely in part on expressions to gauge their needs. Importantly, while the current study observed recognition of others' interoceptive states above chance, over the full sample, variation in state recognition ability was observed. Given the importance of recognising internal states in others, exploring the correlates of individual differences in recognition accuracy is crucial. If, for example, difficulties recognising others' interoceptive states is indeed associated with the ability to empathise with others and provide care, training in interoceptive state recognition may be beneficial for those with lower recognition ability in caring roles.

The current study explored the relationship between the ability to recognise interoceptive states in oneself and others, hypothesising that, as with emotions, difficulties recognising interoceptive states in oneself may be associated with difficulties recognising these states in others (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014). No relationship was observed, however, between self-reported interoceptive accuracy (in the self) and the ability to recognise others' interoceptive states accurately. Encouragingly, these findings suggest that individuals who report difficulties recognising their own internal bodily signals may have typical recognition of others' interoceptive states. It may be the case that cues to others' interoceptive states are learnt through routes other than those involving one's own interoception, for example through others' verbal descriptions of their feelings, or a third observer's descriptions. Parents are likely to tell children, for example, that another person looks tired or in pain, when encouraging empathy (Drummond et al., 2014), or these cues may be associated with interoceptive labels in children's books or television. Context is also likely to provide useful cues to others' states, as others refer to hunger and tiredness, for example, at specific times of the day. These external sources of information about others' internal states may be combined with information about one's own interoceptive signals and their association with one's own expressions. The extent to which external versus internal cues to others' states are utilised may depend on one's beliefs in one's own interoceptive abilities. It is also worth noting that interoceptive expressions tend to be depicted using stereotypical actions (e.g. rubbing stomach for hunger) which may be more easily differentiated from each other than emotional expressions. Therefore, learning to recognise these without a good understanding of one's own states may be easier than is the case for emotions, which are often subtle or high in physical similarity (Frank et al., 2009; Merghani et al., 2018; Zhang & Arandjelovic, 2021). Future research should therefore investigate the relative contributions of multiple routes to identifying others' interoceptive signals, and whether these vary across individuals, for example as a function of interoceptive abilities.

While the above explanation is plausible, it is worth noting that the current study observed relatively low variance in self-reported interoceptive accuracy, with most individuals reporting typical interoceptive ability. As it seems theoretically likely that some understanding of one's own internal states is necessary in order to create representations of these states and, in turn, identify them in others, it might be the case that a relationship between recognition of interoceptive states in oneself and others is only observed where marked difficulties in interoceptive accuracy are present. Interoceptive atypicalities are common in a range of clinical conditions, such as autism spectrum disorder (ASD) (Garfinkel et al., 2016; Hatfield et al., 2019; Mul et al., 2018; Nicholson et al., 2019), depression (Aaronson et al., 2017; Dunn, Stefanovitch, et al., 2010; Furman et al., 2013) feeding and eating disorders (Pollatos et al., 2008) and alcohol and substance abuse (Jakubczyk et al., 2019; Naqvi & Bechara, 2010; Paulus & Stewart, 2014). Indeed, it seems that atypical interoception is a key predictor of general psychopathology (Murphy et al., 2017), potentially representing the 'P-Factor'(Brewer et al., 2021). Given this, comparing recognition of others' interoceptive states across typical and clinical groups, and investigating its relationship with interoceptive abilities in the self, is a clear direction for future research. Notably, exploratory analyses conducted in the current study with individuals who self-reported a mental health condition did not reveal such a relationship, despite many of these individuals self-reporting difficulties perceiving their own internal states precisely. Given that this group was highly heterogenous, however, and clinical measures were not obtained, further research is needed, particularly since many clinical disorders are also associated with social and communication difficulties, including ASD (American Psychiatric Association, 2013) and feeding and eating disorders (Treasure et al., 2012), which may be contributed to or exacerbated by difficulties recognising others' interoceptive states, if observed.

Relatedly, given that emotion recognition increases throughout childhood (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012), it is likely that greater variation in state recognition ability might be present in a broader developmental sample. Again, it is possible that one's own interoceptive accuracy predicts the recognition of others' interoceptive states in young children, but that interoceptive accuracy is sufficiently developed by the age of 16 years, masking this relationship. Within the emotion literature, evidence suggests that adult-level ability to recognise emotions emerges at different ages for different emotions (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012). It is therefore likely that recognition of interoceptive expressions also follows distinct developmental trajectories for different interoceptive states. Longitudinal investigations beginning in early childhood would facilitate understanding of how humans learn to recognise interoceptive states in others. If, for example, increases in one's own interoceptive accuracy are followed by improvements in the recognition of others' interoceptive states, this would suggest that understanding one's own interoceptive states plays a role in learning to infer others. Experimental methods, for example manipulating one's interoceptive accuracy through training or false feedback, would also help to elucidate the potential causal role of one's own interoceptive abilities on the recognition of others' interoceptive states.

Unlike with age, interoceptive state recognition was affected by both actor and observer gender in the current study. Females were significantly more accurate at recognising others' internal states than males, consistent with findings that women tend to outperform men on emotion recognition tasks (Abbruzzese et al., 2019; Olderbak et al., 2019; Sullivan et al., 2017; Thompson & Voyer, 2014), although it has been suggested that this effect only holds for subtle emotions (Hoffmann et al., 2010). Participants were also more accurate at recognising states posed by actors of the same gender (e.g., females judging females), rather than actors of a different gender (e.g., females judging males). Again, this is to be expected given the in-group advantage in emotion recognition tasks, whereby individuals are significantly more accurate at recognising emotional expressions posed by similar individuals (Elfenbein et al., 2002; Soto &

Levenson, 2009). Interestingly, irrespective of participant gender, individuals were more accurate at recognising interoceptive states when they were posed by females, rather than males. Whilst a similar effect has been reported in the emotion literature (Kohler et al., 2003), this is also somewhat surprising considering evidence that in childhood, boys' ambiguous states are more likely to be labelled as interoceptive, and girls' as emotional (Fivush et al., 2000; Kuebli & Fivush, 1992; Mascaro et al., 2017; Prentice & Murphy, 2022). Rather than males being more accurate at depicting internal states, therefore, differences in interpretation of male and female states as either interoceptive or emotional might be driven by social expectations concerning gender differences. Given the importance of assigning appropriate internal state labels to individuals experiencing states such as nausea, breathlessness, and pain, as well as the importance of distinguishing between interoceptive and emotional states, future research should explore potential explanations for differences in internal state labelling across males and females.

Beyond the relationship with the recognition of others' interoceptive states, significant associations were observed between the self-report interoceptive measures. The BPQ-C and IATS-C were strongly positively correlated, suggesting that they measure a similar psychological construct. This is unsurprising, given that the majority of individuals interpret the BPQ-C as measuring interoceptive attention, and the IATS-C explicitly taps into interoceptive attention (Gabriele et al., 2022). While some unexplained variance in the relationship may be due to the questionnaires including different interoceptive sensations, much is likely to result from misinterpretation of the BPQ-C. The BPQ-C instructs participants to report on their "awareness" of a series of internal bodily states, and whilst attention is the most common interpretation, it is also common for participants to interpret this is referring to the frequency with which signals occur or the accuracy with which they can perceive them (Gabriele et al., 2022). In the current sample, significant relationships were also observed between the self-report measures of interoceptive attention and self-reported interoceptive accuracy. These were significantly weaker than the relationship between the two attention measures, however, supporting the theoretical distinction between interoceptive accuracy and attention (Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Whilst these are separable constructs, there are multiple ways in which interoceptive attention and accuracy could be related. Individuals who believe that they are highly accurate at perceiving their internal states could intentionally pay greater attention to their internal bodily signals, since they believe they are a reliable source of internal information. Conversely, these individuals could devote low levels of attention to their interoceptive states, as high accuracy means that little effort is required to determine their internal state. Similarly, individuals who believe they are inaccurate at perceiving their internal states may pay very little attention to these signals as they believe these are not a reliable source of information, or exhibit high interoceptive attention in an attempt to compensate for their lack of accuracy. It is worth noting that there may be subgroups of individuals exhibiting different linear relationships, for example in different clinical populations or age groups. It is also possible that the relationship between interoceptive attention and accuracy is quadratic, rather than linear, for example with individuals with the highest and lowest perceived accuracy exhibiting the greatest interoceptive attention, due to beliefs that the information is particularly reliable, or that increased attention can compensate for low accuracy. Further research is therefore needed to characterise this relationship, which employs both objective and self-report measures of interoceptive accuracy and attention in large samples, spanning both typical and clinical populations and developmental stages.

Notably, the current study relied solely on self-report measures of interoception. Advantages of these measures include the ability to assess interoception across a range of sensory signals, and to capture interoceptive experiences outside of the laboratory. While self-reported interoceptive accuracy appears to be associated with performance on objective interoceptive accuracy tasks in adults, this relationship is weak (Murphy et al., 2020), meaning that self-reported interoceptive accuracy and attention may not reflect individuals' ability accurately. Interoceptive insight (the alignment between subjective and objective measures of interoceptive performance) also appears to vary across individuals (Forkmann et al., 2016; Garfinkel et al., 2015) making self-report measures more valid measures in some individuals than others. With this in mind, future research should employ both objective and self-report measures of interoceptive accuracy and attention when assessing the relationship between the recognition of one's own and others' internal bodily states.

A further limitation of the current study concerns the interoceptive recognition paradigm, which utilised images of actors posing the interoceptive states rather than depicting genuine interoceptive expressions. Evidence suggests differences in the expression of posed and evoked emotions (Schmidt et al., 2006a; Schmidt et al., 2006b; Valstar et al., 2006), although it seems that these can be mainly attributed to differences in expressive intensity (Sowden et al., 2021). It is therefore likely that there will also be differences between posed and evoked interoceptive expressions. Nonetheless, the majority of emotion recognition research also utilises posed expressions from widely used stimulus databases (Ekman & Friesen, 1976; Langner et al., 2010; Lundqvist et al., 1998; Tottenham et al., 2009), and whilst naturally elicited expressions are seen as more ecologically valid, communicative expressions are also used in real world interactions to communicate one's states explicitly (Frith, 2009). Future research should therefore focus on utilising both posed and evoked expressions of interoceptive states to determine whether they are differently related to interoceptive abilities in the self. Another aspect of interoceptive expressions that requires investigation is the universality of expressions, with ongoing debate concerning the extent to which emotional expressions are consistent across individuals and cultures (Ekman, 1973; Ekman et al., 1987; Jack et al., 2012; Mandal & Ambady, 2004). Indeed, a potential explanation for the lack of relationship between one's own interoceptive abilities and recognition of others' interoceptive states in the current study is that interoceptive expressions differ across individuals, meaning that one's own expression cues do not necessarily help one to interpret others. As expressions were recognised above chance, however, and actors employed similar postural cues to express interoceptive states (Biotti et al., 2021), this suggests some level of consistency across individuals.

In conclusion, the current study investigated the recognition of others' non-emotional internal states, observing accuracy greater than chance, demonstrating that individuals can correctly infer others' states from a series of visual cues. Nevertheless, no relationship was found between one's own self-reported interoceptive accuracy or attention and the recognition of others' interoceptive states. The current findings suggest, therefore, that self-reported difficulties identifying or attending to interoceptive states in one's own body do not lead to concurrent difficulties recognising these states in others. As individuals in the current sample did not report marked difficulties in interoception, however, and given the importance of state recognition in social communication and providing adequate care, future research is needed to delineate this relationship further, including in those with interoceptive difficulties. No effect of age was found on recognition accuracy, suggesting that state recognition is stable by late adolescence. However, women appeared more accurate at both depicting and recognising internal states. Future research should also investigate the relationship between the recognition of one's own and others' states developmentally over a broader age range, using both objective and subjective measures of interoception.

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Supplementary Materials

Supplementary Materials 1. Kolmogorov-Smirnov test statistic and significance values for all variables.

Variable	*K-S*	*p*
IAS	0.106	0.004
IATS	0.130	< 0.001
BPQ-C	0.429	< 0.001
Breathlessness Hit Rate	0.118	0.001
Cold Hit Rate	0.483	< 0.001
Tired Hit Rate	0.157	< 0.001
Hot Hit Rate	0.141	< 0.001
Hungry Hit Rate	0.123	< 0.001
Itch Hit Rate	0.396	< 0.001
Nausea Hit Rate	0.122	< 0.001
Pain Hit Rate	0.118	0.001
Satiety Hit Rate	0.070	0.200
Running Hit Rate	0.469	< 0.001
State Hit Rate (Mean)	0.064	0.200
Age	0.119	<0.001
RT (State Trials)	0.222	<0.001
RT (Action Trials)	0.120	<0.001

Supplementary Materials 2. BF_{10} for each stimuli category and IAS-C, IATS-C, and BPQ-C scores

	State Hit Rate (Mean)	Breathlessness	Cold	Tired	Hot	Hungry
IAS-C	0.108	0.659	1.177	0.108	0.104	0.230
IATS-C	0.142	0.152	0.527	0.13	0.138	0.188
BPQ-C	0.108	0.102	0.111	0.126	0.113	0.150
	Itch	**Nausea**	**Pain**	**Satiety**	**Running**	
IAS-C	0.154	0.108	0.101	0.732	0.178	
IATS-C	0.124	0.142	0.151	0.23	0.126	
BPQ-C	0.101	0.129	0.106	0.255	0.102	

Supplementary Materials 3. BF_{10} for RT on state and action trials and IAS-C, IATS-C, and BPQ-C scores

	IAS-C	IATS-C	BPQ-C
RT (State trials)	0.108	0.145	0.110
RT (Action trials)	0.109	0.130	0.111

Supplementary Materials 4. BF_{10} for age and state and action hit rate

	BF_{10}
State Hit Rate (Mean)	0.155
Running	1.394

Supplementary Materials 5. Exploratory analyses including participants who self-reported a mental-health condition

5.1. Correlations between state and action recognition and IAS-C, IATS-C and BPQ-C scores for participants who self-reported a mental-health condition. One-tailed *p* values are reported in brackets (unadjusted for multiple comparisons).

	IAS-C	IATS-C	BPQ-C
State Recognition	-0.129 *(0.439)*	0.031 *(0.870)*	0.129 (0.440)
Action Recognition	-0.053 (0.748)	-0.003 (0.989)	-0.222 *(0.181)*

5.2. Correlations between state and action recognition and IAS-C, IATS-C and BPQ-C scores for all participants (those who did and did not report a mental health condition). One-tailed *p* values are reported in brackets, unadjusted for multiple comparisons.

	IAS-C	IATS-C	BPQ-C
State Recognition	-0.044 *(0.533)*	-0.040 *(0.640)*	-0.018 *(0.794)*
Action Recognition	0.031 *(0.658)*	-0.017 *(0.841)*	-0.051 *(0.464)*

Chapter 4. Study Two: The processing of interoceptive states in oneself and others in adolescence, adulthood, and older age

The processing of interoceptive states in oneself and others in adolescence, adulthood, and older age

Lara Carr, Dawn Watling and Rebecca Brewer

Abstract

Background: Difficulties identifying and describing one's own emotions (alexithymia) are associated with atypical processing of others' emotions across various domains, including memory, appraisals, and attention. While emotion processing and processing of other (non-emotional) interoceptive states share underlying psychological and neural mechanisms, very little research has investigated the processing of others' non-emotional interoceptive states (e.g., temperature, pain, and nausea).
Method: The current study investigated individuals' interpretation of interoceptive states in others, by assessing participants' propensity to assign an interoceptive (e.g., 'feeling cold') or action (e.g., 'rubbing arms') label to images of others posing interoceptive states, and its relationship with self-reported interoceptive accuracy and attention, in adolescence, adulthood, and older age.
Results: A bias towards interoceptive interpretations of stimuli was positively associated with one's own self-reported interoceptive accuracy and negatively associated with age.
Conclusions: Findings suggest that more accurate recognition of one's own interoceptive signals may increase the tendency to detect interoceptive cues in others.

1. Introduction

The processing of one's own emotions has been the focus of much research, particularly as individual differences in emotion processing have implications for a range of cognitive and mental health outcomes (Gross, 2002; Hu et al., 2014; Kret & Ploeger, 2015; Parker et al., 2004; Schutte et al., 2007). Alexithymia is characterised by difficulties recognising and describe one's own emotions, and an externally orientated cognitive style (Apfel & Sifneos, 1979; Nemiah et al., 1976). Alexithymia has been associated with a range of clinically-relevant difficulties, such as depression and interpersonal problems (Joybari, 2014), anxiety (Sayin et al., 2007), and aggressive behaviour (Manninen et al., 2011), with levels of alexithymia also affecting therapeutic outcomes for some psychological therapies (Ogrodniczuk et al., 2011). Moreover, while alexithymia is defined in terms of difficulties processing one's own emotions, it is also associated with impairments in the processing of others' emotions across a range of cognitive domains including recognition accuracy, memory, appraisals, and attention (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014; Luminet et al., 2021). Individuals with alexithymia, for example, have been found to be less accurate at recognising others' emotions from both faces and voices (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), as well as displaying deficits in attention to and memory for emotional stimuli (Luminet et al., 2021). Individuals with alexithymia also tend to appraise emotional stimuli as less emotive than those without alexithymia. It is worth noting, however, that multiple facets of alexithymia have been proposed (difficulty identifying feelings, difficulty describing feelings, and an externally orientated cognitive style), which may be differently related to appraisal of others' emotions (Luminet et al., 2021). Nonetheless, it seems that an understanding of one's own emotions is crucial in learning to process the emotions of others. This relationship appears to hold across both typical and clinical populations, with understanding of one's own emotions predicting a range of socioemotional abilities (Brewer et al., 2015; Cook et al., 2013).

Interoception, defined as the perception of, attention to, and propensity to use internal bodily signals (Gabriele et al., 2022; Garfinkel & Critchley, 2013; Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022) is thought to be a core component of emotion processing, with all leading models of emotion ascribing a role for the perception of physiological changes in emotional experience (e.g., (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013; Gendron & Barrett, 2009; James, 1894; Lange, 1885;

Schachter & Singer, 1962). Empirical evidence in support of these models has reported associations between interoceptive abilities and emotional lability (Schandry, 1981), emotion regulation (Füstös et al., 2013; Kever et al., 2005), and intensity of one's emotional experience (Füstös et al., 2013; Herbert et al., 2007; Pollatos et al., 2007; Wiens et al., 2000). Interoception is therefore essential for both the accurate detection of emotions, and judgements of their intensity, both of which are necessary to identify one's emotional state (e.g., Bechara & Naqvi, 2004). Unsurprisingly, individuals with elevated levels of alexithymia display atypical interoceptive profiles, characterised by deficits in interoceptive accuracy across a range of domains, including cardiac perception (Herbert et al., 2011; Murphy et al., 2018a; Shah et al., 2016), taste (Murphy et al., 2018a), and muscular effort (Murphy et al., 2018a). Alexithymia is also potentially associated with increases in self-reported interoceptive attention, although this finding is not always replicated (Trevisan et al., 2019; Gaggero et al., 2021). While the processing of interoceptive sensations has not received the same interest as the processing of emotions historically, research interest has increased dramatically in recent years (Khalsa & Lapidus, 2016). One potential explanation for this surge in interest is the increased focus on mental health, and the finding that interoceptive atypicalities are common in a multitude of mental health and neurodevelopmental conditions, prompting discussion that interoception may play a casual role in psychopathology (Brewer et al., 2021; Khalsa et al., 2018; Murphy et al., 2017). Beyond the contributions of interoception to psychopathology and emotion processing, interoception also seems key in a host of other cognitive processes, such as learning and decision making (Dunn et al., 2010; Kandasamy et al., 2016; Werner et al., 2009) and memory (Pollatos & Schandry, 2008; Werner et al., 2010), as well as playing a role in physical health (Pauli et al., 1991; Rietveld et al., 2004).

As the importance of interoception in both typical and clinical functioning has become clear, so has the need for an agreed upon model of interoception. Recent models distinguish between interoceptive accuracy (the precision with which an individual can perceive their internal bodily signals), interoceptive attention (one's propensity to attend to internal bodily signals), and one's propensity to use internal signals to guide day to day decisions, as well as distinguishing between whether these abilities are measured objectively or subjectively (Gabriele et al., 2022; Garfinkel & Critchley, 2013; Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Debate also exists concerning the signals that should be viewed as interoceptive (Khalsa & Lapidus, 2016), with much contemporary research adopting a broad definition, such that interoceptive signals are those that are processed by particular neural pathways, for example those projecting via lamina 1 of the spinal and trigeminal dorsal horn to the anterior insular cortex (AIC) or anterior cingulate cortex (ACC; Craig, 2003), or via cranial nerves to the nucleus of the solitary tract (Critchley & Harrison, 2013). This definition includes sensations such as affective touch and itch, as well as more typical visceral sensations such as respiratory and gastric sensations.

Recent research has investigated the developmental trajectory of interoceptive abilities, though this remains in its infancy. Self-report data suggests that individuals' attention to their internal bodily signals reduces throughout the lifespan and continues to decline into older age (Murphy et al., 2018b). It is worth noting, however, that self-reported interoceptive attention was measured in this study using the Body Perception Questionnaire (BPQ; Porges, 1993), which may be open to interpretation issues, making replication using more explicit measures of attention necessary (Gabriele et al., 2022). Older age also appears to be associated with decreases in objective interoceptive accuracy, as assessed in the cardiac domain (Khalsa et al., 2009; Murphy et al., 2018b). Whilst the aforementioned research provides interesting preliminary evidence for the effects of ageing on interoceptive accuracy, it is limited as it only measures interoception across one interoceptive signal channel. Recent research has suggested that interoception may not be a unitary ability, and instead fractionates across bodily axes, with ability to detect signals from one interoceptive channel (e.g., cardiac) not necessarily relating to the ability to perceive signals from another channel (e.g., respiratory; Ferentzi et al., 2018). Considering the potentially fractionated nature of interoception, and the interpretation issues with the BPQ, further research is clearly needed that investigates interoception in older age with validated measures of interoceptive accuracy and attention, across a range of interoceptive signals.

Beyond developmental changes, gender[1] differences in interoceptive abilities have also been observed. Regarding interoceptive attention, research has demonstrated that women tend to self-report greater attention to internal bodily signals than men (Grabauskaite et al., 2017) and men tend to report fewer somatic symptoms than women (Barsky et al., 2001). Where interoceptive accuracy is concerned, a recent meta-analysis revealed that women perform

[1] In this study, we explicitly recorded gender identity and therefore use the term 'gender' throughout. It is worth noting, however, that in previous research the terms gender and sex have often been used interchangeably.

significantly worse than men on objective behavioural tasks in both the cardiac and respiratory domains (Prentice & Murphy, 2022). It is worth noting that no significant differences were observed on tests of interoceptive accuracy in the gastric domain, although, these findings are limited by the small number of studies conducted in this domain. Interestingly, however, gender differences in interoceptive abilities are not present when assessed in more naturalistic settings outside of the laboratory (Cox et al., 1985; Pennebaker & Watson, 1988; Smith, 1986). When estimating blood glucose levels, for example, diabetic men were more accurate when only internal cues were available, whereas there were no gender differences present when both internal and external cues were available (e.g., knowledge about food intake, insulin intake, and physical activity; Cox et al., 1985). Similar findings have also been demonstrated in the perception of blood pressure (Pennebaker & Watson, 1988). Pennebaker & Roberts (1992) proposed that these findings suggest that women and men rely on different cues when gauging their internal states; whilst men are likely to use internal signals (e.g., stomach sensations to indicate hunger), women are more likely to rely on situational cues (e.g., the time of the day to indicate hunger). Women and men, therefore, appear to utilise different mechanisms to gauge their internal states. Research has suggested that gender differences in interoceptive mechanisms might be explained by differences in the social experiences of males and females (Prentice et al., 2022). For example, girls are more likely to be labelled as emotional by their parents than boys (Fivush et al., 2000; Kuebli & Fivush, 1992; Mascaro et al., 2017), while distress in infant boys is more likely to be attributed to pain than in infant girls (Cohen et al., 2014). Differences in internal state labelling are likely to affect the child's interoceptive language and concepts, which may, in turn, prompt females to rely less on their internal feelings to gauge interoceptive states. To better understand differences in the interpretation of males' and females' interoceptive expressions, and its impact on the processing of interoceptive states in oneself, further research is required assessing the labels assigned to men and women posing interoceptive states.

Despite the proliferation of research into interoception in the self, very little research has investigated the processing of interoceptive states in others, beyond emotional displays. Limited evidence has investigated the perception of pain, demonstrating that individuals with AIC lesions display decreased discrimination accuracy and prolonged reaction times when recognising others' pain (Gu et al., 2012). Individuals with alexithymia also assign lower pain ratings to human hands and feet in painful situations, compared to individuals with reduced alexithymia (Moriguchi et al., 2007). Beyond this, individuals can distinguish between those injected or not injected with a bacterial stimulus, successfully detecting acute illness at levels greater than chance (Axelsson et al., 2018). Humans have also been found to successfully judge the likely owner of a heartbeat above chance in a two-alternative forced choice design (Galvez-Pol et al., 2020). Despite this, it is unclear whether interoceptive recognition generalises to other states (e.g., temperature, breathlessness), or if the processing of one's own states is related to the processing of others. As the processing of one's own emotions is closely related to both processing of others' emotions (Luminet et al., 2021; Heaton et al., 2012; Grynberg et al., 2010) and the recognition of one's own non-emotional interoceptive sensations (Brewer et al., 2016, 2021), it is likely that one's own interoceptive abilities are also associated with the processing of others' non-emotional interoceptive states. Investigating the processing of others' interoceptive states is crucial, as the ability to recognise, interpret, and attend to these states is key for social communication; difficulties responding appropriately to interoceptive displays is likely to reduce the quality of social interactions and relationships. Beyond social communication, the misinterpretation of others' interoceptive displays with an evolutionary function (e.g., pain) would impede an individual's ability to provide appropriate care and assistance.

The current study investigated the interpretation of others' non-emotional interoceptive states, assessing whether participants assigned interoceptive or action labels to images of others posing interoceptive states, across adolescence, adulthood, and older age. Self-report measures of interoceptive accuracy and attention were administered to investigate the relationship between the processing of one's own and others' interoceptive states. It was hypothesised that the propensity to use interoceptive labels to describe others' expressions would be positively associated with one's own self-reported interoceptive accuracy and attention. The propensity to assign interoceptive, over action, labels to others was predicted to decline with age, in line with the inverse relationship between interoceptive accuracy and age. Where gender is concerned, it was predicted that female participants would be less likely to interpret expressions as interoceptive than males, based on gender differences in accurate recognition of one's own interoceptive states, and that interoceptive states posed by males would be more likely to be labelled as interoceptive than those posed by females.

2. Method

2.1 Participants

A total of 359 participants were recruited (gender identity: 271 female, 85 male, 2 participants identifying as neither male nor female), ranging in age from 16.17 to 90.33 years (*M* = 34.95, *SD* = 19.78). As participants were recruited from the university student pool and local colleges, departmental policies meant that individuals with mental health conditions could not be excluded from participating. To ensure the sample was representative of the non-clinical population, individuals with mental health conditions were removed from the sample retrospectively, leading to a final sample of 329 participants (gender identity: 246 female, 82 male, 1 participant identifying as neither male nor female). Participants ranged in age from 16.17 – 90.33 years of age (*M* = 36.58, *SD* = 19.84), with 142 young adults (under 25 years of age), 116 middle aged adults (25 – 59 years of age), and 56 older adults (Over 60 years of age; See histogram of age distribution in Supplementary Materials 1). A total of fifteen participants did not provide relevant information on their age (e.g., entering the date they partook in the experiment rather than their date of birth) so were removed from any analyses which investigated the effect of age. IAS and IATS scores were excluded from analyses if the interpretation question for that questionnaire was answered incorrectly (See Section 2.2.1 and Section 2.2.2 respectively for more detail) After exclusions, there were a total of 275 participants for analyses including the IAS and 244 for analyses including the IATS.

Ethical approval was obtained from the Royal Holloway, University of London ethics committee. In line with ethical guidelines, all participants provided informed consent prior to participation and received a full debrief upon completing the study. Younger participants, aged 16 to 21 years, were typically recruited from local sixth form colleges and the Royal Holloway, University of London, student body in exchange for course credit, whilst participants over 21 years of age were typically recruited from social media and from the paid recruitment site, Prolific.com. All participants completed the study online, via Gorilla.com. Participants were permitted to take part on any device with an internet connection.

2.2 Measures

2.2.1 Self–reported interoceptive accuracy

The Interoceptive Accuracy Scale (IAS) was utilised to assess subjective interoceptive accuracy (Murphy et al., 2019). This scale measures participants' beliefs concerning their ability to perceive their interoceptive signal accurately. The scale is composed of 21 items, each relating to a sensation that has been described as interoceptive in nature. For each sensation, participants are required to rate their ability to perceive it accurately (e.g., 'I can always accurately perceive when by heart is beating fast'), by indicating how much they agree or disagree with a statement. Participants responded on a Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree), with total scores ranging from 21 to 105, and higher scores indicative of higher subjective interoceptive accuracy. The IAS was found to have high reliability in this sample (21 items; $\alpha = 0.84$).

In order to ensure that participants interpreted the questionnaire as intended, they were asked upon completion to indicate what they believe the questionnaire was asking them to report on: the accuracy with which they can perceive sensations, the attention they pay to said sensations, the frequency with which these sensations occur in their body, or another construct. If the participant did not correctly indicate that the questionnaire assessed interoceptive accuracy, their IAS score was removed from analyses.

2.2.2 Self-reported interoceptive attention

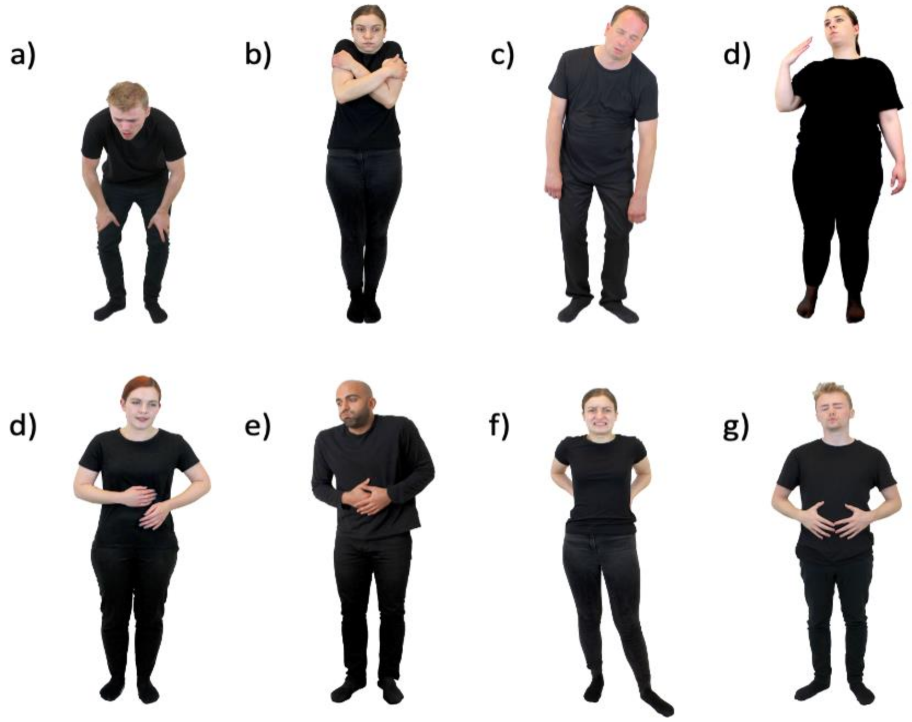
The Interoceptive Attention Scale (IATS; Gabriele et al., 2022) was utilised to assess subjective interoceptive attention. This scale measures participants' beliefs about the extent to which interoceptive signals are the subject of their attention. The scale enquires about an identical set of 21 interoceptive signals to the IAS. For each item participants are asked to report on their attention to this state (e.g., 'Most of the time my attention is focused on whether my heart is beating fast'), by indicating how much they agree or disagree with the statement. The scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree), with total scores ranging from 21 to 105, and higher scores indicative of higher subjective interoceptive attention. The IATS was found to have high reliability in this sample (21 items; $\alpha = 0.91$).

Again, participants were required to indicate what they believe the questionnaire was asking them to report on, using the question described above. IATS data were excluded for any participant who did not correctly identify that the questionnaire assessed interoceptive attention.

2.2.3 Labelling propensity task

Participants' propensity to assign an internal state label to interoceptive stimuli was assessed using a novel paradigm. Participants viewed photographic stimuli taken from the Interoceptive States Static Images database (ISSI; Biotti et al., 2021), depicting six actors (three male, three female) expressing eight internal states through facial and postural cues (Figure 1). The internal states portrayed were breathlessness, cold, hot, fatigue, hunger, satiety, nausea, and pain. Each stimulus was presented once, yielding a total of 48 trials, with presentation order randomised across participants. Images were presented in a two-alternative forced-choice paradigm, with participants being required to select the orthographic label that best described the image. One label described the image using an interoceptive term (e.g., "Feeling hot"), while the other used an action term (e.g., "Fanning face"). Importantly, both labels were valid descriptions of the image, with four independent raters indicating that each term accurately described the image. Participants were instructed to select the label "that YOU feel best fits the image" and were informed that no response was either correct or incorrect. The image remained present until the participant provided a response. Phrases on each trial were perfectly matched across the two conditions on the number of syllables and presentations, so that no internal state phrase appeared more times than an action phrase and vice versa. To further ensure consistency across the action and interoceptive labels, all labels also began with a verb (e.g., feeling hot (interoceptive label), fanning face (action label), or needing air (interoceptive label), holding throat (action label). The word frequency for each individual word across phrases and trials was identified for both interoceptive and action labels, using the CELEX English database (Baayen et al., 1995). This frequency count is derived from the COBUILD corpus of 17.9 million words, 16.6 million of which were sampled from written sources (a set of 284 contemporary written texts), the remaining 1.3 million being sampled from spoken English. The average word frequency across words and phrases was calculated for both interoceptive and action labels. An independent samples *t*-test demonstrated that interoceptive (M = 2,621.18; SD = 7,300.50) and action (M = 2,309.45, SD = 6,391.12) labels did not differ significantly in word frequency, $t(248) = 0.360$, p = 0.719. The propensity to label task was always presented before measures of self-reported interoceptive accuracy and attention to ensure that participants were not primed to select internal state labels.

Figure 1. An example of each state depicted by one of the six actors. From a) to g), the depicted states are; breathlessness, cold, fatigue, hot, hungry, nausea, pain, hunger.



2.3 Analysis strategy

Data were excluded for any participants who began but did not complete the labelling propensity task (*N* = 12). All participants who completed the labelling propensity task also completed the questionnaires with no missing data. For each trial, interoceptive responses were coded as 1 and action responses were coded as 0. Total scores (ranging from 0 to 48) were then divided by 48 (the number of trials), to indicate the proportion of stimuli assigned an interoceptive label. Labelling propensity scores of 1 indicate of the exclusive selection of interoceptive labels, and scores of 0 indicate the exclusive selection of action labels.

Once calculated, correlational analyses were conducted to investigate the relationship between labelling propensity scores, IAS and IATS scores. Correlations with age were also investigated to determine whether the propensity to assign interoceptive labels, or self-reported interoceptive attention or accuracy, varied as a function of age. Regression models were used to explore whether the relationships between interoceptive variables and labelling propensity varied with age. Age and gender interactions were not tested as demographic imbalances led to undersampled older men; however, a robust mixed 2 x 2 ANOVA was used to assess the effects of actor and participant gender on labelling propensity score.

The normality of each variable was inspected (IAS total, IATS total, Labelling Propensity Score, Labelling Propensity Score (Female), Labelling Propensity Score (Male), Age). Visual inspection of histograms was accompanied by a Kolmogorov-Smirnov test with a Lilliefors correction (Lilliefors, 1967). If a variable was not normally distributed the appropriate non-parametric tests were implemented (See Supplementary Materials 2 for all normality statistics). Bayesian statistics were conducted to further explore results. Where directional hypotheses were made, one-sided significance values are reported.

3. Results

3.1 Propensity to assign interoceptive labels

Propensity scores were not normally distributed (see Supplementary Materials 2 for test statistics). Individual differences were observed in the propensity to select interoceptive labels, with scores ranging from 0.00 to 0.85 (M = 0.54, SD = 0.15). A Wilcoxon one-sample signed rank test revealed that across the sample, interoceptive labels were selected significantly more often than chance (0.5), Z = 32386.50, $p < 0.001$, BF_{10} = 7209.54, indicating a bias towards interoceptive, rather than action, labels across the sample as a whole.

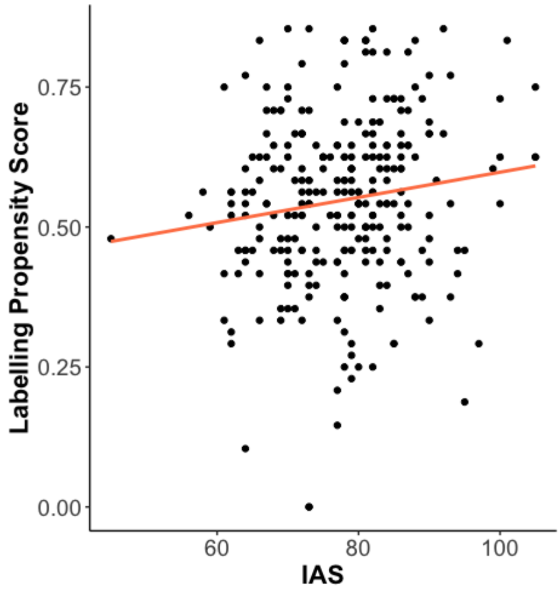
3.2 Interoceptive questionnaires

Neither IAS nor IATS scores were normally distributed. IAS scores ranged from 45 to 105 (M = 77.76, SD = 9.42), and IATS scores ranged from 21 to 105 (M = 52.65, SD = 13.51). Scores on the IAS and IATS were not correlated with each other, $r(212) = -0.024$, p = 0.731 one-tailed, BF_{10} = 0.099, in line with the distinction between interoceptive accuracy and attention.

4.3 The relationship between processing of one’s own and others’ interoceptive states

Propensity to assign interoceptive labels was significantly positively correlated with self-reported interoceptive accuracy, $r(275) = 0.142$, $p = 0.009$ one-tailed, $BF_{10} = 1.609$, such that the more accurate an individual believes they are at perceiving their internal bodily states, the more likely they were to assign an interoceptive label, over an action label, to others' interoceptive state expressions (Figure 2). Propensity to assign an interoceptive label was not associated with self-reported interoceptive attention after correction for multiple comparisons, $r(243) = 0.114$, $p = 0.038$ one-tailed, $BF_{10} = 0.504$.

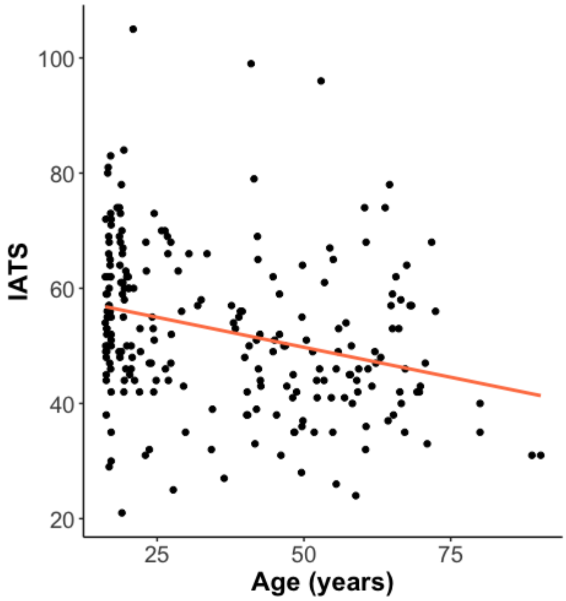
Figure 2. Significant positive relationship between self-reported interoceptive accuracy and propensity to assign an interoceptive label to others.



3.4 Age

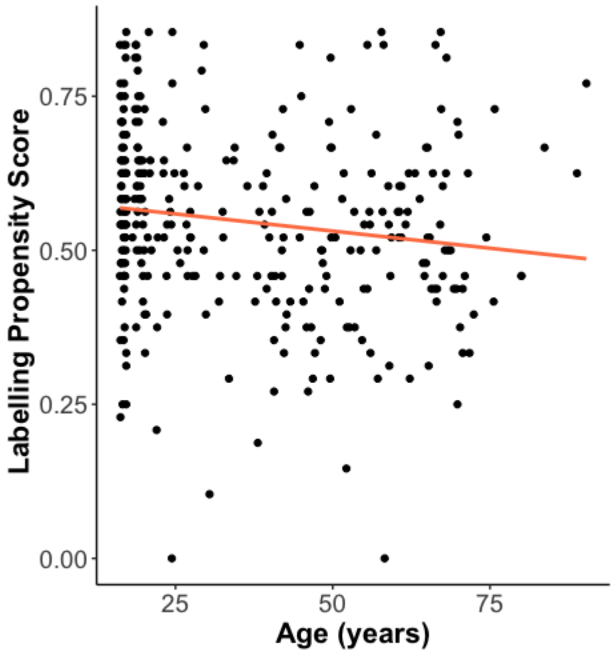
IAS scores were not correlated with age, $r(262) = 0.093$, $p = 0.067$ one-tailed, $BF_{10} = 0.253$. IATS scores were, however, significantly negatively correlated with age, $r(231) = -0.323$, $p < 0.001$ one-tailed, $BF_{10} = 17{,}112.37$, such that older participants reported paying less attention to interoceptive signals (Figure 3).

Figure 3. Significant negative correlation between age and self-reported interoceptive attention.



Labelling propensity scores were also significantly negatively correlated with age, $r(314) = -0.188$, $p = < 0.001$ one-tailed, $BF_{10} = 28.32$, such that as age increased, the likelihood of selecting an interoceptive label, over an action label, decreased (Figure 4).

Figure 4. The significant negative relationship between age and propensity to assign and interoceptive label, over an action label, to others posing interoceptive states.



In order to determine whether the relationship between IAS and labelling propensity varied as a function of age, a linear regression model including IAS score, age, and the interaction between IAS and Age was conducted. This model explained 24.1% of the variance in labelling propensity scores, $F(258, 3) = 5.320$, $p = .001$. Whilst IAS and age remained significant predictors of labelling propensity, the interaction term did not account for a significant proportion of unique variance (Table 1). Similar analysis with the IATS replacing the IAS led to a nonsignificant model, predicting 17.3% of the variance in labelling propensity scores, $F(227, 3) = 2.333$, $p = .075$. Whilst age remained significantly related to labelling propensity, neither IATS scores nor the IATS*Age interaction term were significant predictors (Table 1). These findings suggest that self-reported interoceptive abilities and age are independently related to one's propensity to assign an interoceptive label to others, and that the relationship between IAS and labelling propensity does not vary as a function of age.

Table 1. Linear regressions including the predictor variables a) IAS score, Age, and their interaction, and b) IATS, Age and their interaction, with labelling propensity score as the dependent variable. *p* values are reported two-sided, uncorrected for multiple comparisons.

		Labelling Propensity Score		
Predictors		*B*	*p*	*t*
a)	IAS	0.157	0.011	2.567
	Age	-0.192	0.002	-3.15
	IAS*Age	0.052	0.392	0.858
b)	IATS	0.07	0.309	1.019
	Age	-0.137	0.049	-1.982
	IATS*Age	-0.055	0.403	-0.837

3.5 Gender

An independent samples Mann-Whitney U Test revealed no significant differences between males (*Mdn = 78*) and females (*Mdn* = 78) in scores on the IAS, $U(274) = 6455.50$, $p = .311$ two-tailed. Females (*Mdn* = 53), however, reported paying significantly more attention to their internal bodily signals than males (*Mdn* = 50), indexed by score on the IATS, $U(242) = 5967$, $p = .025$ two-tailed.

Due to non-normally distributed scores on the labelling propensity task, a robust mixed 2 x 2 ANOVA was conducted with actor gender as a within-participants factor, and participant gender as a between-participants factor. The analysis revealed a significant main effect of actor gender on labelling propensity score, $F(1, 327) = 38.281$, $p < .001$ two-tailed, $np^2 = .103$, such that participants were more likely to assign an interoceptive label, over an action label, to male than female actors. Participant gender did not have a significant effect on labelling propensity score, $F(1, 327) = 1.611$, $p = .206$ two-tailed, $np^2 = .004$, and there was no significant interaction between participant and actor gender, $F(1,327) = 1.509$, $p = .0.221$ two-tailed, $np^2 = .006$.

Separate correlational analyses were conducted to assess the relationship between self-reported interoceptive accuracy (IAS) and labelling propensity scores when participants were rating actors of their own gender (e.g., males labelling males), and when rating actors of a different gender (e.g. males labelling females). IAS score was significantly positively related to labelling propensity score when rating actors of a different gender, $r(275) = .137$, $p = .023$ two-tailed, but this relationship fell to a trend level when rating actors of one's own gender, $r(275) = .116$, $p = .055$ two-tailed. Fisher r to z analyses indicated, however, that these correlations did not differ significantly in strength, $z = -0.297$, $p = 0.383$, suggesting that it is actor gender itself (with male actors being rated as interoceptive more frequently), rather than alignment between actor and observer gender, that affects labelling propensity.

Identical analyses were conducted to assess the relationship between self-reported interoceptive attention (IATS) and labelling propensity score when participants were rating actors of their own gender (e.g., males labelling males), and when rating actors of a different gender (e.g., males labelling females). IATS scores were not related to labelling propensity score when rating actors of a different gender, $r(243) = .081$, $p = .210$ two-tailed, or their own gender, $r(243) = .122$, $p = .058$ two-tailed.

4. Discussion

The current study investigated the interpretation of others' non-emotional interoceptive states, and observed individual differences in the propensity to assign interoceptive or action labels to posed interoceptive expressions. In line with predictions, the current study observed a significant positive relationship between self-reported interoceptive accuracy and the propensity to assign an interoceptive label, over an action label, to an individual posing an interoceptive state. Individuals self-reporting higher accuracy perceiving interoceptive states in their own bodies were more likely to interpret others' interoceptive expressions as indicative of interoceptive states. Contrary to hypothesised, however, no relationship was observed between self-reported interoceptive attention and interpretation of others' interoceptive expressions. Age, on the other hand, was negatively related to labelling propensity score; as an individual's age increased, their tendency to assign an interoceptive, over an action, label decreased. Whilst participant gender was unrelated to labelling, actor gender was significantly related to labelling, such that participants, irrespective of their own gender, were more likely to assign an interoceptive label to males than females.

The finding that higher self-reported interoceptive accuracy was associated with a greater bias towards interoceptive interpretations of others' facial and bodily expressions is in line with findings in the emotion literature, whereby accurate recognition of one's own emotions is thought to be crucial for the processing of others' emotions (Luminet et al., 2021; Heaton et al., 2012; Grynberg et al., 2010). If an individual has a poor representation of an interoceptive state within their own body, this might hamper learning of the visual or auditory cues associated with that state, leading to a bias towards non-interoceptive interpretations of these cues. Notably, although the interoceptive and action labels within the current task were both valid descriptions of the stimuli, as actors were deliberately posing interoceptive states, the intention of the actor was to communicate this state. Within a social interaction, therefore, incorrectly interpreting these cues as non-interoceptive may lead to reduced empathy and inappropriate social responses, and in turn less successful interactions. Difficulties interpreting others' interoceptive displays therefore have important implications for social cognition, and may lead to difficulties building and maintaining relationships. As interoceptive cues are often related to health and physical wellbeing, this finding has implications for one's ability to care for others in particular; if one does not interpret others' interoceptive cues correctly, this is likely to impede one's ability to provide appropriate care or medical attention. This may be exacerbated if the observed individual has poor understanding of their interoceptive states themselves, or struggles to communicate, for example in young children (e.g., Feldman, 2019; Schaan et al., 2019), older adults (Khalsa et al., 2009; Murphy et al., 2017; Yorkston et al., 2010), or clinical groups where interoceptive or communication difficulties are common, such as autism spectrum disorder (American Psychiatric Association, 2013; Garfinkel et al., 2016; Hatfield et al., 2017; Mul et al., 2018; Nicholson et al., 2019). Thus, this is also of particular importance when observers have a care-giving role, such as parents, carers, and medical professionals.

Where interoceptive attention is concerned, results did not support a relationship between attending to one's own interoceptive states and interpretation of these states in others. The fact that interoceptive accuracy and attention showed different relationships with performance on the labelling propensity task, and that no relationship was observed between scores on the IAS and IATS, supports theories proposing that accuracy and attention are two dissociable facets of interoception (Gabriele et al., 2022; Murphy et al., 2020). It may be the case that these distinct facets each relate to distinct components of processing of others' interoceptive states, such as recognition accuracy, attention, and interpretation. Attention to one's own interoceptive states, for example, might be more strongly related to attention towards others' interoceptive cues, than to one's interpretation of these cues. Future research should therefore investigate this, including the specific nature of any such relationship; while it is possible that increased focus on interoception leads to both higher attention to one's own and to others' interoceptive signals (i.e., a positive linear relationship), it is also possible that attention to one's own interoceptive states detracts attention from these states in others (i.e., a negative linear relationship). It is also possible that a quadratic relationship exists, whereby increasing attention to interoceptive sensations in one's own body facilitates attention to others' interoceptive states to an optimal point, but beyond this point, particularly high attention to one's own interoceptive distracts one from paying attention to others' internal state cues. Attention towards others' interoceptive states is yet to be investigated, but given the likely importance of processing others' interoceptive states for social communication, and providing adequate care, this is a clear target for future work.

Interestingly, unlike investigations into the impact of gender on objective interoceptive accuracy (Prentice & Murphy, 2021), no effect of participant gender was observed on self-reported interoceptive accuracy in the current sample. On the other hand, women self-reported significantly higher attention to internal bodily signals, which is consistent with prior research (Grabauskaitė et al., 2017). Males and females also did not differ in their propensity to assign interoceptive, over action, labels to others' interoceptive state expressions. Despite this, actor gender was found to affect participants' propensity to interpret expressions as interoceptive. Irrespective of their own gender, participants were more likely to assign interoceptive labels when the states were posed by males, rather than females. There are a number of potential explanations for this. While it is possible that male actors simply expressed the intended interoceptive states more accurately, data on recognition accuracy suggest that recognisability is not higher in males than females (Biotti et al., 2021); indeed, females' interoceptive expressions may be recognised more accurately than males' (Carr et al., *in prep.*), implying that the results are not likely to be explained by differences in actors' depictions. As the perceived intensity of interoceptive expressions has not been assessed, however, it may be the case that the male actors' expressions of the interoceptive states were more intense than the females', making the assignment of interoceptive labels more likely. Beyond stimulus differences, this finding may be explained by social experience and top-down biases. Adults appear to rate boys' pain as greater than girls', even when elicited through identical methods (Cohen et al., 2014). There are also stark gender differences in the quality of healthcare provided to men and women. Women typically receive less invasive treatment for conditions which present in the same way as in men, and, as such, tend to use significantly more healthcare services, whilst the management of several conditions (e.g. breast cancer, osteoporosis, and menopause) does not meet measurable standards (Owens, 2008; Regitz-Zagrosek, 2012). While males and females might differ in, for example, their confidence reporting health problems or assertiveness when exploring treatments, it may be the case that men's health problems are interpreted by others as more serious than women's, their interoceptive state reports are considered to be more reliable. If this generalises across interoceptive states, this might explain the higher propensity to assign interoceptive, over action, labels when the actor is male. Indeed, it has recently been argued that in childhood, boys' ambiguous internal states may be more commonly labelled as interoceptive, and girls' as emotional (Prentice et al., 2022). In one study, women assigned more emotional labels to a series of cries when they were told the child was a girl, rather than a boy (Leerkes & Siepak, 2006), and both men and women have been found to use more emotional language to describe their female than their male children (Fivush et al., 2000; Kuebli & Fivush, 1992; Mascaro et al., 2017). It is therefore possible that social biases affect the way that adults interpret and label others' internal states, which may in turn contribute to gender differences in interoceptive abilities that have previously been observed (Prentice & Murphy, 2021).

Interestingly, a significant negative relationship was also observed between age and propensity to assign interoceptive labels to others' expressions, such that older individuals were less likely to interpret stimuli as interoceptive. Although self-reported interoceptive attention also decreased with age, this was unrelated to task performance, and interoceptive accuracy was not found to vary with age, suggesting the effect of age on labelling propensity scores was not explained by changes in one's own interoceptive abilities. These findings are in line with the emotion recognition literature, which reports decreased accuracy in the recognition of others' emotional expressions with age (e.g. Lambrecht et al., 2012; Ruffman et al., 2008). Ageing is also associated with an increased bias for positive information (for a review see Carstensen et al., 2003). As the interoceptive expressions depicted in this study can be considered negative in valence, decreased sensitivity to others' feelings, as well as a bias away from negative information, may explain the increased propensity to select action labels in older age. It is also possible that the effect of age on interpretation of others' interoceptive states is explained by lower cognitive empathy in older age, whereby older adults have greater difficulties understanding others' thoughts and feelings (Beadle & Vega, 2019). Alternatively, this relationship may be mediated by social interaction. Older age is typically associated with decreased social interaction (Cornwell, 2011), leading to fewer opportunities to observe others experiencing interoceptive changes, and their associated expressions. Presumably alongside one's knowledge of one's own interoceptive changes and their associated expressive cues, one also learns about cues associated with internal states from observing others when they provide objective information alongside their interoceptive expressions, such as stating that they are hungry or in pain while expressing these states non-verbally. Continued exposure to such cues may, therefore, be essential to accurately recognise others' interoceptive cues. Relatedly, it may be the case that facial, bodily, and perhaps vocal, expressions of interoceptive states are heterogeneous, with expression variation across individuals, meaning that exposure to a wider range of interaction partners may increase one's ability to generalise knowledge of interoceptive cues to novel identities, as in the current task. As social networks tend to be smaller in older age (Wrzus et al., 2013), exposure to fewer exemplars of interoceptive expressions may hinder interpretation of these cues as age increases. It is also worth noting that, within the current paradigm, selecting the action label may require a lower level of processing, as it simply describes the objective physical features of the stimuli, while interoceptive interpretations require social inferences about others to be made, increasing the cognitive load. Perhaps the bias away from interpreting state displays as interoceptive with increasing age is explained by individuals selecting the label which requires the lower level of cognitive processing, as cognitive abilities decline with increasing age (Cullum et al., 2000). As these inferences are specifically social, reduced social engagement could exacerbate this pattern, so future work should explicitly assess the role of social contact in this relationship. Although the relationship between age and labelling propensity is theoretically likely, it is worth noting that it is relatively weak in the current sample, making it likely that alternative factors are better predictors of the interpretation of others' states. Future research should aim to not only identify these, but also investigate whether they interact with age in predicting labelling of others' interoceptive states.

Beyond the processing of others' interoceptive states, a negative association between age and interoceptive attention was observed, replicating previous findings (Murphy et al., 2018b). It may be the case that as individuals age and experience an increase in physical discomfort and health problems, reducing attention to interoceptive signals acts as a compensatory mechanism to reduce anxiety concerning one's health. Contrary to previous reports of a significant negative relationship between age and interoceptive accuracy in the cardiac domain (Murphy et al., 2018b; Khalsa et al., 2009), a relationship with self-reported interoceptive accuracy was not observed in the current sample. As the current study did not utilise objective measures of interoception, it is possible that individuals also experience a decline in interoceptive insight with increasing age, becoming less aware of their ability to perceive internal bodily signals accurately. Older participants may, therefore, have overestimated their interoceptive accuracy, so further research is required to assess the effects of age on both interoceptive accuracy and insight into this ability. Alternatively, discrepant findings may relate to the fact that the current interoceptive accuracy measure assessed multiple domains of interoception, rather than the cardiac domain alone. As interoception serves an important homeostatic function, particularly when the risk of medical issues is greater, such as in older adulthood, further research is needed into the effects of ageing on both interoceptive accuracy and attention, across a range of interoceptive channels.

Whilst the current study provides compelling preliminary evidence for a relationship between interoceptive processing in the self and the interpretation of others' interoceptive states, future work should investigate this relationship using objective measures of interoceptive accuracy and attention. Self-report measurements of interoception are beneficial as they cover a range of bodily signals, and generally evidence suggests agreement with objective measures of interoception (Murphy et al., 2020). As general metacognition declines in older age (Palmer et al., 2014; Rogers et al., 2012), however, with interoceptive insight also likely to decrease, future work should focus on employing objective measurements of interoception in older age, and other groups where interoceptive insight may be low, such as those with eating disorders (Kinnaird et al., 2020), and autistic individuals (Garfinkel et al., 2016). It is also worth noting that the behavioural paradigm in the current study relied on interoceptive expressions posed by actors, rather than genuine elicited expressions. While this mirrors the vast majority of research on expression recognition within the emotional domain (Ekman, 1976; Lundqvist et al., 1998; Langner et al., 2010), evidence suggests that posed and evoked emotional expressions vary in their physical properties (Schmidt et al., 2006a; Schmidt et al., 2006b; Sowden et al., 2021; Valstar et al., 2006), although, it seems that these can be mainly attributed to differences in intensity (Sowden et al., 2021). It is likely that differences also exist between posed and evoked interoceptive expressions. While naturally elicited interoceptive cues may be thought to be more ecological valid, it is worth noting that deliberately posed, communicative emotional expressions are also used in real world interactions, in order to explicitly communicate one's internal states (Frith, 2009). Future research should therefore investigate processing of both communicative (posed) and naturally evoked expressions of interoception, as well as determining the extent to which these are similar to each other in terms of physical properties.

In conclusion, the current study is the first to investigate the processing of a range of non-emotional interoceptive states in others, and suggests that interpretation of these states is related to one's own interoceptive accuracy. Interpretation of these state displays as interoceptive was found to decrease with age, potentially owing to decreases in social experience. Interpretations were also affected by actor, but not observer, gender, again potential owing to social mechanisms, such as top-down biases and expectations relating to gender. Future work should aim to test these hypotheses, and to investigate processing of others' internal states beyond the domain of interpretation, such as attention towards and memory of interoceptive cues in others. Further work is also needed to determine how processing of others' interoceptive states varies across individuals, beyond age and gender, for example in clinical samples where interoceptive accuracy and attention in the self are often atypical (Khalsa et al., 2018; Murphy et al., 2017; Brewer et al., 2021). Beyond investigating individual differences in interpretation of others' interoceptive states, the potential impact of these differences should also be a priority for future research, such as whether differences in interpretation of others' interoceptive expressions affect empathy, social communication abilities, and the ability to provide appropriate care for others.

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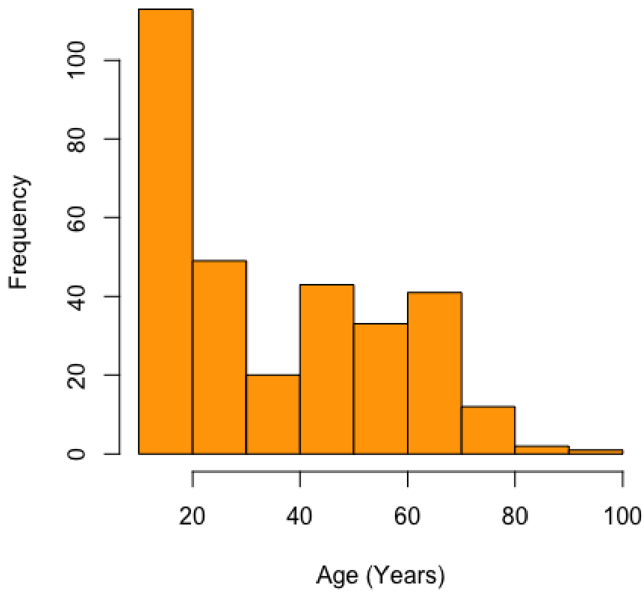
Supplementary Materials

Supplementary Materials 1. Histogram displaying the frequency of participant ages in years.



Supplementary Materials 2. Kolmogorov-Smirnov test statistic and significance values for all variables.

Variable	*K-S*	*p*
Labelling Propensity Score	0.068	0.025
Labelling Propensity Score (Male)	0.088	0.001
Labelling Propensity Score (Female)	0.079	0.004
IAS	0.065	0.039
IATS	0.075	0.008
Age	0.176	<.001

Chapter 5. Study Three: Attention to others' interoceptive expressions and its relationship with the processing of interoceptive states in one's own body.

Attention to others' interoceptive expressions and its relationship with the processing of interoceptive states in one's own body

Lara Carr, Dawn Watling and Rebecca Brewer

Abstract

Background: Interoception refers to the perception of, attention to, and propensity to use internal bodily signals (e.g., cardiac, gastric, and respiratory signals). Atypical interoception is often associated with difficulties identifying and explaining one's own emotions, commonly termed alexithymia. Whilst alexithymia is defined in terms of the processing of one's own emotions, it is also associated with atypical processing of others' emotions, such as a deficit in attention to emotional expressions. Research is yet to investigate, however, attention to others' expressions of interoceptive states and its relationship to the processing of these states in one's own body.

Method: The current study utilised a dot-probe paradigm to investigate early attentional orienting to others' interoceptive expressions, and its relationship to self-reported interoceptive accuracy and attention in 160 participants, aged 15 to 72 years. Images of non-interoceptive actions were utilised as control stimuli. This study also investigated age-related changes in interoception in the self and attention to others' interoceptive attention from adolescence to late adulthood.

Results: Whilst younger adults (under 40 years of age) had a significant attentional bias towards action, relative to neutral, body postures no such bias was observed for interoceptive expressions. Similarly, no relationship was observed between age and attention to others' interoceptive expressions.

Conclusions: Findings therefore did not support the hypothesis that attention to others' interoceptive states is associated with one's own interoceptive abilities or age, although replication utilising alternative measures of attention is required.

1. Introduction

Inferring how others feel is essential for successful social interactions and empathy and has been studied widely in the emotional domain. The end goal of determining another's emotion is a complex process involving multiple stages, such as attending to the individual's expressive cues (e.g., facial and vocal expressions, body posture and motion), perceptual processing of these cues, memory of perceptual cues, their configuration, and the previous contexts in which these cues have been associated, comparison of these cues to conceptual representations of emotions, categorising the expression alongside other similar expressions, and finally attributing a verbal label to the emotion (Adolphs, 2002; Spunt & Adolphs, 2019). As the first stage in this process involves attentional orienting to the other individual and their expressive cues, atypicalities at this stage are likely to lead to incorrect emotional inferences, even in situations where subsequent stages could have been implemented typically. Much research has therefore investigated attention to others' emotions, and the current study extends this work beyond the emotional domain, to investigate attention to others' non-emotional interoceptive states.

Attention refers to the orientation to certain stimuli, over others, for further processing or action. Presumably owing to their importance for social cognition, emotional stimuli typically capture more attention than non-emotional stimuli through increased salience throughout processing (Yiend, 2010). Much research has focused on individual differences in attention towards emotional stimuli, in particular its relationship with alexithymia (difficulties identifying and explaining one's own emotions, difficulties distinguishing emotions from internal bodily sensations, and an externally orientated cognitive style; Taylor et al., 2016). Attentional processing in alexithymia has been investigated in terms of early attentional processing, which occurs automatically without awareness or intention, and more recently through controlled attentional processing, which requires conscious and intentional effort (Luminet et al., 2021). As both early and later controlled attentional processing affect encoding and subsequent memory for emotional stimuli, the impact of a bias at each stage must be considered (Levine & Edelstein, 2009).

A recent meta-analysis concluded that the weight of the evidence points to a deficit throughout attentional processing of emotional stimuli in alexithymia (Luminet et al., 2021). This meta-analysis included studies which assessed attention to emotion concepts (e.g., emotional words in a Stroop task) and emotional expressions (e.g., images of emotional faces). Where others' emotional expressions are concerned, affective priming tasks have indicated reduced priming by congruent facial expressions in those with high alexithymia, consistent with a deficit in early attentional processing of others' emotions (Suslow et al., 2003; Vermeulen et al., 2006). Similarly, using an "Attentional Blink" paradigm, in which participants fail to identify the second of two targets presented closely together in time, Grynberg et al. (2014) reported an increased attentional blink (a greater delay following the first emotional target before the second target could be detected accurately) in those with high alexithymia. This was interpreted as indicative of a larger allocation of attentional resources to emotional stimuli, perhaps owing to slower processing of emotional expressions.

A widely used paradigm to assess early attentional processing is the dot-probe paradigm. In studies of emotion, participants briefly view an emotional and a neutral stimulus presented simultaneously on either side of a screen, immediately followed by a target on one side of the screen. Participants are instructed to indicate which side the target appeared on as quickly as possible. If attention is directed towards emotional stimuli, at the expense of neutral stimuli, response times should be lower when the target replaces the emotional stimulus than the neutral stimulus. While Pfabigan et al. (2014) reported no relationship between early attentional bias in a dot-probe task and alexithymia, a significant negative relationship was observed between alexithymia and P1 amplitudes during this task, suggesting reduced emotional reactivity at a neuronal level. Indeed, a meta-analysis also notes hyporesponsiveness in emotional attention systems (e.g., the amygdala) in alexithymic individuals when processing negative emotional stimuli, such as sad, angry, or fearful facial expressions (Van der Velde et al., 2013). Investigations into later controlled attention have primarily used eye-tracking methods to examine fixation points and dwell times whilst individuals view emotional expressions. While Sharpe et al., (2016) reported no effect of alexithymia on eye-tracking metrics when viewing neutral or emotional faces, Fujiwara (2018) reported reduced dwell time on the eyes in those with high alexithymia. In summary, whilst there are inconsistencies in the literature, individuals with high alexithymia do tend to demonstrate atypical attention to others' emotional expressions. Data on the causal nature of this relationship are lacking, but it is likely that the ability to understand one's own emotions may affect one's attention to others' emotional expressions, both during early orienting and later sustained processing.

Alexithymia has also been linked to atypical interoception, which is defined as the perception of, attention to, and propensity to use internal bodily signals (Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Internal bodily signals are thought to give rise to emotional experience (Barrett, 2014; Critchley & Nagai, 2012; Damasio, 1994; Damasio et al., 1991; Gendron & Feldman Barrett, 2009; Seth, 2013) and individuals with alexithymia have been found to display less accurate perception of a range of interoceptive signals, including cardiac signals (Herbert et al., 2011; Murphy et al., 2018; Shah et al., 2016), muscular effort, and taste (Murphy et al., 2018a), although findings have been mixed (Trevisan et al., 2019). Individuals with alexithymia also tend to self-report difficulties interpreting their interoceptive states (Brewer et al., 2016; Zamariola et al., 2018), potentially alongside higher attention to these states, although again, this is not always replicated (Gaggero et al., 2021; Trevisan et al., 2019).

While previous research has investigated the processing of one's own interoceptive signals, to date very little research has investigated the processing of non-emotional internal bodily states in others. One study found evidence for the ability to infer infection in others from facial images above chance (Axelsson et al., 2018), and another reported above chance ability to identify which of two individuals a heartbeat belongs to (Galvez-Pol et al., 2022). Beyond this, research has investigated the processing of others' pain. Gu et al. (2012) presented participants with images of hands and feet in painful and non-painful situations and reported decreased ability to distinguish painful and non-painful stimuli, alongside prolonged response times in individuals with anterior insular lesions, an area thought to play a key role in interoceptive processing (Craig, 2009). These individuals also demonstrated reduced implicit empathy for others' pain, lacking the normal inference effect of pain when asked to judge the laterality (left/right) of others' feet and hands. Recently, the time course of attentional bias to painful facial expressions has also been compared between individuals with chronic pain and healthy control participants (Mazidi et al., 2021). Probability analyses revealed that all participants had a greater likelihood of attending at first fixation to the painful expression, relative to a neutral expression, with no significant differences between groups. Despite this, as pain is thought to have both emotional and sensory component (Fernandez & Turk, 1992), and interoception is unlikely to be a unitary construct (Ferentzi et al., 2018), there is a need to investigate attention to a broader range of interoceptive states. Until recently (Biotti et al., 2021), however, photographic stimuli of actors posing interoceptive signals were not available with which to investigate processing of others' non-emotional interoceptive states. As alexithymia appears to be associated with decreased attention to others' emotional expressions (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013), and evidence suggests a relationship between alexithymia and atypical interoception, it is likely that interoceptive difficulties are associated with decreased attention to others' interoceptive expressions. In particular, reduced attention to one's own interoceptive states may be associated with reduced attention to others' interoceptive cues. Investigating early attentional orienting to others' interoceptive expressions is of critical importance as attention biases can influence subsequent processing, such as appraisal and memory (Adolphs, 2002; Spunt & Adolphs, 2019), which may affect social interactions and the ability to respond to and care for others.

The relationship between attention and ageing has been well documented. Research points to a positivity effect of ageing on attention; relative to younger adults, older adults have an attentional bias towards positive information over negative information (Carstensen & DeLiema, 2018). The effect does not appear to be explained by cognitive impairment or neural degradation and has been demonstrated across a variety of contexts including attention to others' emotional expressions. Using a dot-probe procedure, early research reported that older adults (over 52 years of age) were significantly quicker at responding to a target when it was preceded by a positive face, rather than a neutral face, but significantly slower at responding to a target when it was preceded by a negative face, rather than a neutral face (Mather & Carstensen, 2003); an effect which was not present in younger adults (under 52 years of age). In a later study, older and younger adults were presented with pairs of simultaneously presented neutral and emotional faces (Isaacowitz et al., 2006). Eye tracking indicated that, relative to neutral faces, older adults exhibited greater attention to happy faces, and reduced attention to angry faces, whereas younger adults showed increased attention to fearful faces. Whilst no research has investigated attention to others' interoceptive expressions in older age, there is some evidence for effects of ageing on attention to one's own interoceptive signals. Investigations utilising the Body Perception Questionnaire (BPQ; Porges, 1993) suggest that older adulthood is associated with decreased self-reported attention to one's internal signals (Murphy et al., 2018b), however, these findings are limited by potential interpretation issues with the BPQ (Gabriele et al., 2022). Encouragingly, recent research has also replicated these findings with the recently developed interoceptive attention scale (IATS; Gabrielle et al., 2022; Carr et al., *in prep*). It is worth noting that research has also investigated the relationship between ageing and interoceptive accuracy, reporting that ageing is associated with decreased objective interoceptive accuracy, at least in the cardiac domain (Murphy et al., 2018b; Khalsa et al., 2009). This relationship does not always pertain into self-reported interoceptive accuracy (Carr et al., *in prep*), however, perhaps owing to decreases in metacognitive insight (Palmer et al., 2014; Rogers et al., 2012), or to limitations of tasks assessing cardiac perception (Brener & Kluvitse, 1988; Corneille et al., 2020; Ring & Brener, 1992; Zamariola et al., 2018). Considering that interoceptive accuracy and attention are dissociable dimensions (Murphy et al., 2019, 2020; Gabrielle et al., 2022), and the interpretation issues with the BPQ, further research is clearly needed which assesses attention to interoceptive states in oneself and others across the lifespan.

The current study is the first to investigate attention to others' non-emotional interoceptive expressions, and age-related changes in this ability from adolescence to older adulthood. A dot-probe paradigm was utilised to assess individuals' implicit attentional bias to interoceptive states, compared to control (non-interoceptive action and neutral) body postures. Given that the timing characteristics of processing and inhibition of return are altered in typical ageing (Langley et al., 2007; Salthouse, 1996), and dot-probe paradigms have not previously been utilised with interoceptive expressions, participants completed the paradigm twice at two different stimulus presentation times (500ms and 800ms). For details of the dot-Probe piloting procedure which informed the selection of stimulus presentation times see Supplementary Materials 1. Self-report measures of one's own interoceptive accuracy and attention were also obtained. In line with the emotion literature, it was predicted that self-reported interoceptive attention would be positively correlated with attention to interoceptive expressions in others. As interoceptive attention and accuracy in the self are thought to be distinct constructs (Murphy et al., 2019, 2020; Gabrielle et al., 2022), self-reported interoceptive accuracy was predicted to be a poorer predictor of attention to others' interoceptive states. As the majority of interoceptive states in the current study can be considered negative in valence, and research reports a positivity bias with ageing, it was predicted that age would be negatively related to attention to others' interoceptive expressions. In line with research that outlines the effects of ageing on interoceptive abilities in the self, a negative relationship was also predicted between age and self-reported interoceptive attention, but age was not predicted to be related to self-reported interoceptive accuracy.

2. Method

2.1 Participants

189 participants were recruited (gender identity: 150 female, 35 male, 2 participants identifying as neither male nor female), ranging in age from 15.75 to 72.42 years (*M* = 29.45, *S.D* = 18.32). Participants were recruited from social media, the Royal Holloway, University of London, student body in exchange for course credit, and from the paid recruitment site, Prolific.com. Due to departmental policies, individuals with mental health conditions could not be excluded from participating. Individuals with mental health conditions were, therefore, removed from analyses retrospectively, leading to a final sample of 160 participants (gender identity: 126 females, 34 males), ranging in age from 15.75 to 72.42 years (*M* = 30.96, *S.D* = 19.34). Exclusions based on a history of mental illness were made to ensure that results were representative of the neurotypical population, and not driven by factors associated with mental health conditions. Six participants were excluded from the 500ms condition and one participant was excluded from the 800ms condition owing to their mean RT being greater than 1.96 SDs from the group mean RT in that condition (See Section 2.3 for more detail). IAS and IATS scores were excluded from analyses if the interpretation question for that questionnaire was answered incorrectly. After exclusions, there were a total of 132 participants for analyses included in the IAS analysis and 118 for analyses included in the IATS analysis (See Section 2.2.1 for more detail).

Ethical approval was obtained from Royal Holloway, University of London. In line with ethical guidelines, all participants provided informed consent prior to participation and received a full debrief upon completing the study.

All measures (see Section 2.2) were programmed using Gorilla.com and were completed online. Participants were only permitted to take part on a laptop or computer with a keyboard, to mitigate against any effect of different response actions (e.g., pushing a button compared to touching a screen; van Rooijen et al., 2017). The Dot-Probe Paradigm (see Section 2.22) was always presented prior to the questionnaires (see Section 2.21) to ensure that any effect was not the result of these priming participants to attend to interoceptive, rather than action, postures.

2.2 Measures

2.2.1 Self-reported interoceptive processing

The Interoceptive accuracy scale (IAS) was utilised to assess subjective interoceptive accuracy (Murphy et al., 2019). This scale measures participants' beliefs about their ability to perceive their interoceptive sensations accurately (e.g., I can always accurately perceive when by heart is beating fast). The scale is composed of 21 items, each relating to a sensation that has been described as interoceptive in nature. For each sensation, participants are required to rate their ability to perceive internal signals precisely, on a Likert Scale from 1 (Strongly Disagree) to 5 (Strongly Agree), with total scores ranging from 21 to 105. Higher IAS scores are indicative of higher subjective interoceptive accuracy. The IAS was found to have high reliability in the current sample (21 items; $\alpha = 0.88$).

In order to ensure that participants interpreted the questionnaire as intended, they were asked upon completion to indicate what they believe the questionnaire was asking them to report on: the accuracy with which they can perceive sensations, the attention they pay to said sensations, the frequency with which these sensations occur in their body, or another construct. If the participant did not correctly indicate that the questionnaire assessed interoceptive accuracy, their IAS data were removed from analyses.

The Interoceptive Attention Scale (IATS; Murphy et al., 2020) was utilised to assess subjective interoceptive attention. This scale measures participants' beliefs about the extent to which internal bodily signals are the subject of their attention (e.g., Most of the time my attention is focused on whether my heart is beating fast). The scale is composed of an identical set of 21 interoceptive sensations to the IAS. Participants are required to rate their attention to each sensation on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree, with total scores ranging from 21 to 105, and higher scores indicative of higher subjective interoceptive attention. The IATS was found to have high reliability in this sample (21 items; $\alpha = 0.90$).

Again, participants were asked what they believed the questionnaire was asking them to report on, using the question described above. IATS data were excluded for any participant who did not correctly identify that the questionnaire assessed interoceptive attention.

2.2.2 Dot-Probe attentional orienting task

Stimuli

In all trials, participants viewed static photographic stimuli (Biotti et al., 2021), depicting six actors (three male, three female) posing six internal states (cold, hot, fatigue, breathlessness, nausea, and itch), six actions (running, clapping, jumping, lifting, walking, and washing hands), and neutral body positions; see Figure 1 for sample stimuli. Due to the nature of the body postures assumed by the actors, stimulus images varied in the extent to which limbs were spread vertically and horizontally, with differences in spread potentially affecting salience of images. The height and width of each stimulus was therefore calculated, and these two dimensions were multiplied, to create an approximation of the area each image occupied. Independent samples *t*-tests revealed no significant difference between the area occupied by interoceptive and action stimuli, $t(70) = .763$, $p = .463$, suggesting the stimulus sets were well matched in this respect.

Procedure

Each trial began with a fixation cross in the centre of the screen, displayed for 500ms. The fixation cross was immediately replaced with two images of the same individual, one positioned on the left side of the screen and the other on the right side of the screen. One of the two images depicted a neutral body position and the other depicted either the actor posing an interoceptive state or an action. Interoceptive and action trials were randomly interspersed and equally frequent. Stimuli were either presented for 500ms or 800ms, with participants completing both presentation times in separate blocks. See Supplementary Materials 1 for details of the piloting procedure used to select Stimulus Presentation Times. Immediately following the offset of the stimuli, a target (an image of a frog) was presented on either the left or right side of the screen, replacing either the neutral stimulus or the interoceptive or action stimulus (See *Figure 1* for examples of stimuli). Participants were instructed to respond with the location of the target as quickly and accurately as possible, pressing “a” on their keyboard if the target appeared on the left and “l” if the target appeared on the right (See *Figure* 2 for a schematic representation of study procedure).

Figure 1. An example of each state, action and neutral posture depicted by one of the six actors. From a) to f), the depicted internal states are: breathlessness, cold, fatigue, hot, hungry, and itch. From g) to k) the depicted actions are: walking, clapping, jumping, lifting, running and washing hands. From m) to r) the actors depict neutral body positions.

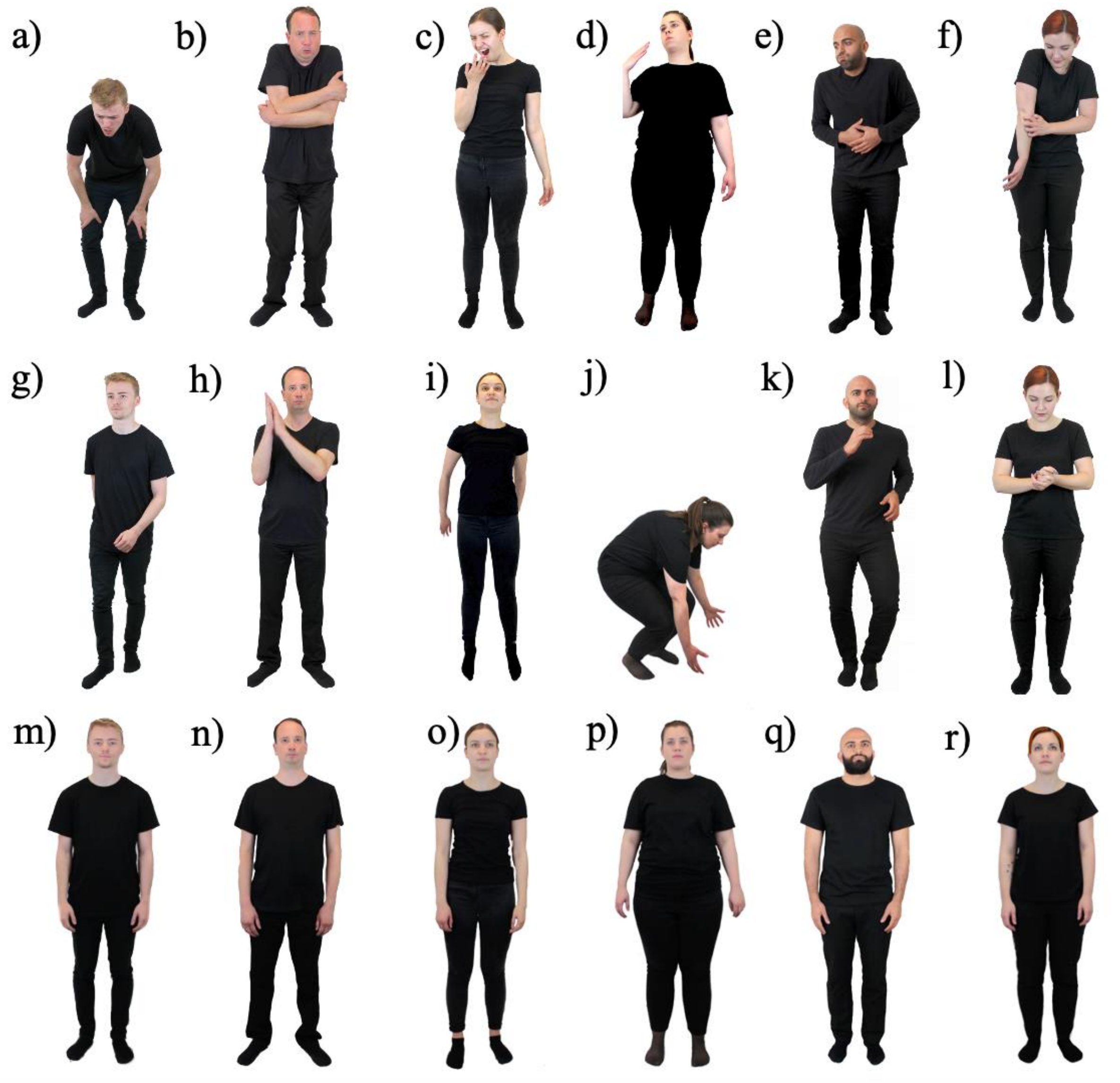
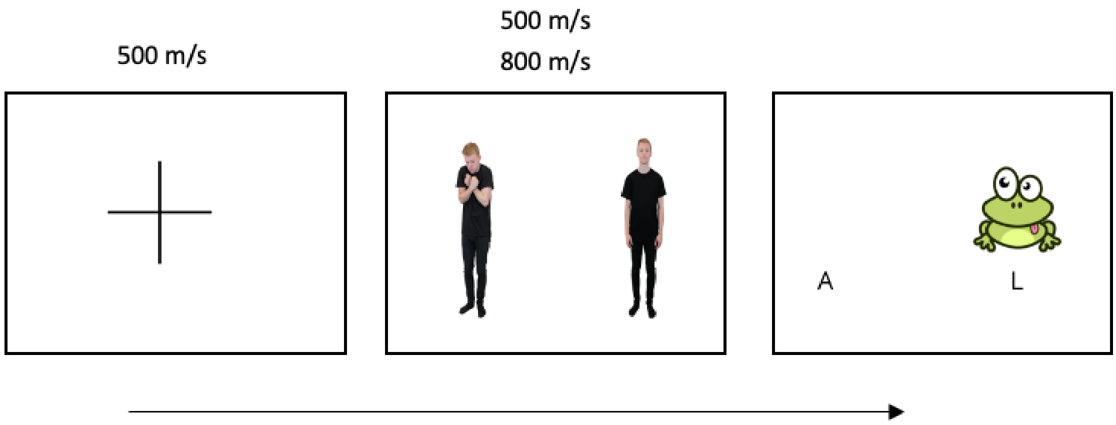


Figure 2. Schematic representation of the dot-probe task.



Each block consisted of 144 trials (six interoceptive + six action postures x six actors x two presentations), yielding a total of 288 trials, with one block for each stimulus presentation time (500ms or 800ms). Block order was counterbalanced across participants. In each block, the participant viewed each action and interoceptive stimulus twice, such that on one presentation the target replaced the non-neutral stimulus (interoceptive or action trials) and on the other the target replaced the neutral stimulus image (neural trials). Stimulus location and target location were pseudorandomised across trials, such that the interoceptive/action stimuli and the target appeared on the left and right sides of the screen equally frequently. 50% of participants viewed each stimulus on the left when preceding the target, while 50% viewed the same stimulus on the right when preceding the target, in two versions of the experiment. No significant differences were observed between participants completing these two versions of the experimental programme. Due to a technical error, a small number of participants only completed the 500ms block (22 participants) or 800ms block (15 participants). As these blocks were analysed separately, these participants remained in the final dataset.

To familiarise participants with the procedure, prior to the experimental blocks, participants completed six practice trials with a stimulus presentation time of 500ms, using two neutral body postures.

2.3 Analysis strategy

Incorrect responses were excluded from analyses. Participants' data were also excluded (separately for each stimulus presentation time block: 500ms and 800ms) if their mean RT (time to respond to the location of the target) across all trials was 1.96 SDs or more from the mean RT for that condition, across all participants, as inspection of histograms indicated a small number of extreme outliers. Overall mean RT was calculated for correct responses, and any trials with RTs 1.96 SDs or more above or below the individual participant's mean were removed from analyses. For each participant, across all interoceptive trials, the mean RT was then calculated separately for trials where the target replaced the interoceptive stimulus and trials where the target replaced the neutral stimulus. The same means were calculated for action trials (i.e., mean RT when the target replaced the action stimulus and mean RT when the target replaced the neutral stimulus).

Paired samples *t*-tests, or the non-parametric equivalent where assumptions were violated, were used to determine whether RTs differed when the target replaced the non-neutral and neutral stimuli, separately for interoceptive and action trials.

To attain a measure of attentional bias, mean RT when the target replaced the action or interoceptive body posture was deducted from mean RT when the target replaced the neutral body posture on those trials. Hereafter, these biases will be referred to as the 'action-neutral', and 'interoceptive-neutral bias', respectively. Positive bias scores indicate preferential attention toward interoceptive, or action postures compared to neutral postures whereas negative scores indicate attentional avoidance of interoceptive or action postures.

The difference in attentional bias towards interoceptive and action stimuli (the 'interoceptive-action bias') was also calculated (mean interoceptive-neutral bias minus mean action-neutral bias), with positive values indicative of a larger bias towards interoceptive stimuli than towards action stimuli, relative to neutral stimuli.

All bias values (interoceptive-neutral, action-neutral and interoceptive-action) were then correlated with self-reported interoceptive accuracy and attention. In order to ensure that individuals without a bias were not masking any effect, independent-samples *t*-tests analysing self-reported interoceptive abilities for participants with extreme biases away from (1st quartile) and towards (4th quartile) non-neutral stimuli across stimulus presentation times (500ms and 800ms) and biases (interoceptive-neutral and interoceptive-action) were conducted.

To determine the effect of age, correlational analyses were conducted with the three attentional bias values (interoceptive-neutral, action-neutral, interoceptive-action) and self-reported interoceptive attention and accuracy. As attentional processes have been found to change in late adulthood (Campbell et al., 2015; Hultsch et al., 2002; Marther & Carstensen, 2003; Ng & Chan, 2012) all analyses were repeated separately for younger (under 40 years of age) and older (over 60 years of age) adults to determine if the pattern of results differed with age.

Bayesian statistics were conducted to further explore results. Where hypotheses were directional one-tailed statistics are reported. Bonferroni correction was utilised throughout where appropriate to correct for multiple comparisons.

3. Results

3.1. Attention to others' interoceptive state displays

The normality of each variable was assessed with visual inspection of histograms and Kolmogorov-Smirnov tests with Lilliefors correction (Lilliefors, 1967). Where normality assumptions were violated, the relevant non-parametric test was employed (see Supplementary Materials *2* for all normality statistics).

Parametric (Paired-samples *t*-tests) or equivalent nonparametric analyses (Wilcoxon signed rank) revealed that there was not a significant difference in RT when the target replaced the interoceptive or neutral stimuli, on interoceptive-neutral trials, at a stimulus presentation time of 500ms or 800ms. Similarly, there was no difference in RT between trials when the target replaced the action and neutral stimuli, on action-neutral trials, at a presentation time of 500ms or 800ms (*Table 1*). Bayesian statistics supported all findings (all $BF_{10} \leq 0.165$), providing moderate support for the alternative hypothesis that there were no differences in RT between when the target replaced the action/interoceptive stimuli or the neutral posture at a stimulus presentation time of 800ms. Acedotal support was provided at a stimulus presentation time of 500ms.

Table 1. Paired-samples *t*-tests or Wilcoxon signed rank tests comparing RT when the target replaced the interoceptive or neutral postures (on interoceptive-neutral trials) and action or neutral postures (on action-neutral trials) for both stimulus presentation times (500ms or 800ms). *p* values are reported one-tailed, uncorrected for multiple comparisons.

Condition	Stimulus Presentation Time	Target Placement	Mean (ms)	SD (ms)	*t*	*Z*	*p*	BF_{10}
Interoceptive -Neutral	500ms	Interoceptive	403.73	80.83	0.968		0.335	0.150
		Neutral	405.59	79.66				
	800ms	Interoceptive	421.74	100.86		4495	0.619	0.098
		Neutral	420.92	100.95				
Action-Neutral	500ms	Action	403.85	76.11		5015	0.536	0.165
		Neutral	408.70	89.25				
		Action	422.12	104.11	0.289		0.773	
	800ms	Neutral	423.19	108.86				0.099

3.2 Self-reported interoceptive accuracy and attention

Visual inspection of histograms and Kolmogorov-Smirnov tests indicated that both IAS and IATS scores were normally distributed (see Supplementary Materials 2*)*. IAS scores ranged from 48 to 105 (M = 77.87, SD = 11.14), and IATS scores ranged from 22 to 99 (M = 53.97, SD = 13.49). Scores on the IAS and IATS were not correlated with each other, $r(97) = 0.134$, $p = 0.184$, $BF_{10} = 0.299$, in line with the distinction between interoceptive accuracy and attention.

3.3 The relationship between self-reported interoceptive abilities and attention to others' interoceptive states or actions

Correlational analyses revealed that attention to others' internal states was not associated with self-reported interoceptive accuracy or attention in either the 500ms or 800ms conditions, even before correcting for multiple comparisons. Unsurprisingly, there was also no relationship between self-reported interoception and attention bias on action trials (Table 2). Bayesian statistics supported all findings (all $BF_{10} \leq 0.414$). There was also no evidence of either a quadratic or cubic relationship between self-reported interoceptive accuracy and attention and attention to others' interoceptive states (all p's > 0.82).

Table 2. Correlations between attention bias scores and self-reported interoceptive accuracy and attention. *p* values are reported one-tailed, uncorrected for multiple comparisons.

	Interoceptive-Neutral Bias						Action-Neutral Bias						Interoceptive-Action Bias					
	IAS			IATS			IAS			IATS			IAS			IATS		
Presentation Time	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
500 m/s	-0.085	0.371	0.174	-0.046	0.321	0.137	-0.035	0.710	0.131	-0.060	0.550	0.148	-0.010	0.911	0.123	0.070	0.241	0.167
800 m/s	-0.077	0.414	0.163	'-0.064	0.266	0.152	-0.060	0.529	0.141	0.056	0.585	0.152	0.040	0.673	0.132	-0.005	0.481	0.131

3.4 A comparison of self-reported interoceptive abilities in participants with particularly high or low biases towards interoceptive expressions

To examine whether there were any differences in self-reported interoceptive abilities in the participants with the largest biases towards or away from interoceptive state displays, participants' Interoceptive-Neutral and Interoceptive-Action RT biases were split into quartiles, separately for the two presentation times. Participants in the 1st quartile had the largest bias away from interoceptive states/actions, and participants in the 4th quartile had the largest bias towards interoceptive states/actions. Independent-samples *t*-tests were then employed to assess whether there was a significant difference in self-reported interoceptive abilities between the two groups (Table 3). No significant difference was observed between the two groups' scores on the IAS or IATS for either presentation time, for either the interoceptive or action condition. Bayesian statistics supported all non-significant findings (all BF_{10} $\leq$ 0.306).

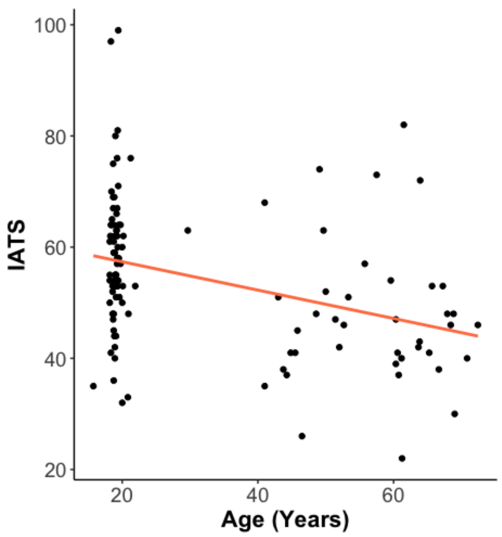
Table 3. Independent-samples *t*-tests analysing self-reported interoceptive abilities for participants with extreme biases away from (1st quartile) and towards (4th quartile) interoceptive expressions/actions. *p* values are reported one-tailed, uncorrected for multiple comparisons.

Condition	Stimulus Presentation Time	Questionnaire	Quartile	Mean (ms)	SD (ms)	*t*	*p*	BF_{10}
Interoceptive -Neutral	500m/s	IAS	1st	77.34	8.81	0.527	0.601	0.306
			4th	75.92	10.82			
		IATS	1st	52.27	9.5	-0.350	0.728	0.300
			4th	53.35	11.64			
	800m/s	IAS	1st	76.70	8.34	-0.041	0.968	0.267
			4th	76.81	12.21			
		IATS	1st	53.61	10.32	0.304	0.763	0.294
			4th	52.59	10.96			
Interoceptive -Action	500m/s	IAS	1st	80.12	10.84	0.274	0.785	0.285
			4th	79.30	11.42			
		IATS	1st	51.17	9.67	-0.120	0.905	0.292
			4th	51.61	14.69			
	800m/s	IAS	1st	75.79	16.57	-0.233	0.817	0.282
			4th	76.46	12.24			
		IATS	1st	53.5	17.24	0.326	0.746	0.296
			4th	52.27	12.19			

3.5 The relationship between age, attention biases, and self-reported interoceptive abilities

IATS scores were significantly negatively correlated with age, $r(115) = -0.338$, $p < 0.001$, $BF_{10} = 76.170$, such that older participants reported paying less attention to their own interoceptive signals (Figure 3). IAS scores, assessing interoceptive accuracy, were not related to age, $r(126) = 0.054$, $p = 0.550$, $BF_{10} = 0.128$.

Figure 3. Significant negative correlation between age and self-reported interoceptive attention.



Correlational analyses revealed that all interoceptive-action and interoceptive-neutral biases in the dot-probe task were unrelated to age. Bayesian statistics supported all findings (all $BF_{10} \leq$ 0.496), providing anecdotal/moderate support for the alternate hypothesis that age was unrealted to attention biases in the processing of interoceptive and action postures. Action-neutral biases were not related to age at a presentation time of 500ms, however they were significantly related to age at the 800ms presentation time. This relationship fell below significance, however, once correcting for multiple comparisons (*Table 4*). A Bayesian correlation indicated that the experimental hypothesis was 3.022 times more likely to be true than the null hypothesis, supporting the theory that age was negatively related to a bias for action over neutral stimuli, on action-neutral trials.

Table 4. Correlational analyses showing the relationship between age and all attentional biases. *p* values are reported one-tailed uncorrected for multiple comparisons.

Attentional Bias	Stimulus Presentation Time	*r*	*p*	BF_{10}
Interoceptive-Neutral	500m/s	-0.018	0.420	0.115
	800m/s	-0.144	0.051	0.425
Action-Neutral	500m/s	-0.229	0.008	3.022
	800m/s	0.123	0.164	0.296
Interoceptive-Action	500m/s	0.114	0.098	0.245
	800m/s	-0.157	0.037	0.496

Ageing is associated with decreased attentional control, indexed through increased variability in RTs (Campbell et al., 2015; Hultsch et al., 2002), and decreased response speed to visual stimuli in adults over 40 years of age (Ng & Chan, 2012). As the current task is likely sensitive to response speed and levels of attentional control, analyses were repeated excluding participants over 40 years of age. This resulted in a sample of 100 younger adult participants ranging in age from 15.75 to 29.67 years (M = 19.21 years, SD = 1.299).

Paired-samples *t*-tests revealed that there was not a significant difference in RT when the target replaced the interoceptive or neutral stimuli on interoceptive-neutral trials at a stimulus presentation time of 500 or 800ms (Table 5). However, participants were significantly faster at responding to the target when it replaced the action posture, compared to when it replaced the neutral posture, at both 500 and 800ms (Table 5). Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 0.573$). A Bayesian correlation indicated that the experimental hypothesis was 2.539 times more likely to be true than the null hypothesis, supporting the theory that younger adult participants (all under the age of 30 years) have a bias towards action, over neutral postures, at a stimulus presentation time of 500ms.

Table 5. Paired-samples *t*-tests comparing RT on interoceptive-neutral and action-neutral trials, at 500 and 800ms presentation times, for participants under 30 years of age. *p* values are reported one-tailed, uncorrected for multiple comparisons.

Condition	Stimulus Presentation Time	Target Placement	RT Mean (ms)	RT SD (ms)	Test Statistic *t*	*p*	BF_{10}
Interoceptive -Neutral	500ms	Interoceptive	382.58	75.54	1.817	0.073	0.573
		Neutral	386.74	81.47			
	800ms	Interoceptive	394.30	80.34	0.230	0.819	0.123
		Neutral	394.95	83.44			
Action-Neutral	500ms	Action	378.85	65.93	**2.559**	**0.012**	**2.539**
		Neutral	385.69	74.94			
	800ms	Action	392.84	84.12	0.435	0.664	0.141
		Neutral	396.00	96.92			

Bold text is indicative of statistical significance

Correlational analyses revealed that attention to others' interoceptive states (interoceptive-neutral bias) was not associated with self-reported interoceptive accuracy or attention in either the 500ms or 800ms condition, even before correcting for multiple comparisons. There was also no relationship between self-reported interoception and attention bias on action trials (Table 6). Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 0.438$), offering moderate support for the alternative hypothesis that attention to others' interoceptive states is unrealted to the processing of these states in one's own body.

Table 6. Correlations between attention bias scores and self-reported interoceptive accuracy and attention in participants under 30 years of age; *p* values are reported one-tailed, uncorrected for multiple comparisons.

	Interoceptive-Neutal Bias						Action-Neutral Bias						Interoceptive-Action Bias					
	IAS			IATS			IAS			IATS			IAS			IATS		
Presentation Time	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
500 m/s	-0.143	0.239	0.295	-0.139	0.132	0.281	0.032	0.795	0.154	-0.169	0.172	0.380	0.048	0.617	0.173	0.062	0.308	0.181
800 m/s	-0.095	0.446	0.203	-0.112	0.193	0.229	-0.010	0.934	0.159	0.168	0.192	0.438	-0.040	0.747	0.177	-0.067	0.303	0.193

When these analyses were repeated in a group of older adults (≥ 60 years of age), no significant attentional biases were observed, and biases were unrelated to self-reported interoception (see Supplementary Materials 3).

4. Discussion

The current study was the first to investigate implicit and automatic attention to others' interoceptive expressions, and its relationship with self-reported interoceptive abilities. In a dot-probe paradigm, no significant difference in response speed was observed on trials when the target replaced the neutral or interoceptive posture, suggesting that participants did not have an attentional bias towards or away from interoceptive expressions, across two stimulus presentation times (500ms and 800ms). When only younger adult participants (under 30 years of age) were analysed, however, responses were significantly faster when the target replaced the action than when it replaced the neutral posture, indicating an attentional bias towards action postures at both stimulus presentation times. Encouragingly, this suggests that body postures can be used in dot-probe paradigms to capture biases in early orienting attention but raises interesting questions on the processing speed of actions and interoceptive expressions. The current study found no evidence for a relationship between biases towards others' interoceptive states or actions, and either self-reported interoceptive abilities or age. It therefore seems that attention to others' interoceptive expressions is not affected by ageing or the processing of one's own interoceptive states. Given that this is the first investigation of its type, however, and the lack of attentional biases reported on interoceptive-neutral trials, factors for consideration in future research are discussed below.

The processing of others' interoceptive expressions is presumably important for social communication and providing necessary care; failing to respond appropriately when another individual is hungry, tired, or unwell may impede one's ability to build successful relationships. Considering the likely impact of early attentional orienting on subsequent stages of processing (Adolphs, 2002; Spunt & Adolphs, 2019), understanding biases in automatic attention to interoceptive expressions is crucial. Whist attention to others' interoceptive expressions has not been studied previously, experimental paradigms designed to assess attention are well documented in the emotion literature. Dot-probe paradigms are commonly used to study attention to others' emotions, but it is worth noting that the current study presented interoceptive expressions using whole body postures, rather than isolated facial expressions, which are most frequently utilised in the emotion literature. Body postures are a useful source of information when inferring another's state (de Gelder et al., 2010, 2015), and the processing of facial and body expressions appear to follow similar time courses. For example, facial (Hinojosa et al., 2015) and bodily (Borhani et al., 2015, 2016) expressions of emotion give rise to N170 and N190 event-related potentials respectively, suggesting that early perceptual processing occurs at a similar time point. Similarly, at a later stage of processing (approximately 300ms post-stimulus onset) both negative facial expressions (Bayer & Schacht, 2014; Rellecke et al., 2012; Valdés-Conroy et al., 2014) and fearful body postures (Borhani et al., 2015) result in pronounced early posterior negativity (EPN), thought to index visual attention and early encoding (Schacht & Sommer, 2009; Schupp et al., 2004). These findings suggest that as with facial expressions, dot-probe paradigms should successfully capture early orienting attentional biases in the processing of body postures. Indeed, in younger adults, the current data suggest an attentional bias towards action, over neutral body postures. As a similar bias was not observed towards others' interoceptive expressions, the current findings imply that either no such bias exists, or it was not captured in the current paradigm, potentially owing to an altered time course in the processing of interoceptive whole body expressions. Here it is worth noting that whilst hypothesis testing indicated no significant effect, probability analyses only suggested anecdotal evidence for the null hypothesis. Given that previous research using bodily expressions of emotion has observed modulation of the EPN at 290-350ms post-stimulus onset (Borhani et al., 2016), processing of interoceptive body postures may occur along a similar time course. If so, even within the shortest presentation time in the current study, attention may be initially captured by the interoceptive stimuli and then redistributed before the target onset, reducing detection of initial attentional bias. Replication of the current paradigm across shorter stimulus presentation times is therefore required to determine whether attentional biases exist at very early processing stages. It is worth noting that during piloting, a stimulus presentation time of 300ms did not elicit a significant bias towards interoceptive body postures. A larger range of presentation times is therefore needed to further delineate the time course of processing (for example ranging in 100ms increments between 100 and 500ms), and in a larger sample.

It is also worth noting that, due to the restriction on in person testing, the current study was completed online and therefore relies on RT as its dependent variable, which may be lacking in reliability (Chapman et al., 2019). The use of eye tracking in future investigations would enable analysis of participants' first fixation, total number of fixations, and dwell time, providing further insight into attentional allocation. Interestingly, investigations using eye tracking to measure the processing of painful facial expressions report initial fixation on painful stimuli, followed by avoidance, across a 500ms presentation time (Mazidi et al., 2021). It is possible that a similar pattern of attentional orienting exists for a range of interoceptive expressions. Utilising electroencephalography (EEG) during the dot-probe task would also enable greater understanding of the time course underlying the processing of others' interoceptive expressions. When EEG has been utilised alongside dot-probe procedures, this has unveiled a relationship between alexithymia and attention to others' emotions that was not present when considering the behavioural data in isolation (Pfabigan et al., 2014). Including neuroimaging techniques may, therefore, reveal a relationship between the processing of one's own interoceptive states and attention to others' interoceptive expressions that is not detectable at the behavioural level in this task.

No relationship was observed between age and attention to interoceptive expressions or actions over neutral body postures. This is surprising given that older adults are more likely to recall and attend to positive than negative emotional information (Carstensen & DeLiema, 2018), and the majority of interoceptive expressions utilised can be considered negative in valence. Again, however, it is possible that attentional biases towards interoceptive cues change with age, but that the employed experimental paradigm was not sensitive to these biases. As ageing is thought to be associated with decreased attentional control (Campbell et al., 2015; Hultsch et al., 2002), it might be that older adults struggled to maintain or direct attention throughout the current dot-probe task. In support of this hypothesis, a bias towards action postures was observed in younger adults which was not present in this group. Perhaps, therefore, the paradigm is not appropriate for use in older adults, and again techniques such as eye tracking and EEG would provide more valid evidence concerning the processing of interoceptive expressions at this age. Considering that a shift in attention away from interoceptive information is likely to affect later processing stages including memory and retrieval (Adolphs, 2002; Spunt & Adolphs, 2019), and that social networks and cognition have been found to decrease with ageing (Cullum et al., 2000; Natelson Love & Ruff, 2016; Wrzus et al., 2012), future research into age-related changes in attention to others' interoceptive expressions using a range of experimental paradigms is required.

Beyond attention to others' interoceptive expressions, the current study also investigated the relationship between age and self-reported ability to perceive and attend to one's own interoceptive states. Whilst no association was observed between self-reported interoceptive accuracy and age, older participants reported paying less attention to their own internal bodily signals, in line with previous findings (Murphy et al., 2018b; Carr et al., *in prep.*). As this finding is correlational in nature, potential explanations are speculative, but as age is associated with increased vulnerability to physical discomfort and physical health issues, reducing attention to interoceptive signals may act as a compensatory mechanism to reduce anxiety concerning one's health. The lack of association between self-reported interoceptive accuracy and age also replicates previous findings (Carr et al., *in prep.*), despite objective measurements pointing to decreasing accuracy with age, at least in the cardiac domain (Khalsa et al., 2009; Murphy et al., 2018b). This result is somewhat unsurprising given that general metacognition decreases with increasing age (Palmer et al., 2014; Rogers et al., 2012), meaning this discrepancy may reflect of a lack of interoceptive insight. Alternatively, as the validity of objective cardiac perception measures utilised in previous studies has been questioned (Brener & Kluvitse, 1988; Corneille et al., 2020; Ring & Brener, 1992; Zamariola et al., 2018), and interoceptive accuracy is likely to fractionate across interoceptive signals (Ferentzi et al., 2018), it is possible that interoceptive accuracy is stable across the lifespan for some internal signals but not others. Investigation of the effects of ageing on objective interoceptive accuracy across multiple interoceptive domains is therefore required. Recent conceptualisations of interoception outline the multiple dimensions with which it can be measured, advocating for future research to incorporate as many of these as possible (Suksasilp & Garfinkel, 2022). Of course, whilst self-report methods are useful as they assess a range of interoceptive states and may capture many of the day-to-day difficulties faced by individuals outside of the laboratory, their correlation with objective measures is relatively small (Murphy et al., 2019). Therefore, employing both objective and self-report measures in the same individuals throughout adulthood will shed further light on changes in interoceptive abilities, including metacognitive insight, across the lifespan.

In summary, the current study was the first to investigate implicit attention to others' interoceptive expressions and actions. Whilst younger adults exhibited an attentional bias towards action postures, no such bias was observed towards others' interoceptive whole body expressions. Similarly, no relationship was reported between attentional biases towards interoceptive states or actions and either self-reported interoceptive abilities or age. The current findings therefore suggest that attention to others' interoceptive expressions is unaffected by the processing of these states in oneself and advancing age. However, as this is the first investigation of its type, and given the likely importance of processing interoceptive expressions in social communication and providing effective care, further work is needed to further elucidate these relationships. In particular, future research should investigate the time course of potential attentional biases to interoceptive expressions using techniques such as eye tracking and EEG. Future research should also employ a range of objective and self-report measures of interoceptive processing, across multiple interoceptive channels, to further delineate the relationship between the processing of interoceptive states in oneself, and its relationship with attention to others' interoceptive expressions and age.

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Supplementary Materials

Supplementary Materials 1. Pilot Dot-Probe Attentional Orienting Task

A pilot study was conducted with 24 participants, ranging in age from 18 to 21 years, to trial three stimulus presentation times (300ms/500ms/800ms). The Dot-Probe procedure was identical to that outlined in Section 2.2, but an additional interoceptive state (pain) and action (twirling) were depicted. Internal state depictions consisted of cold, hot, fatigue, breathlessness, nausea, pain, and itch, whereas action depictions included running, clapping, jumping, lifting, walking, washing hands, and twirling. Participants also completed three blocks of the task, one for each stimulus presentation time (300ms/500ms/800ms), rather than the two stimulus presentation times (500ms/800ms) outlined in Section 2.2.

Paired-samples *t*-tests revealed that there was not a significant difference in RT when the target replaced the interoceptive or neutral stimuli, on interoceptive-neutral trials, at a stimulus presentation time of 300ms, 500ms, or 800ms. Similarly, there was no difference in RT between trials when the target replaced the action and neutral stimuli, on action-neutral trials, at a presentation time of 300ms, 500ms or, 800ms (Table S1).

Table S1. Paired-samples *t*-tests comparing RT when the target replaced the interoceptive or neutral postures (on interoceptive-neutral trials) and action or neutral postures (on action-neutral trials) for both stimulus presentation times (300ms, 500ms, or 800ms). *p* values are reported one-sided, uncorrected for multiple comparisons.

Condition	Stimulus Presentation Time	Target Placement	Mean (ms)	SD (ms)	*t*	*p*
Interoceptive -Neutral	300ms	Interoceptive	363.35	68.42	1.042	0.308
		Neutral	366.79	64.07		
	500ms	Interoceptive	349.34	47.9	1.483	0.152
		Neutral	353.37	49.41		
	800ms	Interoceptive	383.73	64.58	1.148	0.264
		Neutral	378.60	60.34		
Interoceptive - Action	300ms	Action	363.73	65.01	0.700	0.491
		Neutral	360.78	54.50		
	500ms	Action	354.14	50.31	-0.297	0.769
		Neutral	354.89	47.81		
	800ms	Action	384.62	63.76	1.213	0.238
		Neutral	377.90	70.89		

Analyses were then conducted separately for each stimulus category, to determine whether the response pattern was similar across all categories, or whether any individual state or action may be masking an attentional effect, by exhibiting attentional effects in the opposite direction.

Interestingly, pain stimuli appeared to elicit different attentional effects to other internal states (see Table S2).

Table S2. RT for pain-neutral trials when the probe replaces the pain and neutral stimulus at a presentation time of 300, 500, and 800 ms.

Stimulus Presentation Time	Target Placement	Mean (ms)	SD (ms)
300m/s	Pain	356.46	65.28
	Neutral	369.14	73.97
500m/s	Pain	358.46	64.13
	Neutral	339.87	64.12
800m/s	Pain	377.96	61.49
	Neutral	363.28	80.32

RTs for all interoceptive states except pain were numerically lower when the target replaced the interoceptive stimuli than the neutral stimuli. On pain trials, however, RTs were lower when the target replaced the neutral stimulus than the pain stimulus. Given that pain is a complex interoceptive signal, including both emotional and sensory components (Fernandez & Turk, 1992), it was removed from the set of internal state stimuli. To balance stimulus sets, twirling was subsequently removed as depictions included greater spread of the limbs, both vertically and horizontally, from the neutral body posture compared to other internal states and control actions, which is likely to increase attentional capture. As outlined in Section 2.22, the final stimulus set included actors depicting breathlessness, cold, fatigue, hot, nausea and itch as internal states, and walking, clapping, jumping, lifting, running, and washing hands as actions.

Paired-samples *t*-tests were repeated excluding pain and twirling trials to investigate whether the paradigm then yielded significant differences in RT on internal state trials. Indeed, a significant difference in RT was then observed when the target replaced the interoceptive (M = 341.58) or neutral (M = 353.71) stimuli on interoceptive-neutral trials, at a stimulus presentation time of 500ms, $t(24) = -2.471$, $p = 0.22$.

With this in mind, 500ms was selected as the fastest stimulus presentation time. As older adults were included in the sample (see Section 2.1) and ageing is associated with decreased attentional control, indexed through increased variability in RTs (Hultsch et al., 2002; Campbell et al., 2015), and decreased response speed to visual stimuli (Ng & Chan, 2012), a stimulus presentation time of 800ms was also included.

Supplementary Materials 2. Kolmogorov-Smirnov test statistic and significance values for all variables.

Variable	*K-S*	*p*
IAS Total	0.081	0.200
IATS Total	0.101	0.072
Action (No target, 500ms)	0.124	0.008
Interoceptive (No target, 500ms)	0.086	0.200
Action (Target, 500ms)	0.105	0.052
Interoceptive (Target, 500ms)	0.090	0.200
Action (No target, 800ms)	0.092	0.200
Interoceptive (No target, 800ms)	0.120	0.012
Action (Target, 800ms)	0.097	0.094
Interoceptive (Target, 800ms)	0.103	0.060
Action - Neutral Bias (500ms)	0.320	< 0.001
Interoceptive-Neutral Bias (500ms)	0.102	0.063
Action-Neutral Bias (500ms)	0.165	< 0.001
Interoceptive-Neutral RT Bias (800ms)	0.073	0.200
Interoceptive-Action 500ms	0.211	< 0.001
Interoceptive-Action 800ms	0.172	< 0.001

Supplementary Materials 3. Analyses with participants over 60 years of age.

Analyses with only participants over 60 years of age were run to assess whether results differed between the two groups. This resulted in a sample of 25 participants, ranging in age from 60.33 to 72.42 years of age (*M* = 65.23, *SD* = 3.66).

Paired-samples *t*-tests revealed that there was not a significant difference in RT when the target replaced the interoceptive or neutral stimuli on interoceptive-neutral trials, or the action or neutral stimuli on interoceptive-action trials, at a stimulus presentation time of 500 or 800ms (Table S3). Bayesian statistics supported all non-significant findings (all BF_{10} 0.358).

Table S3. Paired-samples *t*-tests comparing RT on interoceptive-neutral and action-neutral trials, across both 500 and 800ms presentation times, for participants over 60 years of age. *p* values are reported one-tailed, uncorrected for multiple comparisons.

			RT		Test Statistic		
Condition	Stimulus Presentation Time	Target Placement	Mean (ms)	SD (ms)	*t*	*p*	BF_{10}
Interoceptive -Neutral	500ms	Interoceptive	447.26	73.07	0.458	0.652	0.250
		Neutral	448.98	67.23			
	800ms	Interoceptive	448.92	77.48	0.160	0.875	0.235
		Neutral	449.41	77.02			
Action-Neutral	500ms	Action	451.73	68.98	-1.011	0.324	0.358
		Neutral	449.24	67.21			
	800ms	Action	450.42	74.53	0.048	0.962	0.235
		Neutral	450.98	82.42			

Correlational analyses revealed that attention to others' internal states was not associated with self-reported interoceptive accuracy or attention in either the 500ms or 800ms condition, even before correcting for multiple comparisons. There was also no relationship between self-reported interoception and attention bias on action trials (Table S4). Bayesian statistics supported all non-significant findings (all $BF_{10} \leq 0.662$).

Table S4. Correlations between attention bias scores and self-reported interoceptive accuracy and attention in participants over 60 years of age. *p* values are reported uncorrected for multiple comparisons. *p* values are reported one-tailed, uncorrected for multiple comparisons.

	Interoceptive-Neutal Bias						Action-Neutral Bias						Interoceptive-Action Bias					
	IAS			IATS			IAS			IATS			IAS			IATS		
Presentation Time	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
500 m/s	0.105	0.689	0.323	0.189	0.234	0.282	0.051	0.845	0.305	-0.243	0.347	0.451	0.073	0.780	0.311	0.333	0.096	0.662
800 m/s	-0.421	0.092	1.112	0.069	0.397	0.309	0.002	0.994	0.300	0.130	0.618	0.336	0.296	0.249	0.554	0.160	0.270	0.357

Chapter 6. Study Four: Memory Bias for interoceptive expressions, over actions, and its relationship with self-reported interoceptive accuracy and attention.

Memory Bias for interoceptive expressions, over actions, and its relationship with self-reported interoceptive accuracy and attention.

Lara Carr, Dawn Watling and Rebecca Brewer

Abstract

Background: Interoception refers to the perception of, attention to, and propensity to use one's internal bodily signals (e.g., heart rate, breathlessness, temperature). While individual differences in the ability to process one's own emotional states have been associated with memory for others' emotional expressions, research is yet to investigate memory for others' interoceptive expressions and its relationship with the processing of one's own interoceptive states.

Method: 168 participants, ranging in age from 18 to 47 years, viewed images of actors expressing interoceptive states (e.g., breathlessness, nausea) and actions (e.g., running, clapping) and then completed an unexpected recognition memory task, in which they were asked whether they had viewed each stimulus previously. Memory for interoceptive expressions and actions, bias towards memory for interoceptive expressions, and its relationship with self-reported interoceptive processing were investigated.

Results: No significant difference between long-term memory for interoceptive and action postures was observed. Results also did not indicate a relationship between the processing of interoceptive states in oneself and memory for others' interoceptive expressions.

Conclusions: Findings suggest that interoceptive states have no memory advantage over actions, and that memory for interoceptive expressions is unrelated to the processing of these states in oneself. The implications of these findings for social cognition and future research directions are discussed.

1. Introduction

Interoception refers to the perception of, attention to, and propensity to use internal bodily signals across both conscious and unconscious levels of cognition (Khalsa et al., 2018; Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Contemporary definitions highlight the multidimensional nature of interoception, including different facets of interoceptive ability (e.g., attention, accuracy, and metacognitive insight), measurement types (e.g., objective performance tasks and beliefs about one's abilities), and interoceptive signal channels (e.g., cardiac, respiratory, gastric). While early definitions of interoception were restrictive, only including signals which originated in the viscera (e.g., heart rate, breathlessness, hunger; Sherrington, 1948), many recent definitions include a vast range of bodily signals, including those that are seemingly less internal in nature (e.g., itch and affective touch), each of which is processed by a common neural substate, terminating in the anterior insula cortex (AIC) or anterior cingulate cortex (ACC; Craig, 2003, 2009). Whilst the conceptualisation of interoception continues to be debated (Garfinkel & Critchley, 2013), the current paper utilises this broad definition in line with the majority of recent literature.

Interoception is thought to play a role in a range of cognitive abilities, including emotion processing (Barrett, 2014; Critchley & Nagai, 2012; Damasio, 1994; Damasio et al., 1991; Gendron & Feldman Barrett, 2009; Seth, 2013), learning and decision making (Dunn et al., 2010; Kandasamy et al., 2016; Werner et al., 2009), advantageous risk taking (Kandasamy et al., 2016), attention (Matthias et al., 2009) and memory (Garfinkel et al., 2013; Pollatos & Schandry, 2008; Werner et al., 2010). Memory refers to the process of acquiring, storing, retaining, and later retrieving information. Individual differences exist throughout this process, including in the way that events are initially experienced, subsequently encoded, and then later retrieved (Kensinger, 2009). Of interest to the current investigation is memory for others' internal states, as reduced memory for others' interoceptive expressions may affect social relationships and caring ability. If, for example, one does not remember interoceptive expressions seen in a particular context (e.g., expressions of satiety following a meal), one's ability to build a conceptual representation of satiety in others may be compromised. Similarly, if a parent fails to notice that over the course of a week their child has expressed a range of atypical interoceptive signals, they may not seek medical advice for the child where appropriate.

Where the role of interoception in memory has been investigated, research tends to have focused on memory for emotional information. Individuals with higher interoceptive accuracy, measured using the Heartbeat Counting Task (HCT; Schandry, 1981), have superior memory for positive and negative words than those with lower interoceptive accuracy (Werner et al., 2010), an effect which did not extend into neutral words. Evidence also suggests an effect of the cardiac cycle on memory for emotional words, such that words presented at diastole (relaxation of the heart following contraction) were better remembered than those at systole (contraction of the heart; Garfinkel et al., 2013). The impact of cardiac cycle appears to be greater in individuals with low interoceptive accuracy, as indexed by the HCT, with a greater reduction in memory for positive and negative words presented at systole in these individuals. Individuals with greater cardiac interoceptive accuracy (again measured using the HCT) also appear to possess superior recall for emotion-inducing images (Pollatos & Schandry, 2008); memory for neutral images did not vary as a function of cardiac interoceptive accuracy. Although the superior recall effect was likely driven by better detection of one's own interoceptive changes induced by the pleasant and unpleasant stimuli, it should be noted that individuals with greater interoceptive accuracy also displayed greater heart rate changes in response to the emotion-inducing stimuli, meaning cardiac signals may have been more salient and easier to detect in these individuals (Pollatos & Schandry, 2008). Existing research therefore suggests that interoceptive abilities may play a role in memory, at least for emotional stimuli, perhaps owing to these stimuli evoking interoceptive changes. Notably, reliance on the HCT is problematic due to a number of methodological issues (for thorough reviews see Brener et al., 2016; Corneille et al., 2020; Zamariola et al., 2018), meaning replication utilising alternative measures of interoceptive accuracy is required.

Relatedly, a body of work has investigated the relationship between alexithymia (difficulties describing and identifying one's own emotional states) and memory for emotional stimuli. The majority of investigations have examined the association between alexithymia and memory for emotive words, reporting decreased memory for emotional words in those with high alexithymia, which did not pertain for neutral words (Luminet et al., 2006; Meltzer & Nielson, 2010; Vermeulen & Luminet, 2009). High alexithymia also appears to be associated with reduced memory for emotional faces and scenes (DiStefanio & Koven, 2012; Donges & Suslow, 2015; Ridout et al., 2021) and for changes in facial expression (Takahashi et al., 2015). It is worth noting that some of the effects were limited to specific expressions, such as anger or fear, rather than happy or neutral (Donges & Suslow, 2015; Ridout et al., 2021), but this may simply be due to happiness being a more physically distinctive expression (Brewer et al., 2015) and neutral expressions posing less of a recognition challenge for those with alexithymia. Research in the domain of emotion therefore suggests that not only understanding of one's own emotions, but also one's own interoceptive abilities, are associated with memory for others' emotions. Although processing of emotions and interoceptive signals are closely related (Brewer et al., 2016; Herbert et al., 2011; Murphy et al., 2018; Zamariola et al., 2018) due to a lack of appropriate stimuli, research is yet to investigate the relationship between interoception in the self and memory for others' interoceptive expressions, such as expressions of nausea, breathlessness, and fatigue.

This study was the first to investigate memory for interoceptive expressions, as well as any differences in memory for interoceptive and action postures, when posed by the same actors. Self-reported interoceptive abilities were also examined, allowing investigation of the relationship between self-reported interoceptive accuracy and attention, and memory for interoceptive expressions. Given the close relationship between the processing of interoceptive and emotional states, and evidence of decreased memory for emotional stimuli in alexithymia and those with poorer interoceptive accuracy, a positive relationship was predicted between self-reported interoceptive accuracy and memory for interoceptive expressions. This study also investigated whether attention to one's own interoceptive states was associated with memory for others' interoceptive states, although as previous work has not investigated this relationship, no directional predictions were made.

2. Method

2.1 Participants

A total of 168 participants were recruited (gender identity: 145 females, 22 males, 1 participant who identified as neither male nor female) ranging in age from 18.00 to 47.17 years (*M* = 19.77 years, *SD* = 2.75). As participants were recruited from the Royal Holloway, University of London student body in exchange for course credit, departmental policies meant that individuals with mental health conditions were not excluded from participating but were removed from the sample retrospectively, leading to the exclusion of 47 participants. Exclusions based on a history of mental illness were made to ensure that results were representative of the neurotypical population, and not driven by factors associated with mental health conditions. Participants were also excluded if they made more than three errors on the gender assignment task (see details of memory task below), leaving a final sample of 114 participants (gender identity: 100 females, 14 males), ranging in age from 18.00 to 47.17 years (*M* = 19.62 years, *SD* = 3.02). IAS and IATS scores were excluded if the interpretation question was answered incorrectly, resulting in a final total of 94 IAS responses and 87 IATS responses for subsequent analyses (See section 2.2.1 for more detail).

Ethical approval was obtained from the Royal Holloway, University of London ethics committee. In line with ethical guidelines, all participants provided informed consent prior to participation and received a full debrief upon completing the study.

All participants completed the study online, via Gorilla.com. Participants could participate on any device with an internet connection. The memory task was always presented before the questionnaires, to ensure the completion of these did not alter participants' encoding of interoceptive, relative to action, expressions.

2.2 Measures

2.2.1 Self-Reported Interoceptive Processing

Self-reported interoceptive accuracy was assessed using the Interoceptive Accuracy Scale (IAS; Murphy et al., 2019). The IAS is composed of 21 items, each of which has been described as interoceptive. For each item participants are asked to report on their beliefs about their ability to perceive that internal bodily signal accurately (e.g., I can always accurately perceive when by heart is beating fast) by indicating how much they agree or disagree with the statement. Participants responded using a Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree), with total scores ranging from 21 to 105, and higher scores indicative of higher self-reported interoceptive accuracy. The IAS was found to have high reliability in the current sample (21 items; α = 0.87).

In order to ensure the scale had been interpreted as intended, upon completing the IAS, participants were asked to describe what they believed the questionnaire was asking them to report on: the accuracy with which they can perceive sensations, the attention they pay to said sensations, the frequency with which these sensations occur in their body, or another construct.

If the participant did not correctly indicate that the questionnaire assessed interoceptive accuracy, their IAS score was removed from analyses.

Self-reported interoceptive attention was assessed using the Interoceptive Attention Scale (IATS; Gabrielle et al., 2022). The IATS is composed of an identical set of 21 items to the IAS. For each item participants are asked to report on their beliefs concerning the amount of time that internal bodily signal is the focus of their attention (e.g., Most of the time my attention is focused on whether my heart is beating fast), by indicating how much they agree or disagree with the statement. The scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree), with total scores ranging from 21 to 105, and higher scores indicative of higher self-reported interoceptive attention. The IATS was found to have high reliability in this sample (21 items; $\alpha = 0.90$).

Again, participants were required to report on what they believe the questionnaire was asking them to report on, using the question described above. IATS data were excluded for any participant who did not correctly identify that the questionnaire assessed interoceptive attention.

2.2.2 Memory Task

Stimuli

Participants viewed stimuli taken from the Interoceptive Static States Images (ISSI Database; Biotti et al., 2021). Each participant viewed four exemplars (posed by two male and two female actors) of nine interoceptive states, expressed with facial and postural cues (See Figure 1). The interoceptive states depicted were breathlessness, cold, fatigue, hot, hunger, nausea, itch, pain, and satiety. Participants also viewed four exemplars (2 males, 2 females) of nine action postures (see Figure 2). The nine actions depicted were beckoning, clapping, jumping, lifting, running, twirling, walking, washing hands, and waving.

Figure 1. An example of each interoceptive state depicted by one of the four actors. From a) to i), the depicted states are: breathlessness, cold, fatigue, hot, hungry, itch, nausea, pain, and hunger.

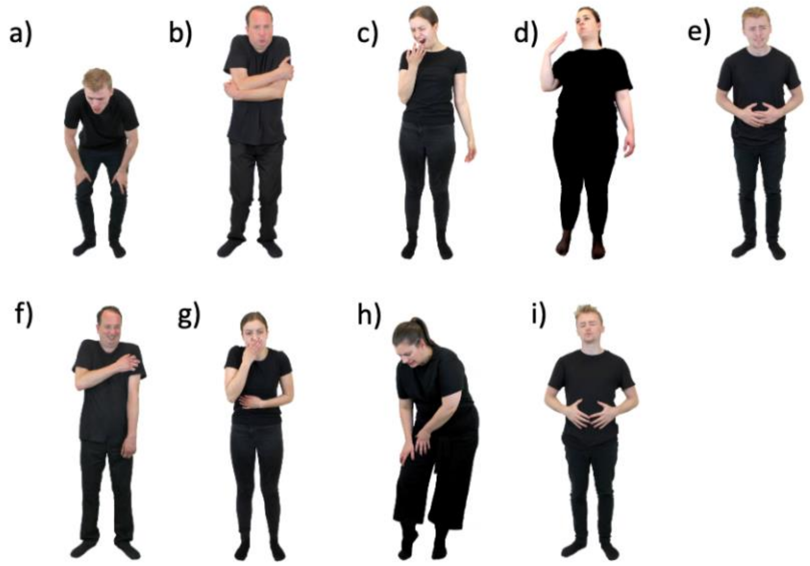
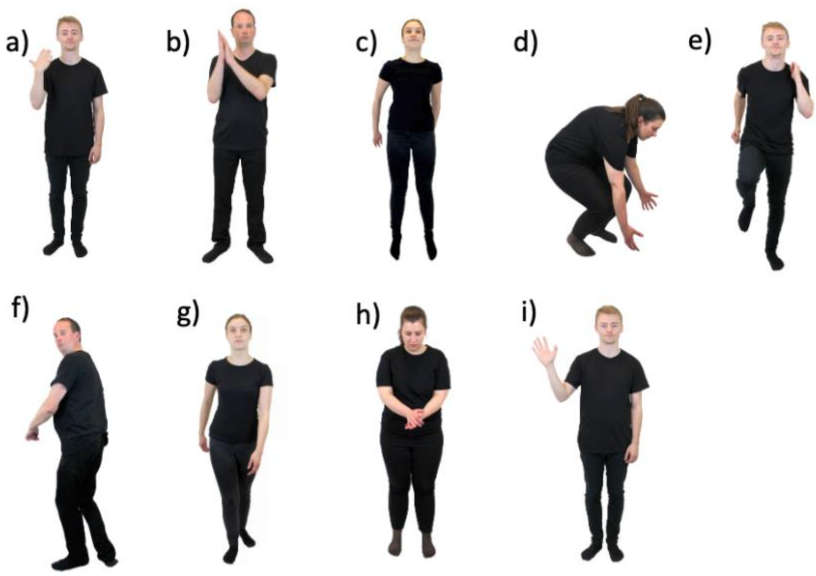


Figure 2. An example of each action depicted by one of the four actors. From a) to i), the depicted actions are: beckoning, clapping, jumping, lifting, running, twirling, walking, washing hands, and waving.



Procedure

Memory for stimuli depicting actions and interoceptive expressions was assessed using an 'old or new' recognition memory paradigm. Participants first completed the training phase of the paradigm, during which they viewed stimuli that they did not know that they would be subsequently assessed on, and asked to make a task-irrelevant judgement concerning each stimulus (see training phase below). Following this, participants completed an audio distractor task (see distractor task below). Finally, participants proceeded to the test phase of the paradigm (see test phase below).

Training Phase

Participants viewed 18 interoceptive (nine states x two actors (one male, one female)) and 18 action postures (nine actions x two actors (one male, one female)) and were asked to report the sex of the actor. Each stimulus was presented twice, with the order of presentation randomised across participants. The sex recognition task was purposefully unambiguous, as this task was simply used to ensure that participants were attending to the stimuli. With this in mind, any participant who responded incorrectly on more than 3 trials was excluded from the analyses.

Distractor task

During the distractor task, participants were asked to listen to a 90 second audio clip and report the number of tones that were presented. Before commencing the distractor task participants were instructed to plug in headphones, or to sit in a quiet place where they could play the audio clip through their device speakers.

Test phase

Participants viewed 36 interoceptive (nine states x four actors (two male, two female)) and 36 action postures (nine actions x four actors (two male, two female)), and were required to respond indicating whether they viewed the image in the training phase or not. Half of the stimuli had been viewed before while half were novel exemplars of the same states, posed by the same actors. Participants were not informed what proportion of the test stimuli had been viewed previously. Two versions of the experiment were utilised, whereby one set of 36 images was used as training stimuli and another set of 36 images as the novel stimuli in one version, and these two sets were reversed in the second version.

2.3 Analysis plan

To analyse memory for interoceptive and action postures, d-prime (d') scores were calculated. In a signal detection theory framework, d' represents participants' sensitivity to a signal (e.g., a stimulus having been viewed previously), having removed response bias as a confound. d' was calculated separately for action and interoceptive postures, using the following equation (where hits were defined as correctly identifying that a stimulus had been viewed previously, false alarms were defined as mislabelling a novel stimulus as a previously viewed stimulus, and z(H) and z(FA) are the z transforms of hit rates and false alarm rates respectively):

$$d' = z(H) - z(FA)$$

A Hautus (1995) adjustment was employed to adjust for extreme values.

One-sample *t*-tests were employed to compare interoceptive d' and action d' to a score of 0 (chance performance), and a paired-samples *t*-test was utilised to compare the d' scores in the interoceptive condition to those in the action condition.

A memory bias score was then computed as the difference between the two conditions (interoceptive d' – action d'). Positive scores indicated a memory bias towards interoceptive postures, such that the participant's memory for interoceptive postures was greater than for action postures.

Correlational analyses were then employed to examine the relationship between memory for interoceptive and action postures and self-reported interoceptive abilities. A mixed 2 x 2 ANOVA was used to assess the effects of actor and participant gender on memory.

The normality of each variable was inspected (IAS total, IATS total, interoceptive d', action d', and memory bias). Visual inspection of histograms was accompanied by a Kolmogorov-Smirnov test with a Lilliefors correction (Lilliefors, 1967). If a variable was not normally distributed the appropriate non-parametric tests were implemented (see Supplementary Materials 1 for all normality statistics).

Bayesian statistics were conducted to further explore results. Where directional hypotheses were made, one-sided significance values are reported.

3. Results

3.1. Self-reported interoceptive abilities

IAS scores were not normally distributed and ranged from 42 to 104 (*M* = 75.40, *SD* = 11.78). IATS scores were normally distributed and ranged from 22 to 105 (*M* = 56.14, *SD* = 14.20). IAS and IATS scores were not significantly correlated, $r(74) = 0.185$, $p = 0.114$, in line with the distinction between interoceptive accuracy and attention.

3.2 Memory for interoceptive and action postures

Interoceptive d' scores ranged from -0.534 – 2.070 (*M* = 0.671, *SD* = 0.464), with participants H ranging from 0.222 – 1.00 (*M* = 0.710, *SD* = 0.170) and participants FA ranging from 0.056 to 1.00 (*M* = 0.455, *SD* = 0.184). Action d' scores ranged from -1.038 – 1.531 (*M* = 0.635, *SD* = 0.442), with participant H ranging from 0 to 1 (*M* = 0.604, *SD* = 0.173) and participants FA ranging from 0.056 – 1.00 (*M* = 0.455, *SD* = 0.184). Neither interoceptive nor action d' scores were normally distributed. Memory bias scores (Interoceptive d' – Action d') ranged from -1.271 – 1.603 (*M* = 0.0351, *SD* = 0.544) and were also not normally distributed.

Wilcoxon one-sample tests revealed that participants performed significantly above chance on the action, $Z = 5802$, $p = 0.001$, and interoceptive, $Z = 5897$, $p < 0.001$, memory task. There was no significant difference, however, between memory for interoceptive and action stimuli, $Z(113) = 6323$, $p = 0.726$.

Correlational analyses revealed that self-reported interoceptive abilities, measured with the IAS and IATS, were not related to memory for interoceptive or action postures, or the difference between these (see Table 1). *p* values are reported one-tailed for investigations with the IAS and two-sided for investigations with the IATS, uncorrected for multiple comparisons.

Table 1. Correlational analyses assessing the relationship between self-reported interoceptive abilities and memory for interoceptive and action body postures.

	IAS			IATS		
d'	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
Interoceptive	0.061	0.279	0.158	-0.019	0.893	0.142
Action	0.040	0.699	0.149	0.027	0.803	0.143
Bias (Interoceptive - Action)	0.002	0.491	0.135	-0.048	0.660	0.154

3.3 Gender

A mixed 2 x 2 ANOVA was conducted with actor gender as a within-participants factor, and participant gender as a between-participants factor. Neither actor gender, $F(1, 112) = 1.572$, $p = .212$, $np^2 = 014$, nor participant gender, $F(1, 112)= .248$, $p = .619$, $np^2 = .002$, had a significant effect on memory, and there was no significant interaction between participant and actor gender, $F(1,112) = .170$, $p = .681$, $np^2 = .002$. It is worth noting that this analysis should be interpreted with caution, however, owing to the very small sample of male participants.

4. Discussion

The current study was the first to investigate memory for others' interoceptive expressions and actions, posed by identical actors, and its relationship with self-reported interoceptive processing. Using an 'old or new' recognition memory paradigm, no difference in long-term memory was observed for interoceptive and action postures, which might suggest that neither posture type is more salient in the encoding phase. Findings also suggested no relationship between memory for others' interoceptive expressions or actions and the processing of interoceptive states in oneself (self-reported interoceptive accuracy or attention). These findings suggest that, unlike with emotion, memory for others' interoceptive expressions is not related to the processing of these states in one's own body.

The finding that interoceptive expressions were not remembered better than the control action postures was unpredicted, and contrasts with the well-documented salience of emotional stimuli, presumably owing to their importance in social cognition (Yiend, 2010). Arguably, the perception of interoceptive expressions is as important, if not more, for social cognition, as failing to recognise when another person is tired, hungry, or unwell, for example, may impede one's ability to respond appropriately, negatively affecting relationships. Identifying these states in others is also likely to have an evolutionary function, as identifying signals of hunger, fatigue, illness, or pain in others is likely to lead to appropriate care, increasing group survival levels. Similarly, detecting nausea or pain in another may help one to avoid dangerous stimuli in the environment, again playing an adaptive role. Future research is therefore needed to further understand the salience of interoceptive, relative to emotional, stimuli in visual processing. It is possible that the lack of a superior memory effect for interoceptive stimuli in the current paradigm relates to the set of control stimuli used; others' actions are also likely to be salient, and the action stimuli in the current study were matched in terms of furthest horizontal and vertical points in the image (i.e., spread from a neutral posture), which may be a key predictor of salience. In Yiend's (2010) study, on the other hand, memory for emotional stimuli was compared to that for neutral stimuli, which may be less salient in part due to their lack of variability, the high frequency with which neutral postures are viewed in everyday life giving them low novelty, and their low level visual properties (e.g., arms by side and legs together rather than spread). Replication of the current paradigm including both interoceptive and emotion stimuli alongside the well-matched action control stimuli, rather than neutral stimuli as in Yiend (2010), is therefore required in order to assess the relative memory bias for others' emotional and interoceptive states. The inclusion of neurophysiological (such as fMRI and EEG) and eye-tracking measurements during the visual processing of these stimuli would also enable better understanding of the ways in which encoding of and memory for others' emotional and interoceptive states may vary.

The current study also found no relationship between the processing of one's own and others' interoceptive expressions. Again, this was unpredicted given the relationship between difficulties identifying one's own emotions (alexithymia) and reduced memory for others' emotional expressions (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout et al., 2021.; Takahashi et al., 2015; Vermeulen et al., 2006; Vermeulen & Luminet, 2009). Notably, however, the current authors observed no relationship between the processing of one's own interoceptive states and implicit attention to others' interoceptive expressions (Carr et al., *in prep.)*. As biases in attention are likely to affect subsequent stages of processing, such as memory (Adolphs, 2002; Spunt & Adolphs, 2019), perhaps the lack of relationship between memory for others' interoceptive expressions and self-reported interoceptive processing is unsurprising. In line with this, whilst findings have been mixed, overall alexithymia appears to be associated with both a deficit in both attention and memory for others' emotions (Luminet et al., 2021). While investigations within the same individuals are lacking, it is possible that memory deficits for others' emotions are only observed where attention deficits are also exhibited, and the same pattern may be true for others' interoceptive expressions. Future research should therefore investigate the relationship between both attention to and memory for others' interoceptive expressions, and their relationship with interoceptive processing in the self, within the same individuals. It is also worth noting that in studies of alexithymia, the spread of alexithymia scores tends to be broad, with a large proportion of the sample exhibiting marked deficits in understanding of their own emotions. In the current study, however, self-reported interoceptive accuracy tended to be in the typical range. It is possible that, if participants with substantial difficulty perceiving their own interoceptive states were included, a relationship between self-reported interoceptive accuracy and memory for others' interoceptive expressions would have been observed. Future research should also, therefore, replicate the current study in groups with interoceptive difficulties, such as clinical groups, children, and older adults. If such a relationship is observed, investigation of underlying mechanisms, such as effects of the cardiac cycle on memory (Garfinkel et al., 2013), would be warranted.

Where self-reported interoception itself is concerned, no significant relationship was seen between self-reported interoceptive accuracy and attention, supporting the hypothesis that these are two dissociable dimensions of interoception (Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Unlike previous investigations, which have reported greater self-reported interoceptive attention in women than men (Carr et al., *in prep*; Grabauskaite et al., 2017), the current study found no difference in self-reported interoceptive accuracy or attention in males and females, although this may be due to the small sample of males. It is also worth noting that, whilst self-report measures are useful for capturing a range of interoceptive states, their correlation with objective measurements is relatively small (Murphy et al., 2018). In line with recommendations for multidimensional assessments of interoception (Suksaslip & Garfinkel, 2022), future research should aim to employ both objective and self-report methods of both interoceptive accuracy and attention. Of course, selecting reliable and valid objective measurements of interoception is challenging. The most commonly used task to measure objective interoceptive accuracy is the heartbeat counting task (HCT; Schandry, 1981). Although this task has high face validity and allows for ease of measurement, it has a number of limitations, such as the large number of participants who cannot complete the task, the influence of heart rate belifs, and the lack of correlation between actual and reported heartbeats in the highest perceivers (for a review, see Corneille et al., 2020). Encouragingly, novel tasks such as the phase adjustment task (PAT; Plans et al., 2021) seem to overcome many of these difficulties, despite being limited to the cardiac domain. Tasks assessing non-cardiac domains of interoception have also been used, but are again limited, for example by difficulties obtaining objective measures of the interoceptive signal strength; difficulties assessing lung capacity in respiratory tasks (Nikolova et al., 2022) and stomach volume in tasks assessing satiety (Dyck et al., 2016), for example, make interpretation of task performance challenging. Objective measures of interoceptive attention are particularly lacking within the field, although recent attempts to use experience sampling may overcome this issue (Murphy et al., 2020). The inclusion of multiple objective and self-report measures of interoceptive accuracy and attention in subsequent investigations would provide additional evidence on the relationship between these measures, as well as providing a more comprehensive estimate of interoceptive abilities with which to test the association with memory for others' interoceptive expressions.

In summary, no significant differences were observed in long-term memory for interoceptive or action postures, suggesting that there is no difference in salience between these in the encoding or retrieval phase. Furthermore, this study found no significant relationship between the processing of interoceptive states in oneself and memory for others' interoceptive expressions, suggesting that memory is unaffected by the processing of interoceptive states in oneself. Considering that the processing of others' interoceptive expressions may be key for social communication and providing necessary care, future research should focus on examining in which, if any, situations these postures do elicit priority in encoding or memory. In particular, it is necessary to investigate this in those with marked difficulties interpreting their own interoceptive signals, such as in clinical and developmental samples.

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Supplementary Materials 1. Kolmogorov-Smirnov test statistic and significance values for all variables.

Variable	*K-S*	*p*
d' action	0.122	0.008
d' state	0.112	0.021
d' bias (d' state - d' action)	0.085	0.200
d' male	0.075	0.200
d' female	0.121	0.010
IAS	0.109	0.029
IATS	0.076	0.200

Chapter 7. Study Five: Interoception and alexithymia in children and adolescents with Medically Unexplained Symptoms and Tourette Syndrome

Interoception and alexithymia in children and adolescents with Medically Unexplained Symptoms and Tourette Syndrome

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**Contributed equally to this work

Abstract

Background: Atypicalities in interoception (the perception of internal bodily signals) are highly prevalent in a range of clinical conditions and are commonly associated with difficulties processing emotions, including reduced emotional intelligence and elevated alexithymia (difficulties identifying and recognising one's own emotions). Medically Unexplained Symptoms and Tourette Syndrome are two clinical conditions that share a fundamental misinterpretation of interoceptive signals as a key contributing factor to their development and maintenance. Very little research, however, has investigated interoception, emotional abilities, and their relationship in children and adolescents with these disorders.

Methods: This audit assessed interoceptive accuracy, emotional intelligence, alexithymia, somatic symptom complaints, quality of life, and symptom severity using self and parent-report measures in a sample of children and adolescents with Medically Unexplained Symptoms or Tourette Syndrome.

Results: Both children with Medically Unexplained Symptoms and Tourette Syndrome reported significantly reduced interoceptive accuracy and emotional intelligence, alongside significantly increased alexithymia, when compared to normative samples. Individual differences in interoception, emotional intelligence and alexithymia were also related to disorder symptom severity and quality of life,

Conclusions: These findings suggest that interoception and emotion processing may contribute to disorder manifestations in children and adolescents, with implications for diagnosis and treatment. The assessment of interoception and emotional processing may

improve clinical outcomes for those with Medically Unexplained Symptoms and Tourette Syndrome by informing treatment approaches.

1. Introduction

The term Medically Unexplained Symptoms (MUS) refers to persistent bodily complaints, such as headaches, dizziness, and pain, for which medical examination does not reveal sufficient explanatory pathology (Chew-Graham et al., 2017). With at least one medically unexplained symptom diagnosed in up to 49% of all primary care patients (Haller et al., 2015), and MUS contributing to debilitating somatic symptom disorders (American Psychiatric Association; APA, 2013), obtaining a better understanding of the mechanisms underlying these symptoms is of paramount importance. MUS is one of two focal conditions addressed in this work, with the other being Tourette Syndrome (TS), a neurological condition characterised by tics (sudden, repetitive, rapid, and unwanted movements or vocalisations). Over 90% of those diagnosed with TS report that tics are typically preceded by an unpleasant sensation, referred to as a "premonitory urge" (Reese et al., 2014). Premonitory urges are described by patients as feelings of discomfort, tension, or pressure, and are likely to represent a causal factor in the subsequent tic expression, which serves to temporarily alleviate these feelings of discomfort (Conceição et al., 2017). While MUS and TS manifest quite differently, they appear to share fundamental atypicalities in interoception - the processing of internal bodily signals - as a key contributing factor to their development and maintenance (Rae et al., 2019; Witthöft & Hiller, 2010), which often develop in childhood and adolescence.

Interoception is a broad term referring to the sensing, interpretation, and integration of signals originating from within the body, including the perception of, and attention to, signals such as one's heartbeat or breathing (Gabriele et al., 2022; Garfinkel & Critchley, 2013; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Whilst there is some debate over precisely what constitutes an interoceptive signal, many contemporary definitions include visceral sensations such as hunger, respiration, and cardiac perception, as well as sensations that are not necessarily internally generated, but which share underlying neural substrates, such as itch and affective touch (Khalsa & Lapidus, 2016). Recent definitions of interoception have also identified dissociable dimensions of interoception; initial work distinguished between objective and self-reported measures of interoception (Garfinkel et al., 2015; Garfinkel & Critchley, 2013) and more recent models also distinguish between interoceptive accuracy (how precisely an individual can perceive their internal bodily signals), interoceptive attention (the extent to which these signals are the focus of one's attention), and one's propensity to use interoceptive signals to gauge internal states (Murphy, 2022; Murphy et al., 2019, 2020; Suksasilp & Garfinkel, 2022). Individual differences in interoceptive accuracy, attention, and propensity to use interoceptive signals exist, with these differences predicting various cognitive, affective, and mental health outcomes (Barrett & Simmons, 2015; Bonaz et al., 2021; Brewer et al., 2021; Khalsa et al., 2018; Murphy et al., 2017; Quadt et al., 2018; Tsakiris & Critchley, 2016).

Interoceptive atypicalities, both behavioural and neural, are common across a range of clinical conditions. Within the TS population, grey matter volume of anterior cingulate cortex (ACC), a key interoceptive region, is significantly reduced in patients relative to neurotypical controls (Wen et al., 2021), and the strength of functional coupling between the anterior insula (another region strongly implicated in interoception) and supplementary motor areas has been found to be positively associated with both the urge to tic and tic severity (Cavanna et al., 2017; Tinaz et al., 2015). While these neural atypicalities are likely associated with interoceptive difficulties, research investigating interoception in this population has been limited. The few studies available suggest that adults with TS display typical detection of exteroceptive stimuli, implicating aberrant interoceptive processing in the sensory abnormalities associated with TS (Schunke et al., 2016). Where interoception has been assessed more explicitly in TS, low cardiac interoceptive accuracy has been observed in adults (Ganos et al., 2015; Rae et al., 2019), and one study reported significantly reduced cardiac interoceptive accuracy in children, when compared to neurotypical individuals (Pile et al., 2018). Interestingly, when the children were instructed not to move during the task, the TS and neurotypical groups performed similarly, suggesting that interoceptive accuracy can be manipulated in young people with TS, at least in the cardiac domain, implicating interoception as a potential target for intervention. While no study has explicitly investigated interoceptive attention in TS, scores on a questionnaire most commonly interpreted as assessing interoceptive attention (Gabriele et al., 2021) have been found to be higher in TS than in the typical population, and significantly related to premonitory urges to tic in adults (Rae et al., 2019). Taken together, these findings suggest altered interoceptive processing in TS. As little research has investigated interoception beyond the cardiac domain, however, further research is required across multiple interoceptive signals, and in childhood and adolescence when TS symptoms first emerge (Khalifa et al., 2005; Leckman et al., 2014).

Interoceptive atypicalities have also been observed in MUS. In the clinical population, individuals with MUS appear to exhibit reduced interoceptive accuracy, in the respiratory domain, compared to neurotypical individuals (Bogaerts et al., 2010). MUS symptoms have also been found to decrease following heartbeat perception training, indicating a causal association between interoception and MUS (Schafer et al., 2014), although notably training only improved interoceptive accuracy in a sub-sample of individuals with MUS with low health anxiety. In the general population, individuals reporting particularly high and low levels of medically unexplained symptoms over the previous two years (highest and lowest 10% of scores) did not differ in terms of cardiac interoceptive accuracy. Those reporting higher symptom levels, however, exhibited a greater increase in heartbeat-evoked potentials (thought to represent the cortical processing of heartbeats; (Coll et al., 2021) when attention was focused on heartbeats relative to when attention was directed elsewhere, than did individuals reporting lower symptom levels (Schulz et al., 2020). As the groups exhibited equivalent heartbeat-evoked potentials at baseline, this suggests that individuals experiencing higher levels of bodily symptoms deploy greater attentional resources towards bodily signals when instructed to do so. At present, no studies have investigated the propensity to attend to internal signals in daily life in MUS, and research on interoception in MUS has mostly focused on adult samples in a small number of interoceptive domains (typically cardiac and respiratory). Examination of interoceptive abilities across multiple signal domains, as well as at key developmental stages, in MUS samples is therefore required.

As well as potentially contributing to the aetiology of clinical disorders, interoception is thought to be necessary for emotional awareness (e.g., Barrett, 2014; James, 1894; Lange, 1885; Schachter & Singer, 1962). Accordingly, atypical interoception has been associated with decreased emotional intelligence (Dobrushina et al., 2020; Pollatos & Koch, 2015; Terasawa et al., 2015), as has alexithymia (Ghiabi & Besharat, 2011; Parker et al., 2001), a sub-clinical construct characterised by difficulties identifying and describing one’s own emotional states. Atypical interoception is, in fact, thought to play a causal role in alexithymia (Brewer et al., 2016, 2021). While there may also be non-interoceptive routes to alexithymia (e.g. through language deficits; Hobson et al., 2019), individuals with higher alexithymia are more likely to confuse interoceptive states (Brewer et al., 2016), and have been found to be less likely to rely on interoceptive, relative to exteroceptive, cues to gauge their respiratory effort (Murphy et al., 2017). Relatedly, a negative relationship between alexithymia and the accuracy of cardiac perception (Herbert et al., 2011; Murphy et al., 2018;

Shah et al., 2016), and perception of muscular effort and taste (Murphy et al., 2017) has been reported, suggesting that if an individual struggles to recognise interoceptive signals, they are also likely to have difficulties identifying and describing their emotions. Studies of alexithymia and interoception have sometimes provided no evidence of a relationship (Trevisan et al., 2019), however this is likely due to the use of poor tests of cardiac interoceptive accuracy, in particular the heartbeat counting task (HCT; for a review see Corneille et al., 2020). Further to methodological criticisms, research suggests that interoception may not be a unitary ability, but instead fractionate across bodily axis, with ability to detect signals from one interoceptive domain (e.g., cardiac) not necessarily relating to the ability to perceive signals from another domain (e.g., respiratory) (Ferentzi et al., 2018). Given this, further investigations are needed which measure interoception using alternative techniques across a range of bodily axes.

Unsurprisingly, given the link with interoceptive difficulties, alexithymia co-occurs with a number of clinical conditions (e.g., eating disorders (Bourke et al., 1992; Cochrane et al., 1993; Jimerson et al., 1994; Rozenstein et al., 2011), depression (Honkalampi et al., 2001), and autism spectrum disorder (Berthoz & Hill, 2005; Hill et al., 2004; Kinnaird et al., 2019)). While previous research has reported elevated levels of alexithymia in adults and children with MUS (De Gucht & Heiser, 2003), children with and without TS have been found to report similar ability to identify and describe their emotions (Silvestri et al., 2019). Individuals with TS did, however, report significantly higher levels of the 'externally orientated thinking' facet of alexithymia, and their degree of alexithymia was significantly positively related to the intensity of premonitory urges. Importantly, while recent evidence suggests a strong relationship between alexithymia and interoceptive difficulty in the general population, whether the relationship between these variables holds across clinical groups is yet to be determined in the majority of psychological disorders. Current research has also neglected to investigate the prevalence of alexithymia and interoceptive atypicalities, and their relationship, throughout development. This is of particular importance in MUS and TS, as both conditions frequently emerge during childhood and adolescence (Eapen & Črnčec, 2009; Rask et al., 2009). Furthering our understanding of the relationship between alexithymia, interoception, and MUS and TS symptoms will aid in the detection of emotional and interoceptive difficulties in these patients, potentially enabling clinicians to tailor treatments to individuals based on their specific profile of needs.

The current study is the first to utilise a multi-domain measure of interoceptive accuracy, and measure both child- and parent-reported alexithymia, to investigate these constructs and their relationship in children and adolescents with TS and MUS. It is worth noting that measures of alexithymia and emotional intelligence typically rely on self-report methods (Bagby, Parker, & Taylor, 1994; Vorst & Bermond, 2001), as do measures of multiple interoceptive signals (Murphy et al., 2019; Gabrielle et al., 2022). Given that insight may be decreased in children and clinical groups (Barbosa et al., 2002; Eiser & Varni, 2013; Garfinkel et al., 2016; Sherifali & Pinelli, 2007; Van Roy et al., 2010) obtaining parental-reports can provide complimentary evidence of potential difficulties faced by these individuals. Considering this, wherever possible both parent and child reports were collected in the current study to corroborate findings, as well as to allow for analysis of the relationship between reports. Somatic and core symptom severity, and mental health variables, were also measured to investigate their relationship with interoception and alexithymia. It was hypothesised that children with MUS and TS would report reduced interoceptive accuracy and emotional intelligence, and higher levels of alexithymia, compared to existing normative samples. In line with previous research, interoceptive accuracy was expected to correlate positively with emotional intelligence and negatively with alexithymia. In the general population and clinical groups, alexithymia has been negatively associated with overall and health-related quality of life (Grassi et al., 2004; Henry et al., 2006; Honkalampi et al., 2000; Mattila et al., 2009; Valkamo et al., 2001) and treatment outcomes for some psychological therapies (Ogrodniczuk et al., 2011). Whilst research is yet to investigate this in MUS and TS, it was predicted that higher alexithymia, and lower emotional intelligence and interoceptive accuracy would be associated with greater symptom severity, and lower quality of life.

2. Methods

2.1 Participants

A total of 52 child and adolescent participants took part in this clinical audit. Within this sample, 32 participants (24 male, 8 female), ranging in age from 8 – 17 years (*M* = 11.72 years, *SD* = 2.56), had a clinical diagnosis of Tourette Syndrome (TS). 20 participants (6 male, 14 female), ranging in age from 9 – 17 years (*M* = 12.95 years, *SD* = 2.16), were diagnosed with medically unexplained symptoms (MUS). The two groups did not differ significantly in age, $t(50) = -1.79$, $p = .08$, but differed significantly in sex composition, $x^2(1, N = 52) = 10.21$, $p = .001$. Sex differences reflect those observed in the TS (approximately three times as likely in males than females; CDC., 2007) and MUS (approximately four times as likely in females than males; Trapani et al., 2008)) populations. One of each participant's parents/guardians also completed measures relating to the participants. All participants were recruited from Great Ormond Street Hospital. Participants were included if a diagnosis had been made by a health professional and their first language was English. Both participants and parents/guardians gave informed consent and were fully debriefed following completion of the study. Data was collected as part of a service evaluation with the Great Ormond Street audit team (Audit Number 2366).

2.1.2 Comorbidities

Additional mental health and neurodevelopmental conditions, beyond the primary diagnosis of TS or MUS, were recorded for every participant (Table 1). 17 participants were not diagnosed with co-occurring conditions, 16 participants were diagnosed with one co-occurring condition, 14 participants with two co-occurring conditions, and 5 participants with three co-occurring conditions.

Table 1. Comorbidities for both TS and MUS participants

	TS		MUS	
	Frequency	Percentage of TS sample	Frequency	Percentage of MUS sample
Mental Health				
Anxiety	12	38%	8	40%
Depression	1	3%	5	25%
OCD	5	16%	0	0%
FNS	3	9%	9	45%
NES	1	3%	10	50%
Somatoform Pain	0	0%	1	5%
Neurodevelopmental				
ADHD	7	22%		0%
ASD	4	13%		0%
SpLD (Specific Learning Disorder)	2	6%	5	25%
LD (Learning Disorder)	1	3%	1	5%
TS/MTD			4	20%

2.2 Procedure

Participants attended an outpatient appointment, during which the initial assessment was conducted. Following this appointment, participants completed all questionnaires described in Section 2.3 at home or in the clinic.

2.3 Measures

Self-reported general emotional intelligence was assessed using the Total Emotional Intelligence score (sum of four subscales) on the Emotional Quotient Inventory (Youth Version) (EQ-i:YV; Bar-On & Parker, 2000). As the intrapersonal subscale of the EQ-i:YV includes items assessing the ability to process one's own emotions, scores on this subscale were treated as assessing self-reported alexithymia. Note that lower scores on the EQ-i:YV intrapersonal subscale are indicative of higher alexithymia. Parent-reported child alexithymia was measured with the Child Alexithymia Measure (CAM; Way et al., 2010).

The Child Interoceptive Accuracy Scale (IAS-C; Barker et al., 2021) was utilised to assess self-reported interoceptive accuracy, adapted from the adult Interoceptive Accuracy Scale (Murphy et al., 2019).

The Child report: Children's Somatic Symptoms Inventory (CSI; Walker et al., 1991) and the Children's Somatic Symptoms Inventory – Parent Version (CSI – P; Walker et al., 1991) were used to measure self-reported and parent-reported child somatic complaints, respectively.
Three items were removed from the CSI and CSI-P (Item 10: Lump in throat, Item 20: Deafness, Item 21: Double Vision) as these involve exteroceptive or emotional, rather than specifically interoceptive, symptoms.

The Pediatric Quality of Life Inventory (PEDSQL™) and PEDSQL™ parent-report were used to assess self- and parent-reported health-related quality of life, respectively.

For detailed descriptions of all measures, see Supplementary Materials 1.

3. Results

Information on distributions and normality assumptions for all variables is reported in Supplementary Materials 2. Where assumptions for parametric tests were not met, non-parametric alternatives were utilised. One-tailed tests are reported where hypotheses were directional. Where parent- and self-report measures of the same construct were obtained, measures were well correlated in the expected direction (see Supplementary Materials 3). As small samples limit interpretation of *p* values (Leppink et al., 2016) and to balance the risk of Type I and Type II errors, all results are first reported uncorrected for multiple comparisons. Multiple comparisons were then either corrected for using Bonferroni correction (if four or fewer analyses were conducted), or using an adjusted alpha of .0125, so as to avoid tests being overly conservative, and where corrections alter the pattern of significance, this is identified.

3.1 Self-reported emotional intelligence and alexithymia in MUS and TS

Self-reported emotional intelligence (EQ-i:YV total emotional intelligence score) was significantly higher in both the TS (*M* = 102.94, *SD* = 16.98) and MUS (*M* = 101.60, *SD* = 19.93) groups than in multiple existing normative samples of children and adolescents (Table 1). Self-reported alexithymia was also higher (lower EQ-i:YV intrapersonal scores) in both the TS (*M* = 14.45, *SD* = 3.70) and MUS (*M* = 13.25, *SD* = 3.75) groups than the typical samples, though the pattern of significance varied across samples (see Table 1).

Table 1. Independent samples *t*-tests comparing emotional intelligence and alexithymia in the TS and MUS groups to normative samples of children and adolescents. Statistically significant differences are shown in bold text.

	Sample			EQ:i-YV (Total)		Intrapersonal Scale		Group	EQ:i-YV		Intrapersonal Scale	
Normative Sample	*n*	Age (*M*)	Age (*SD*)	*M*	*SD*	*M*	*SD*		*t*	*p*	*t*	*p*
Parker et al., 2004	667	16.19	1.8	129.8	16.48	17.66	3.92	TS	**8.622**	**<0.001**	**4.715**	**<0.001**
								MUS	**6.265**	**<0.001**	**5.207**	**<0.001**
Qualter et al., 2012	413	11.17	not reported	115.32	20.00	14.62	3.66	TS	**3.862**	**<0.001**	0.240	0.405
								MUS	**3.006**	**0.003**	1.601	0.055
Fernández et al., 2012	1655	11.1	3.11	113.12	13.2	14.74	3.45	TS	**3.320**	**<0.001**	0.284	0.388
								MUS	**2.579**	**0.010**	**1.660**	**0.049**

Note. Statistically significant differences are shown in bold text

3.2 Self-reported interoceptive accuracy in MUS and TS

Mann-Whitney U tests were employed to compare IAS scores in both the TS (*Mdn* = 72, *range* = 35 – 87) and MUS (*Mdn* = 71.50, *range* = 38 - 87) groups to a normative sample (*Mdn* = 78.00, *range* = 40 – 100), composed of 166 females and 46 males, ranging in age from 16 years to 21 years and 6 months (*M* = 18.00, *SD* = 1.07) (Carr et al., in prep). IAS scores were significantly lower in both the TS, U ($N = 213_{\text{normative}}$, $N = 31_{\text{TS}}$) = 2145.00, z = -3.150, p = .002, and MUS groups, U($N = 213_{\text{normative}}$, $N = 20_{\text{MUS}}$) = 1311.00, z = -2.844, p = .004, than the comparison sample.

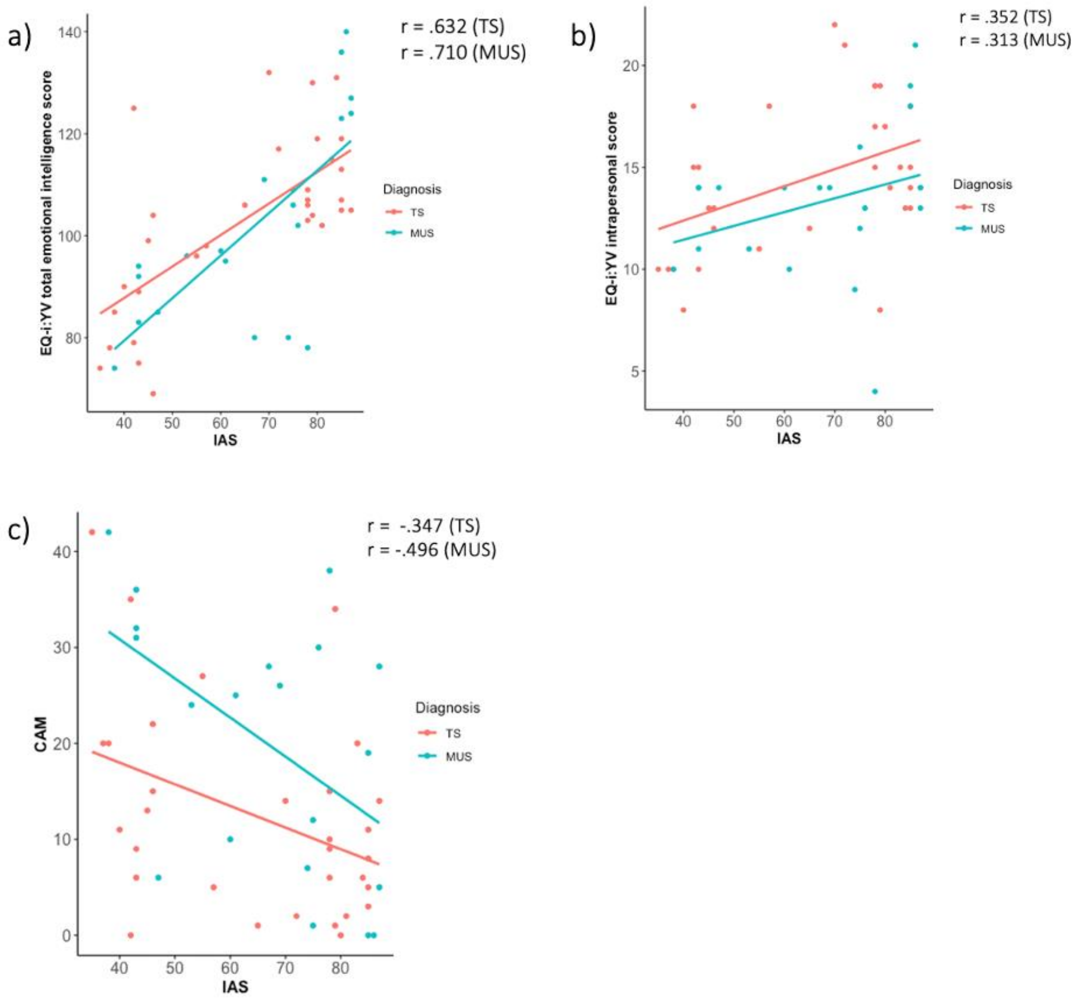
3.3 Relationship between emotional intelligence, alexithymia, and interoception in MUS and TS

Self-reported interoceptive accuracy was significantly positively associated with self-reported emotional intelligence, for both TS, $r(29) = .632$, p < .001, and MUS, $r(18) = .710$, p <.001, participants. These correlations remained significant when controlling for age and sex, TS: $r(29) = .546$, p < .001, MUS: $r(18) = .748$, p <.001. The strength of the relationship, measured with Fisher r-to-z analyses, did not differ between the TS and MUS groups, z = -0.463, p = 0.322. Potthoff analysis revealed that the slope of the relationship was also similar in the TS and MUS groups, $t(47) = .980$, p = .332, or intercept, $t(47) = -1.131$, p = .264, of the relationship.

Self-reported interoceptive accuracy was also significantly associated with self-reported alexithymia in the TS group, $r(29) = .352$, p = .026, whereby children reporting higher interoceptive accuracy also reported increased ability to recognise and communicate their own emotions. In line with this, self-reported interoceptive accuracy was negatively associated with parent-reported alexithymia in the TS group, $r(29) = -.347$, p = .028. It is worth noting that these relationships fell to a trend following correction for multiple comparisons.

In the MUS group, while self-reported interoceptive accuracy was not significantly associated with self-reported alexithymia, $r(18) = .313$, p = .090 it was significantly negatively associated with parent-reported alexithymia, $r(18) = -.496$, p = .013, whereby children reporting lower accuracy perceiving internal bodily signals were rated by their parents as having more problems recognising their emotions. See Figure 1 for scatter plots depicting these relationships.

Figure 1. (a) Scatter plot showing significant positive correlation between emotional intelligence (EQ-i:YV) and interoceptive accuracy (IAS) in TS and MUS individuals. (b) Scatter plot showing relationship between the intrapersonal emotional intelligence scale (EQ-i:YV) and interoceptive accuracy (IAS) across TS and MUS individuals. (c) Scatter plot showing the relationship between parent-reported alexithymia (CAM) and interoceptive accuracy (IAS) across TS and MUS individuals.



3.4. The relationship between interoception, emotional intelligence, alexithymia, and somatic complaints in TS and MUS populations

The TS and MUS groups reported higher levels of somatic symptoms (CSI scores) than a normative sample (see Supplementary Materials 4 for details).

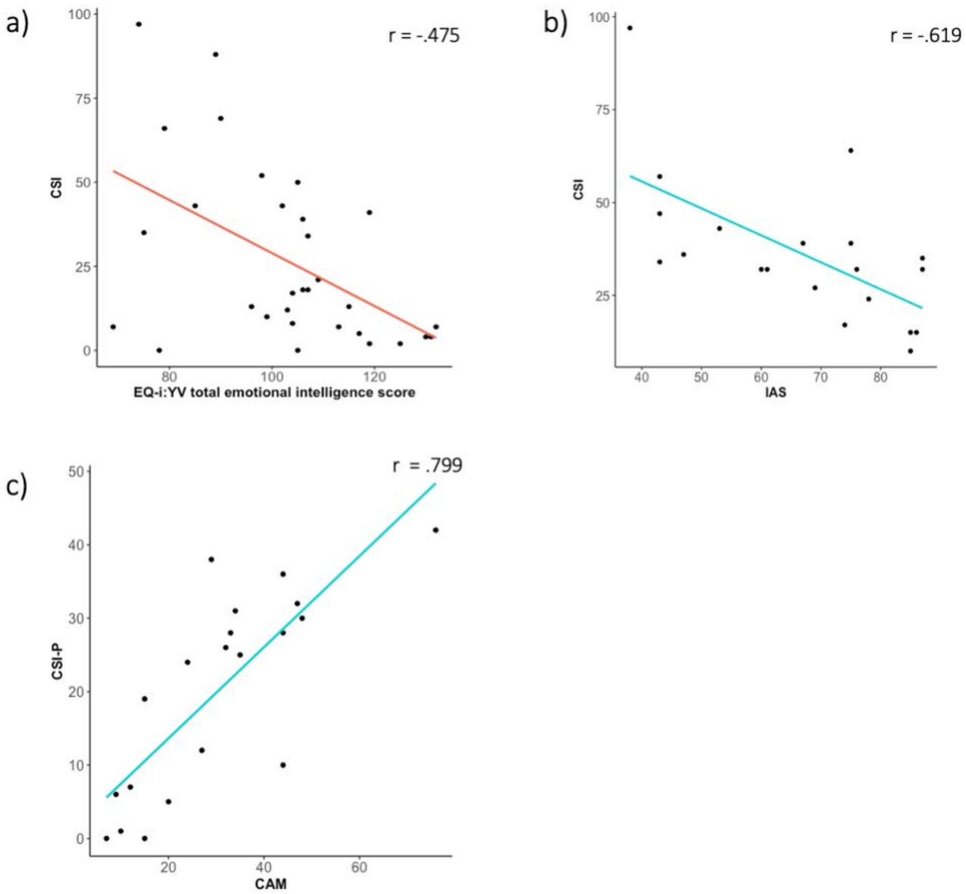
In the TS group, self-reported somatic complaints (CSI) were significantly associated with self-reported emotional intelligence (EQ-i:YV; Figure 2a), indicating that those reporting lower emotional intelligence also reported more somatic complaints. In the MUS group, self-reported somatic complaints (CSI) were significantly associated with self-reported interoceptive accuracy (IAS); greater difficulty recognising and identifying one's internal bodily signals was associated with more somatic complaints (Figure 3b). Finally, parental reports of child alexithymia (CAM) were significantly positively correlated with parent-reported somatic complaints (CSI-P) in children with MUS (Figure 3c). See Table 3 for a summary of all correlations between somatic complaints, emotional intelligence, alexithymia and interoceptive accuracy. Correlations with the severity and impairment subscales of the CSI and CSI-P were also calculated (Supplementary Materials 5). Bonferroni corrections were applied across the four correlational tests run for each somatic complaint measure (α = .0125).

Table 3. Spearman's rho correlations between somatic complaints, emotional intelligence, alexithymia and interoceptive accuracy, for TS and MUS individuals.

		EQ:i-YV Total		Intrapersonal Scale		CAM		IAS	
Diagnosis	Somatic Complaints Measure	*r*	*p*	r	*p*	*r*	*p*	*r*	*p*
TS	CSI Severity - C	-0.329	0.035	-0.244	0.093	0.058	0.377	-0.145	0.219
	CSI Severity - P	-0.340	0.030	-0.388	0.016	0.349	0.025	-0.254	0.084
	CSI Impairment - C	-0.328	0.036	-0.269	0.071	0.004	0.491	-0.119	0.261
	CSI Impairment - P	-0.401	0.013	**-0.417**	**0.010**	0.288	0.055	-0.288	0.058
MUS	CSI Severity - C	-0.220	0.176	-0.227	0.168	0.417	0.034	-0.437	0.027
	CSI Severity - P	-0.306	0.095	-0.181	0.223	**0.719**	**<.001**	**-0.537**	**0.007**
	CSI Impairment - C	-0.310	0.092	-0.219	0.177	0.461	0.020	**-0.506**	**0.011**
	CSI Impairment - P	-0.242	0.152	-0.202	0.197	**0.713**	**<.001**	-0.437	0.027

Note. Correlations that remained significant following correction for multiple comparisons are shown in bold text.

Figure 2. (a) Significant negative relationship between self-reported emotional intelligence (EQ-I:YV total emotional intelligence) and somatic complaints (CSI) in TS participants. (b) Significant negative relationship between self-reported interoceptive accuracy (IAS) and somatic complaints (CSI) in MUS participants. (c) Significant positive relationship between parent-reported alexithymia (CAM) and somatic complaints (CSI-P) in MUS participants.



3.5. Predictors of TS symptom severity and quality of life

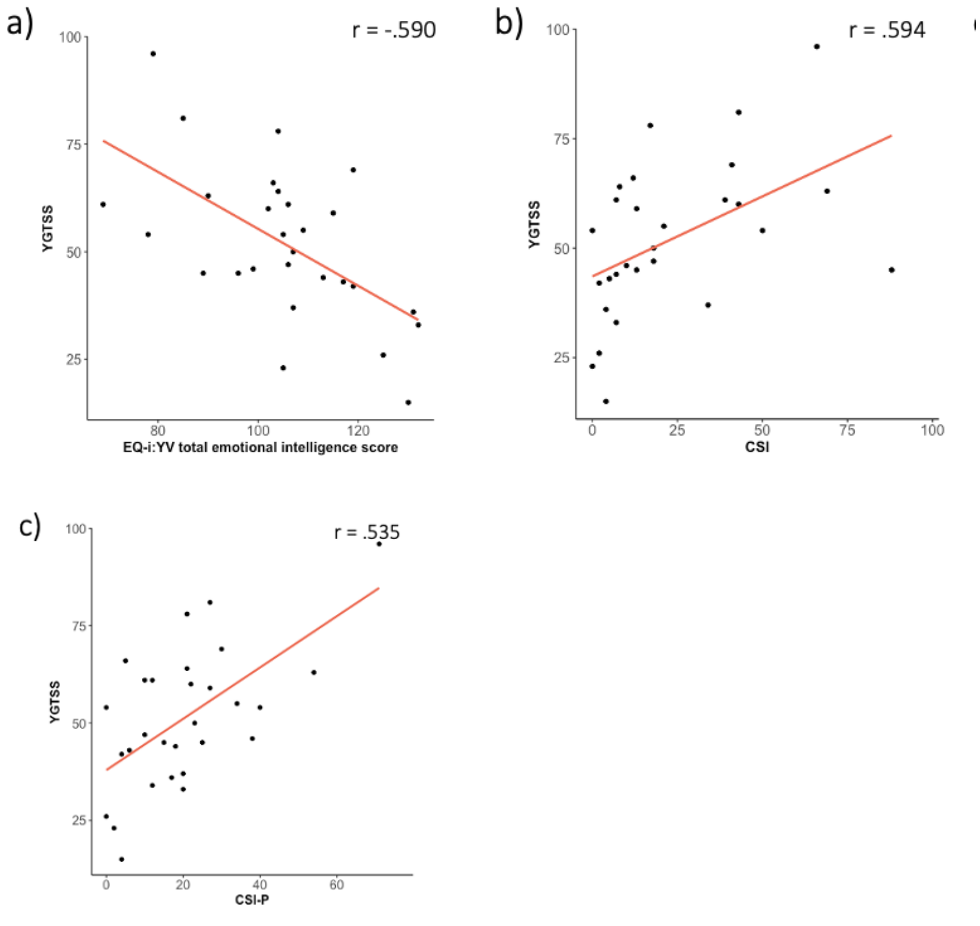
Correlations assessed the extent to which TS symptom severity (YGTSS score) was associated with emotional intelligence, alexithymia, interoceptive accuracy, and somatic complaints in the TS group (Table 5). Although YGTSS scores were unrelated to self-reported alexithymia, they were significantly negatively associated with self-reported emotional intelligence; participants who reported lower emotional intelligence had more severe TS symptoms (Figure 3a). Somatic complaints (as rated by children (Figure 3b) and their parents (Figure 3c)) were also higher in those with more severe TS symptomology.

Table 5. YGTSS correlations with total EQ-i:YV, intrapersonal scale, CAM, IAS, CSI & CSI-P scores

Statistic	EQ:i-YV	Intrapersonal Scale	CAM	IAS	CSI	CSI-P
r	**-0.590**	-0.310	0.33	-0.25	**0.594**	**0.535**
p	**<0.001**	0.054	0.042	0.098	**<0.001**	**0.001**

Note. Correlations that remained significant following correction for multiple comparisons are shown in bold text.

Figure 3. (a) Significant negative relationship between TS symptoms (YGTSS) and self-reported emotional intelligence (EQ:i-YV total emotional intelligence scores) (b) Significant positive relationship between TS symptoms (YGTSS) and self-reported somatic complaints (CSI-C) c) Significant positive relationship between TS symptoms (YGTSS) and parent-reported somatic complaints (CSI-P)



Correlations also investigated the relationship between physical and psychosocial quality of life, emotional intelligence, alexithymia, interoceptive accuracy, and somatic complaints, for both TS and MUS participants (Table 7). Multiple comparisons were corrected for using an adjusted alpha of .0125, and correlations surviving this correction are shown in bold text.

In the TS group, self-reported emotional intelligence was higher in children with better psychosocial quality of life (as reported by themselves and their parents). Physical and psychosocial quality of life were also higher in those with fewer somatic complaints in the TS group, again as measured with both self- and parent-report. In the MUS group, a similar relationship was reported with physical quality of life, such that as children reported an increased number of somatic complaints both self and parent-reported physical quality of life reduced; however, this relationship only pertained to parent-reported physical quality of life when somatic complaints were reported by the parent.

Table 7. Correlations between physical and psychosocial quality of life (child and parent-report) and EQ-i:YV total score, intrapersonal scale score, CAM, IAS scores, and somatic complaints (child and parent-report) for both TS and MUS individuals

		EQ-i:YV Total		Intrapersonal Scale		CAM		IAS		CSI - C		CSI - P	
Diagnosis	PEDSQL scale	*r*	*p*	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
TS	Physical - C	0.35	0.027	0.322	0.038	-0.101	0.295	0.09	0.316	**-0.655**	**<0.001**	**-0.575**	**<0.001**
	Physical - P	0.211	0.128	0.218	0.119	-0.252	0.082	0.092	0.311	**-0.428**	**0.008**	**-0.561**	**<0.001**
	Psychosocial - C	**0.515**	**0.002**	0.229	0.108	-0.135	0.234	0.332	0.034	**-0.734**	**<0.001**	**-0.716**	**<0.001**
	Psychosocial - P	**0.476**	**0.003**	0.361	0.023	-0.295	0.051	0.271	0.070	**-0.480**	**0.003**	**-0.479**	**0.003**
MUS	Physical - C	0.193	0.208	0.163	0.247	-0.117	0.312	0.349	0.066	**-0.604**	**0.002**	-0.351	0.064
	Physical - P	0.215	0.182	0.201	0.197	-0.321	0.079	0.508	0.011	**-0.560**	**0.005**	**-0.563**	**0.005**
	Psychosocial - C	0.450	0.023	0.195	0.205	0.041	0.569	0.528	0.008	-0.437	0.023	-0.118	0.310
	Psychosocial - P	0.398	0.041	0.154	0.259	-0.044	0.427	0.371	0.054	-0.408	0.037	-0.115	0.314

Note. Correlations that remained significant after correcting for multiple comparisons are shown in bold text.

4. Discussion

Using self- and parent-report measures, the current study investigated emotional intelligence, alexithymia severity, interoceptive accuracy, and the relationship between these in children and adolescents with clinical diagnoses of either MUS or TS. Results indicated that children with MUS and TS have greater difficulties processing emotions (as rated by themselves and their parents) and reduced self-reported interoceptive accuracy, when compared to existing normative samples. In both groups, children reporting greater difficulty recognising their internal body sensations also reported greater difficulty recognising and communicating their own and others' emotions. These interoceptive and emotion processing difficulties were also associated with TS and MUS symptom severity and quality of life, highlighting the potential clinical impact of these atypicalities.

Recent work has demonstrated a negative relationship between interoceptive accuracy and alexithymia in neurotypical individuals (Brewer et al., 2016; Herbert et al., 2011; Murphy et al., 2018) and those with a range of mental health and neurodevelopmental conditions (e.g., (Brewer et al., 2016; Shah et al., 2016). The current findings extend this literature by demonstrating an association between interoceptive accuracy and alexithymia in two new clinical groups. Parent-reported child alexithymia and self-reported emotional intelligence were both associated with children's self-reported interoceptive accuracy, in both the TS and MUS samples. Self-reported interoceptive accuracy was also associated with self-reported alexithymia in the TS group. Individuals who reported reduced interoceptive accuracy in these populations are therefore likely to experience difficulties recognising their own emotions, and be susceptible to developing the range of difficulties associated with alexithymia, such as with regulating their emotions, recognising and empathising with the emotions of others, depression and interpersonal problems, anxiety, and aggressive behaviour (Aleksitimi et al., 2007; Grynberg et al., 2012; Stasiewicz et al., 2012; Joybari, 2014; Manninen et al., 2011). While the current data are correlational, it is theoretically likely that reductions in self-reported interoceptive accuracy contribute to alexithymia, and the current data suggest that these difficulties emerge in the TS and MUS populations relatively early in life.

The current findings also indicate an association between self-reported interoceptive accuracy, emotion processing, and TS symptomology. Much research has suggested that the perception of internal bodily signals may be a crucial contributing factor to TS. It has been argued that voluntary action is distinguished from neuromotor noise by setting a movement initiation threshold, above which premotor signals are acted upon (Ganos et al., 2015). To distinguish between motor noise and voluntary action effectively, precise interpretation of sensorimotor signals is required, meaning those with high interoceptive accuracy are likely to set an appropriate threshold. Conversely, individuals with reduced interoceptive accuracy may set thresholds that are too low, with neuromotor noise frequently being acted upon and either being interpreted as either an urge to tic, or producing the tic itself.

The current results provide support for this hypothesis, indicating reduced interoceptive accuracy in a developmental sample with TS. These findings are consistent with previous experimental investigations in adults, which observed reduced interoceptive accuracy in those with TS compared to age-matched typical controls (Ganos et al., 2015; Rae et al., 2019; Pile et al., 2018). Interestingly, although those with TS had lower interoceptive accuracy as a group, the authors also noted a positive relationship within the TS sample between interoceptive accuracy and premonitory urges, such that those experiencing more premonitory urges also exhibited greater interoceptive accuracy (Ganos et al., 2015). Notably, interoceptive accuracy and attention are distinct abilities (Gabriele et al., 2022.; Murphy et al., 2019, 2020), and it is possible that increased interoceptive attention, or over-interpretation of interoceptive signals as significant, explains the relationship between perceived increases in interoceptive accuracy and urge to tic. Indeed, among multiple limitations of the heartbeat counting task (Corneille et al., 2020) is the finding that, while 95% of individuals under-report their heartbeats, over-reporting errors also occur, and are disproportionately common amongst high performers (Zamariola et al., 2018). This suggests that good performance on the heartbeat counting task may be driven partially by being more willing to report perceiving a heartbeat, or interpreting ambiguous or weak signals as perceived heartbeats. Individuals with higher premonitory urges, who set an unduly low perceptual threshold for the perception of movement, may also set a low perceptual threshold for the perception of heartbeats. While premonitory urges may be associated with increased accuracy in this specific task, therefore, further research is needed utilising a range of interoceptive accuracy measures, alongside measures assessing interoceptive attention and interpretation of internal signals more explicitly.

In line with the theory that interoceptive attention may be increased in TS, the current study observed more somatic complaints (measured by CSI scores) in those with more severe TS symptoms. While the CSI is not generally utilised as a measure of interoceptive attention, it is similar to measures such as the Body Perception Questionnaire (BPQ; Porges, 1993), which is most frequently interpreted as assessing interoceptive attention (Gabriele et al., 2022). Somatic complaints were significantly higher in the TS group than in the normative comparison group, and crucially within the TS group, higher CSI scores were associated with reduced quality of life. However, as the somatic complaints checklist confounds objective presence of internal signals and attention to these signals, replication is required using specific interoceptive attention measures, such as the recently developed Interoceptive Attention Scale (Gabriele et al., 2022). Beyond interoception, self-reported emotional intelligence was also negatively associated with TS symptom severity. As interoception and emotion processing abilities were also associated with each other in the current TS sample, and it is possible that emotional difficulties either contribute to or are a consequence of TS symptoms, longitudinal and intervention or training-based studies are required to determine the nature of these relationships in this population, and remain a priority for future research.

Similarly to in TS participants, the current findings indicated reduced self-reported interoceptive accuracy in children with MUS. Further, significant relationships were observed between symptom complaints and both child-reported interoceptive accuracy and parent-reported alexithymia, suggesting that if a child struggles to recognise interoceptive or emotional states, they also experience more somatic symptoms. This is in line with previous findings of decreased interoceptive accuracy in adults with somatoform disorder (characterised by medically unexplained symptoms), across both cardiac and respiratory domains, when compared to matched neurotypical control participants (Bogaerts et al., 2010; Pollatos et al., 2011), and with previously reported reductions in symptoms following interoceptive training in adults with MUS (Schaefer et al., 2014). The existing literature is inconsistent, however, with some authors reporting increased interoceptive accuracy, indexed by more precise interpretation of muscle tension, in patients with somatoform disorder (Berndt Scholz et al., 2001), and others reporting no difference between patients and controls on cardiac perception tasks (Schaefer et al., 2012). Interestingly, while cardiac interoceptive accuracy in a heterogeneous group of participants (including patients with somatoform disorders) was negatively associated with self-reported cardiovascular symptom distress (Witthöft et al., 2020), this relationship did not pertain in any other symptom complaint category. This in line with evidence that interoception may not be a unitary ability, but rather fractionated into distinct domains (Ferentzi et al., 2018), making it possible that individuals with MUS only exhibit decreased interoceptive accuracy in specific symptom-related domains, potentially explaining inconsistencies in the field. As the current study found reduced self-reported interoceptive accuracy across a range of interoceptive signals in children and adolescents with MUS, however, further research investigating objective interoceptive accuracy across multiple interoceptive domains and in relation to specific symptom complaints across development is warranted.

As noted above, there is an important distinction between interoceptive accuracy and attention (Gabriele et al., 2022; Murphy et al., 2019, 2020), and the high levels of somatic symptom reporting observed in the current MUS group relative to normative samples, ostensibly in the absence of objective differences in physiological signals, suggests that individuals with MUS may allocate disproportionate attentional resources towards bodily symptoms. It is possible that, as hypothesised for those with TS, individuals with MUS pay greater attention to internal bodily signals, with an atypically low threshold set for consciously perceiving these sensations. Again, future research is required using measures specifically assessing interoceptive attention, and investigating the impact of interventions aiming to reduce interoceptive attention on both TS and MUS symptoms.

Interestingly, relationships with symptom severity and quality of life tended to be stronger with measures of overall emotional intelligence than alexithymia. This suggests that broader social perception difficulties, beyond difficulties recognising and explaining one's own emotions specifically, may contribute to symptom severity and quality of life in TS and MUS. If one has difficulty interpreting and empathising with others' emotions, for example, this is likely to lead to less successful interpersonal relationships. This may negatively affect quality of life and potentially exacerbate clinical symptoms, due to lower mood and less effective social support. It is worth noting, however, that emotion processing difficulties and interoceptive atypicalities are not universal within clinical groups, including TS and MUS. Quantifying individual differences within clinical groups could therefore be beneficial in determining the most effective treatment for patients. Emotion and interoceptive processing difficulties may exacerbate symptoms, meaning that assessing these at diagnosis could predict the severity of manifestations of conditions such as TS and MUS. If, for example, failure to regulate one's emotions leads to a heightened or prolonged state of anxiety, this may in turn lead to stronger premonitory urges (Rozenman et al., 2015) or catastrophising internal signals and interpreting them as painful or uncomfortable (Tsao et al., 2009). Additionally, treatments may be ineffective if they require participants to reflect upon their emotions or interoceptive signals. Habit reversal therapy, for example, is a common treatment for TS that encourages patients to focus on their internal bodily sensations in the hope of reducing symptomology (Van de Griendt et al., 2013). For those individuals with decreased interoceptive accuracy, this may lead to an increased focus on sensations that are not perceived precisely, including premonitory urges. As increased premonitory urges appear to predict increased tic severity and reduced quality of life (Crossley & Eugenio Cavanna, 2013), this therapy may worsen, rather than improve, outcomes for these individuals. Assessing interoceptive abilities, emotional processing, and alexithymia in TS and MUS patients may, therefore, lead to better case formulation and more appropriate treatment selection based on each individual patient's needs.

While the current findings provide initial evidence for the role of interoception and alexithymia in TS and MUS across development, a number of limitations are worth taking into account and addressing in future research. First, whilst self-report measures are important tools as objective measures often focus on a single interoceptive channel and may not be sensitive to interoceptive difficulties experienced outside the laboratory, the extent to which questionnaire measures reflect interoceptive abilities accurately, in particular in developmental and clinical samples, is unclear. Encouragingly, child and adult reports generally correlated well in both groups, with relationships occasionally being stronger in the MUS than TS group. As different patterns of significance were sometimes observed across the self- and parent-report measures, however, further work should investigate the degree of insight that children with TS or MUS and their parents have into their symptoms and related difficulties, such as interoceptive atypicalities and alexithymia. Investigating the relationships between objective measures and self- and parent-report measures of the same construct would enable future research to select the most reliable questionnaire measures. Second, comparisons were made with published normative samples, rather than an additional control sample, as it was not possible to recruit a control group since the project was registered as a service evaluation, rather than a research project. Although child and adolescent samples were selected for comparison, these were not matched exactly on variables such as age, sex or IQ. It is also worth noting that findings are limited by the small sample sizes, resulting in low power to detect correlations. Finally, whilst the current study is unique in providing evidence for disrupted interoception, elevated alexithymia, and the relationship between these in children recently diagnosed with TS and MUS, it is as yet unknown whether interoceptive difficulties and alexithymia precede or follow development of MUS or TS. It is possible that those with TS or MUS experience disrupted interoceptive attention as a response to their symptomology, as they may attempt to ignore or increase attention to atypical internal signals. Similarly, reduced interoceptive accuracy may follow the onset of either disorder, as internal signals likely become noisier and harder to distinguish. Alternatively, disrupted interoception may contribute causally to the development and maintenance of both TS and MUS. Given the results of the current study, future research should employ longitudinal and intervention-based methods to further elucidate these relationships.

In conclusion, the current study replicated findings of a negative association between alexithymia and self-reported interoceptive accuracy, extending this relationship into samples of children and adolescents with TS and MUS, utilising self-report measures of interoceptive accuracy. Both emotional processing abilities and self-reported interoceptive accuracy appeared to be reduced in children with TS and MUS, again in line with findings across a range of clinical disorders. Further, these findings suggest that MUS symptoms are more severe in those who report poorer interoceptive accuracy and more pronounced alexithymia, and TS symptoms are higher in those with poorer emotional processing abilities, and potentially higher interoceptive attention, suggesting that interoception and emotional processing relate directly to disorder manifestations in children and adolescents. While further research employing objective measurements of interoceptive accuracy and attention separately in children with TS, MUS, and matched control groups is needed to further elucidate this relationship, the current findings suggest that interoception and alexithymia could play a key role in disorder development and maintenance and may affect TS and MUS treatment efficacy.

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Supplementary Materials

Supplementary Materials 1. Measures.

1.1 EQ-i:YV

The EQ-i:YV includes subscales assessing intrapersonal and interpersonal functioning, stress management, and adaptability of children and adolescents aged 7 to 18 years. For all items participants rated the extent to which they thought the items described them on a scale from 1, “very seldom true,” to 4, “very often true,” yielding total scores between 60 and 240. Higher scores on any scale are indicative of better self-reported emotional or social functioning. The EQ-i:YV factor structure has been replicated in samples across multiple nationalities (el Hassan & el Sader, 2005; Esnaola et al., 2016; Parker et al., 2005) and the scale shows high external validity, correlating with other child and adolescent trait emotional intelligence measures (Esnaola et al., 2016).

1.2 Child Alexithymia Measures (CAM)

The CAM is composed of 14 items, rated on a scale from 0, “almost never,” to 3, “almost always,” yielding scores from 0 to 42, with higher scores indicative of higher levels of alexithymia in the child/adolescent, as reported by the parent/guardian. The CAM has been found to have high internal consistency and external validity (Way et al., 2010).

1.3 Interoceptive Accuracy Scale – Child Adaptation (IAS-C)

This scale measures participants’ beliefs about their ability to perceive their internal bodily sensations accurately. The scale is composed of 20 items, each relating to a sensation that has been described as interoceptive in nature. For each sensation, participants are required to rate their ability to perceive it accurately (e.g. “I am always correct at feeling when my heart is beating quickly” on a scale from 1 (strongly disagree) to 5 (strongly agree), with total scores ranging from 20 to 100. Higher scores are indicative of higher self-reported interoceptive accuracy. In adults, IAS scores have been found to correlate moderately with measures of objective interoceptive accuracy (Murphy et al., 2020).

1.4 The Child report: Children's Somatic Symptoms Inventory (CSI; Walker et al., 1991) and the Children's Somatic Symptoms Inventory – Parent Version (CSI – P; Walker et al., 1991).

The CSI is a self-report questionnaire comprising 35 physical symptoms that the participant may have experienced, such as headaches, sore muscles and difficulty swallowing. For the purpose of this study, three items were removed from the CSI and CSI-P (Item 10: Lump in throat, Item 20: Deafness, Item 21: Double Vision) as these involve exteroceptive or emotional, rather than specifically interoceptive, symptoms.

For each symptom, participants are required to report the extent to which they are "bothered" by the symptom (overall score), how severe the symptom is (severity score), and how much it "stops [them] from doing things in [their] life" (impairment score). Each symptom is rated on a scale from 0, "Not at all," to 4, "A whole lot," with higher scores indicative of higher somatic symptom complaints, severity, and impairment.

The CSI – P is composed of identical items and scales but asks the parent/guardian to report on the frequency, severity, and impairment of each symptom in their child.

1.5. The Paediatric Quality of Life Inventory (PEDSQL™) and the PEDSQL™ parent-report

The PEDSQL is composed of 4 scales measuring parent and self-reported functioning across a number of areas (physical functioning, emotional functioning, social functioning, and school functioning). The emotional, social, and school functioning scales are summed to yield a total psychosocial scale, with the remaining items summed to provide a quality of life measure specific to physical functioning. The PEDSQL™ parent-report is composed of identical items and scales, but instead asks parents to report on their child's psychosocial and physical quality of life.

Supplementary Materials 2. Normality and outlier information for all variables.

1.1 Self-reported emotional intelligence and parent reported alexithymia

EQ-i:YV (self-reported emotional intelligence) total emotional intelligence scores were normally distributed for both TS and MUS participants. CAM (parent-reported alexithymia) scores were normally distributed for the MUS participants, but not the TS participants. Non-parametric tests were therefore employed in the TS group. No outliers were detected for either group for either measure.

1.2 Interoceptive accuracy

Child IAS (self-reported interoceptive accuracy) scores were not normally distributed in the MUS or TS group, so non-parametric (Spearman's Rho) tests of association were employed.

1.2 Somatic Complaints

CSI (somatic complaints) overall scores were not normally distributed for either the TS or MUS group. CSI-P overall scores were normally distributed for the MUS group, but not the TS group. Non-parametric tests of association were therefore employed. There was one CSI overall score outlier, greater than the 3rd quartile plus 1 .5 times the interquartile range or less than the 1st quartile minus 1.5 times the interquartile range, for both the TS and MUS groups and two outliers for the CSI-P scores in the TS group. Analyses are reported including these individuals, but their exclusion did not alter the pattern of significance observed.

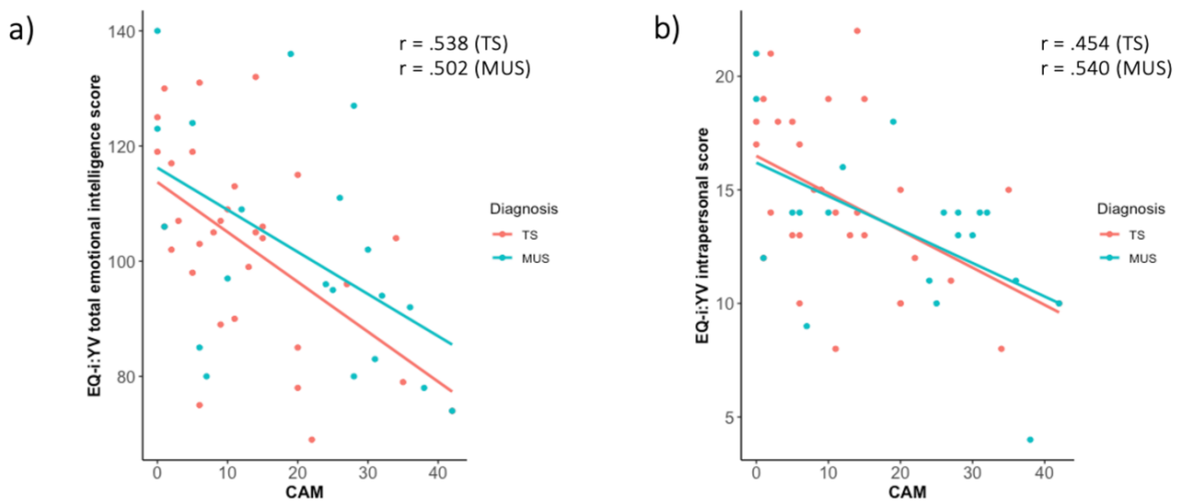
1.3 Impairment

Child and parent-reported psychophysical quality of life scores were not normally distributed for the TS or MUS group. Child-reported physical quality of life scores were not normally distributed for either group, nor were parent-reported physical quality of life scores in the TS group. Therefore, non-parametric tests were employed for these scales. In the MUS group, parent-reported physical quality of life scores were normally distributed, so parametric analyses were employed for this scale where appropriate.

Supplementary Materials 3. The relationship between child and parent-report for all measures.

Parental reports of alexithymia were significantly negatively correlated with child reports of both emotional intelligence and alexithymia, as expected, within both the TS, emotional intelligence: $r(29) = -.538$, $p = .001$; alexithymia: ($r(29) = -.454$, $p = .005$, and MUS, emotional intelligence: $r(18) = -.502$, $p = .012$; alexithymia: $r(18) = -.540$, $p = .007$, groups, with parents reporting higher alexithymia in their children as children rated themselves as having lower emotional intelligence (Figure S1). Fisher r-to-z analyses indicated that the strength of the relationship did not differ between the two groups, emotional intelligence: $z = -0.152$, $p = 0.440$; alexithymia: $z = 0.353$, $p = 0.362$, suggesting that parents of children with TS and MUS have similar insight into their child's emotional abilities.

Figure S1. (a) Scatter plot showing significant negative correlation between self-reported emotional intelligence (EQ-i:YV total emotional intelligence score) and parent-reported alexithymia (CAM) across TS and MUS individuals. (b) Scatter plot showing significant negative correlation between alexithymia (EQ-i:YV intrapersonal subscale) and parent-reported alexithymia (CAM)



CSI and CSI-P overall scores were significantly positively correlated in both the TS ($r(29) = .775$, $p < .001$) and MUS ($r(18) = .447$, $p = .024$) groups (Figure S2). Fisher r-to-z analyses indicated that the correlation between child and parent reports was significantly stronger for the TS than MUS group ($z = 1.702$, $p = 0.044$), suggesting even greater parental insight into their child's somatic symptoms in the TS group. Correlations were also assessed between the impairment and severity subscales of the CSI and CSI-P, with these scores significantly positively correlated in both groups. 2.

Figure S2. Scatterplot depicting the significant positive correlation between CSI and CSI-P scores for both TS and MUS individuals.

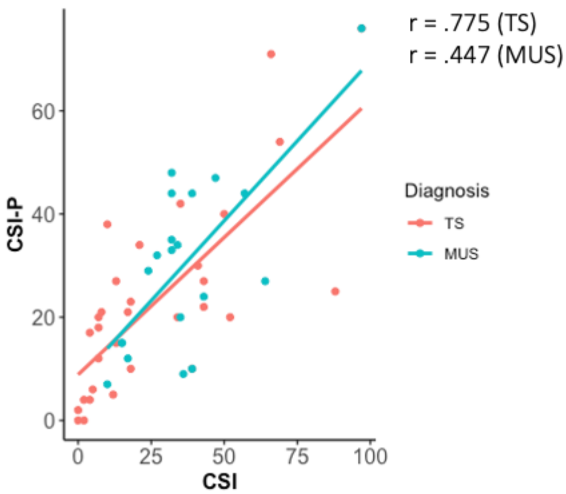


Table S1. Nonparametric correlations (Spearman's rho) between the CSI-C and CSI-P impairment and severity subscales in TS and MUS groups

	Subscale (CSI)			
	Impairment		Severity	
Diagnosis	*r*	*p*	*r*	*p*
TS	**0.653**	**<.001**	**0.664**	**<.001**
MUS	**0.655**	**0.001**	**0.539**	**0.007**

Parental and child-reports were significantly positively correlated for both physical and psychosocial quality of life in the TS and MUS groups (Table S3). Fisher r to z tests suggested the strength of the correlation did not differ between the MUS and TS groups for physical quality of life (z = -0.602, p = 0.274). The correlation between parent and child-reports of psychosocial quality of life, however, was significantly stronger within the MUS than TS group (z = -1.90, p = 0.029).

Table S2. Nonparametric correlations (Spearman's rho) between the Physical and Psychosocial PEDSQL scales in TS and MUS groups. Correlations that remained significant following Bonferroni correction for multiple comparisons are shown in bold text.

	PEDSQL Scale			
	Physical		Psychosocial	
Diagnosis	*r*	*p*	*r*	*p*
TS	**0.499**	**0.002**	**0.560**	**0.001**
MUS	**0.631**	**0.001**	**0.848**	**<.001**

Supplementary Materials 4. Somatic complaints in TS, MUS, and a non-clinical sample.

Further analyses were conducted to compare CSI scores for TS and MUS participants to an existing normative sample (Vila et al., 2009), ranging in age from 11 – 17 (M = 13.5, SD = 1.5). Children in the normative group completed the 35-item CSI, as opposed to the 32-item version which was administered in the current study. As the total CSI score is a sum of each item, to enable comparison of scores, scores from the current sample were multiplied by 35/32 before conducting further analyses. Although the current CSI scores were not normally distributed, non-parametric independent sample analyses (Mann Whitney U tests) were not possible without access to the full comparison dataset. Therefore, both independent samples *t*-tests and non-parametric one-sample (Wilcoxon signed rank) tests were conducted.

Independent samples *t*-tests revealed that both TS (M = 29.11, SD = 28.96; $t(29) = 2.319$, p = 0.02) and MUS (M = 39.76, SD = 21.50; $t(18) = 4.708$, $p < 0.001$) group CSI scores were significantly higher than in the normative sample (M = 16.98, SD = 17.1). Furthermore, one sample Wilcoxon signed rank tests revealed that CSI scores were significantly greater in both the TS (*Mdn* = 18.59, *Range* = 0, 106.09; V = 369, z = -2.362, p = 0.009) and MUS groups (*Mdn* = 36.09, *Range* = 10.94 – 106.09; V = 209, z = -4.034, $p < .001$), such that participants reported a significantly higher number of somatic complaints than the median from a normative sample (*Mdn* = 12, *range* = 5, 23; Vila et al., 2009).

Supplementary Materials 5. Correlations between somatic complaints, self-reported emotional intelligence, alexithymia (child and parent-report), and self-reported interoceptive accuracy

Table S3. Nonparametric correlations (Spearman's rho) between somatic complaint severity and impairment (child and parent-report) and EQ-i:YV total score, intrapersonal scale score, CAM and IAS scores, for both TS and MUS individuals

		EQ:i-YV Total		Intrapersonal Scale		CAM		IAS	
Diagnosis	Somatic Complaints Measure	*r*	*p*	r	*p*	*r*	*p*	*r*	*p*
TS	CSI Severity - C	-0.329	0.035	-0.244	0.093	0.058	0.377	-0.145	0.219
	CSI Severity - P	-0.340	0.030	-0.388	0.016	0.349	0.025	-0.254	0.084
	CSI Impairment - C	-0.328	0.036	-0.269	0.071	0.004	0.491	-0.119	0.261
	CSI Impairment - P	-0.401	0.013	**-0.417**	**0.010**	0.288	0.055	-0.288	0.058
MUS	CSI Severity - C	-0.220	0.176	-0.227	0.168	0.417	0.034	-0.437	0.027
	CSI Severity - P	-0.306	0.095	-0.181	0.223	**0.719**	**<.001**	**-0.537**	**0.007**
	CSI Impairment - C	-0.310	0.092	-0.219	0.177	0.461	0.020	**-0.506**	**0.011**
	CSI Impairment - P	-0.242	0.152	-0.202	0.197	**0.713**	**<.001**	-0.437	0.027

Note. Correlations that remained significant following correction for multiple comparisons are shown in bold text.

Chapter 8. Discussion

8.1 Brief Summary

The current thesis aimed to investigate the processing of others' interoceptive expressions, and its relationship with the processing of interoceptive states in one's own body, across various cognitive domains. Very little research has investigated the processing of these states in others, beyond the emotional domain. Where emotions are concerned, the processing of one's own emotions is theorised to be crucial for the processing of others' emotions (Bird & Viding, 2014). Empirical evidence supports this assertation, reporting an inverse relationship between the processing of others' emotions and alexithymia (difficulties identifying and describing one's own emotions; Luminet et al., 2021), such that elevated alexithymia is associated with decreased recognition of (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), memory for (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout, 2021.; Vermeulen et al., 2006; Vermeulen & Luminet, 2009) and attention to (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013) others' emotions. Individuals with higher levels of alexithymia also tend to appraise emotional stimuli as less emotive (Luminet et al., 2021). The processing of others' emotions also plays a role in a range of cognitive and mental health outcomes (Gross, 2002; Hu et al., 2014; Kret & Ploeger, 2015; Parker et al., 2004; Schutte et al., 2007). It is likely that the same is true for others' interoceptive expressions; beyond the obvious implications for providing adequate care, failing to recognise or attend to another person who is feeling tired, hungry, or unwell, may lead to difficulties in responding appropriately, in turn, negatively affecting social relationships.

Using the recently released Interoceptive Static State Stimuli database (ISSI; Biotti et al., 2021), this thesis addresses the gap in the literature investigating the processing of others' interoceptive expressions and its relationship with self-reported interoceptive processing, across multiple cognitive domains. As the processing of one's own interoceptive and emotional states appear closely related (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013; Gendron & Barrett, 2009; James, 1894; Lange, 1885; Schachter & Singer, 1962) it was predicted that we might learn to process others' interoceptive states by a similar mechanism as we do emotions. If so, a more precise perception of your own internal bodily states might improve your mental concept of that state (Barrett, 2014). With both, a better-defined mental concept of what internal state feelings are and a more precise understanding of what they feel like, you would be better equipped to learn to process the expressions associated with others' interoceptive states. We would, therefore, expect that the processing of one's own internal states would be closely related to the processing of others. Recognition accuracy, attention to and memory for interoceptive expressions are investigated in this thesis, as well as propensity to assign interoceptive labels to others' interoceptive expressions. As well as in relation to the processing of one's own internal staes, individual differences in the processing of others' interoceptive expressions were investigated in relation to age and gender.

Finally, this thesis investigated self- and parent-reported interoceptive and emotional functioning in children and adolescents with Medically Unexplained Symptoms (MUS) and Tourette Syndrome (TS), as well as their relationship with symptom severity and quality of life. Research in children and adolescents with MUS and TS not only informs findings on whether interoceptive and emotional atypicalities exist in these groups, as they do in other clinical disorders (Garfinkel et al., 2016; Hatfield et al., 2019; Mul et al., 2018; Nicholson et al., 2019; Aaronson et al., 2017; Dunn, Stefanovitch, et al., 2010; Furman et al., 2013; Pollatos et al., 2008; Jakubczyk et al., 2019; Naqvi & Bechara, 2010; Paulus & Stewart, 2014), but also paves the way for future research aimed at investigating the impact of interoceptive atypicalities on the processing of others' interoceptive expressions in clinical populations.

8.1.1 Study One: summary and interpretation.

Study One explored the relationship between the recognition of others' interoceptive expressions and self-reported interoceptive accuracy and attention, in participants aged 16 to 21 years. Study One aimed to assess whether, as with emotions (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), self-reported difficulties recognising or attending to one's own interoceptive states were associated with reduced accuracy in the recognition of others' interoceptive expressions. Results indicated that participants could successfully infer others' internal states from static images, posed by actors, evidenced by performance significantly greater than chance on an alternative forced choice task. Whilst this finding is perhaps unsurprising, given that recognising how others feel is essential for positive social interactions (Izard et al., 2001; Wang et al., 2019), substantial variance in performance was observed across participants. It therefore seems that, as with emotion recognition, the recognition of interoceptive expressions may be related to other psychosocial and mental health factors (Besel & Yuille, 2010; Wells et al., 2020). Despite this, contrary to predictions, no relationship was observed between the recognition of others' interoceptive expressions and self-reported interoceptive accuracy and attention, assessed with the Child-Adapted Interoceptive Accuracy (IAS-C) and Attention Scale (IATS-C) respectively. These findings suggest that, unlike with emotions (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014), difficulties recognising one's own interoceptive states are not associated with difficulties recognising these states in others.

No relationship was found between age and recognition of others' interoceptive expressions, or one's own interoceptive processing, perhaps owing to the small age range in Study One. Interoceptive state recognition was, however, affected by both actor and observer gender. Similarly to with emotions (Abbruzzese et al., 2019; Olderbak et al., 2019; Sullivan et al., 2017; Thompson & Voyer, 2014), women were significantly more accurate at recognising others' interoceptive expressions than men. Perhaps unsurprisingly, given research that demonstrates a similarity advantage in the recognition of others' emotions (Elfenbein et al., 2002; Soto & Levenson, 2009), participants were also significantly more accurate at recognising others' interoceptive expressions when they were posed by an actor of their own gender (e.g., females observing females), rather than an actor of another gender (e.g., females observing males). Overall, participants were also significantly more accurate at recognising interoceptive expressions when they were posed by females, rather than males. Interestingly, research has previously suggested that ambiguous internal states in children are more likely to be labelled by adults as interoceptive in boys (Prentice et al., 2022). Conversely, both male and female adults appear to use more emotional language to describe their female than their male children (Fivush et al., 2000; Kuebli & Fivush, 1992; Mascaro et al., 2017). The findings of Study One, however, suggest that, at least in adulthood, women portray interoceptive states more recognisably than do men. Differences in labelling children's states may, therefore, result from the contrasting societal expectations for boys and girls, rather than being explained by less reliable state depictions by females. Alternatively, this pattern of results may be driven by differences between naturally elicited expressions and posed expressions, or changes that occur between childhood and adulthood.

Despite the gender differences concerning the recognition of others' interoceptive expressions, males and females self-reported similar interoceptive accuracy and attention. These findings contrast with previous literature, which reports reduced objective interoceptive accuracy in women, at least in the cardiac and respiratory domains (Prentice & Murphy, 2022). While this may suggest that women have decreased interoceptive insight, the lack of gender differences in self-reported interoceptive attention also contradicts existing literature (Grabauskaite et al., 2017), so perhaps the current findings are reflective of the small number of males in Study One. Given the inconsistencies in findings, future research is clearly needed which investigates gender differences in self-reported and objective interoceptive accuracy and attention within the same individuals.

8.1.2 Study Two: summary and interpretation.

Study Two investigated the propensity to assign interoceptive, over action, labels to others' interoceptive expressions. Similarly to Study One, Study Two aimed to assess whether the identification of one's own and others' interoceptive expressions were related, as is the case for the identification of one's own and others' emotions (Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014; Luminet et al., 2021). Whilst Study One assessed recognition by asking participants to select the correct interoceptive state label from multiple options, Study Two provided two valid labels to describe the image, with one being interoceptive and one simply describing the actor's actions. Study Two, therefore, extends the findings of Study One by assessing the tendency to interpret another's actions as indicative of interoceptive sensations, rather than the ability to distinguish between multiple interoceptive expressions. These are two separable processes that will affect the likelihood of one correctly interpreting another's internal state in real world settings.

Overall, participants selected significantly more interoceptive than action labels, but individual differences were also observed. Whilst no relationship was observed between self-reported interoceptive attention and labelling propensity, self-reported interoceptive accuracy was positively associated with the propensity to assign an interoceptive label. As an individual self-reported increased precision in the processing of their own internal states, they were also more likely to interpret others' actions as indicative of a change in interoceptive state. In contrast to Study One, therefore, these findings suggest that the processing of one's own interoceptive states is related to the processing of these states in others.

Further conflicting with the findings of Study One, age was associated with both self-reported interoceptive attention and the labelling of others' interoceptive expressions in Study Two, likely due to the wider age range that was employed. As age increased, participants reported paying less attention to their internal bodily signals, replicating previous findings (Murphy, et al., 2018c). Given that increasing age is associated with vulnerability to numerous health problems, it is likely that this serves as a compensatory mechanism to reduce health-related anxiety. Propensity to assign an interoceptive label to others was also negatively related to age, such that as age increased participants were more likely to assign an action, over an interoceptive, label to others' interoceptive expressions. Whilst this was in line with predictions, the effect of age on labelling did not appear to be explained by changes in self-reported interoceptive processing. Instead, it is possible that this effect is mediated by changes in social interaction. Indeed, older age is typically associated with reduced social interaction and smaller social networks (Cornwell, 2011; Wrzus et al., 2012), which are likely to lead to fewer opportunities to observe others experiencing internal states. It is plausible that, as well as using knowledge of one's own interoceptive states and their associated expressive cues, humans also learn about interoceptive cues from observing others' interoceptive expressions when they are accompanied by objective information. Decreased social contact is, therefore, likely to hinder the processing of others' interoceptive expressions through reduced exposure to a variety of interoceptive state depictions.

As in Study One, self-reported interoceptive accuracy was unrelated to gender in Study Two, with males and females reporting similar precision in the recognition of their own interoceptive states. Contrary to Study One, however, and in line with previous research (Grabauskaite et al., 2017), women self-reported significantly higher interoceptive attention than did men. Whilst participant gender had no effect on propensity to assign an interoceptive label to others, participants were more likely to assign an interoceptive label to an expression posed by a male than by a female. As Studies One and Two utilised identical stimuli, and Study One found that interoceptive expressions depicted by females were recognised more accurately than those posed by males, it is unlikely that this effect is explained by differences in actors' depictions. Rather, differences in labelling may be explained by social experiences and top-down biases in the perception and interpretation of others' interoceptive expressions.

8.1.3 Study Three: summary and interpretation.

Study Three investigated attentional biases in the processing of others' interoceptive and action expressions, and their relationship with self-reported interoceptive accuracy and attention. As difficulties recognising one's own emotions (alexithymia) appear associated with reduced attention to others' emotional expressions (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013), Study Three aimed to assess whether the same is true for interoceptive states. Early attentional biases were assessed using a dot-probe paradigm, whereby participants were presented with neutral and action or interoceptive body postures, immediately followed by a target on one side of the screen. No attentional biases were reported in the processing of interoceptive expressions, for younger or older adults, such that there were no differences in reaction time when the target replaced the interoceptive or neutral stimulus, across either presentation time (500ms and 800ms). Despite this, younger adults did appear to possess an attentional bias towards action, over neutral, postures. Whilst these findings suggest that dot-probe paradigms can be utilised to elicit attentional biases in the processing of body postures, they raise interesting questions concerning the processing speed of actions and interoceptive expressions. It is possible that interoceptive expressions do elicit an attentional advantage, but that this occurs at earlier stages of processing and was therefore not captured in Study Three, perhaps owing to inhibition of return attentional effects (Klein, 2000; Lupiáñez et al., 2006). Additionally, contrary to hypotheses, no relationship was reported between attention to others' interoceptive expressions and self-reported interoceptive attention. It seems, therefore, that unlike with emotion (Pfabigan et al., 2014; Luminet et al., 2021; Van der Velde et al., 2013), attention to others' interoceptive expressions may not be associated with self-reported interoceptive processing. Alternatively, this relationship may again have been masked by paradigm-specific factors, such as stimulus presentation time.

Similarly, age was unrelated to attention to others' interoceptive states in Study Three. As significantly greater attention to actions was observed when the younger sample (under 30 years of age) was considered in isolation, however, it may be the case that dot-probe paradigms are inappropriate for exploring attentional biases in older adults, perhaps owing to reduced attentional control and longer response times (Campbell et al., 2015; Hultsch et al., 2002). As in Study Two, Study Three also replicated previous findings of a negative relationship between self-reported interoceptive attention and age (Murphy et al., 2018c), whereby increasing age was associated with participants reporting paying less attention to their own interoceptive signals. In line with Study Two, Study Three also found no relationship between self-reported interoceptive accuracy and age.

8.1.4 Study Four: summary and interpretation.

Study Four investigated memory for others' interoceptive expressions and actions, using an 'old or new' recognition memory paradigm. As previous research has reported a negative relationship between reduced memory for emotional stimuli and alexithymia (Donges & Suslow, 2014; Meltzer & Nielson, 2010; Ridout et al., 2021; Takahashi et al., 2015; Vermeulen et al., 2006; Vermeulen & Luminet, 2009), Study Four aimed to investigate whether self-reported interoceptive accuracy and attention would be similarly related to memory for others' interoceptive expressions. Contrary to predictions, no significant difference was observed between long-term memory for interoceptive and action postures. Findings suggest, therefore, that interoceptive states are no better encoded than actions, contrasting with the well-documented salience effect and memory advantage for emotional stimuli (Yiend, 2010).

Further, no relationship was reported between memory for others' interoceptive expressions and self-reported interoceptive accuracy or attention, suggesting that the processing of interoceptive states in oneself is unrelated to memory for others' interoceptive expressions. Interestingly, in Study Three, no relationship was observed between self-reported interoceptive attention and attention to others' interoceptive expressions. As biases in attention are likely to affect subsequent stages of processing, such as memory (Adolphs, 2002; Spunt & Adolphs, 2019), perhaps the lack of relationship between memory for others' interoceptive expressions and self-reported interoceptive processing is, in fact, to be expected. It might be the case that reduced memory for interoceptive expressions only occurs following reduced attention to interoceptive expressions. Future research assessing attentional and memory biases in the same individuals is therefore required to investigate this hypothesis.

8.1.5 Study Five: summary and interpretation.

Study Five differed from Studies One to Four as it did not investigate the processing of others' interoceptive expressions. Instead, Study Five investigated self- and parent-reported emotional intelligence, alexithymia, interoceptive accuracy, and the relationship between these in children and adolescents, aged 8 to 17 years, with a clinical diagnosis of either Medically Unexplained Symptoms (MUS) or Tourette Syndrome (TS). As previous research has reported interoceptive and emotional atypicalities in a range of clinical disorders (Aaronson et al., 2017; Dunn et al., 2010; Furman et al., 2013; Garfinkel et al., 2016; Hatfield et al., 2019; Jakubczyk et al., 2019; Mul et al., 2018; Naqvi & Bechara, 2010; Nicholson et al., 2019; Paulus & Stewart, 2014; Pollatos et al., 2008), Study Five compared self- and parental-reports to normative groups, and explored their relationship with symptom severity and quality of life. The use of parental reports provided additional evidence on the potential difficulties faced by children with MUS and TS, which was particularly important given reports of reduced insight in children and clinical groups (Barbosa et al., 2002; Eiser & Varni, 2013; Garfinkel et al., 2016; Sherifali & Pinelli, 2007; Van Roy et al., 2010), as well as providing insight into the alignment of parent and child reports.

Results indicated that children with MUS and TS experience significantly more difficulties recognising and describing their emotions, as rated by themselves and their parents, when compared to a normative sample. Children with MUS and TS also self-reported more difficulties perceiving their interoceptive states accurately, in line with existing findings in other clinical groups (Aaronson et al., 2017; Dunn et al., 2010; Furman et al., 2013; Garfinkel et al., 2016; Hatfield et al., 2019; Jakubczyk et al., 2019; Mul et al., 2018; Naqvi & Bechara, 2010; Nicholson et al., 2019; Paulus & Stewart, 2014; Pollatos et al., 2008). In line with predictions, self- and parent-reported emotional processing also appeared closely related to self-reported interoceptive accuracy in children with TS and MUS; as children and their parents reported more difficulties processing emotions, children also self-reported more difficulties in perceiving their interoceptive states precisely. As individual differences in interoception, emotional intelligence, and alexithymia were also closely related to symptom severity and quality of life, it is likely that individual differences in interoceptive accuracy and emotional processing play a role in the development and maintenance of these conditions, as well as clinical outcomes.

8.2 Overall implications

This thesis highlights the limited evidence which has investigated the processing of others' internal states, beyond the emotional domain, whilst beginning to address this by exploring the processing of others' interoceptive expressions, across a range of cognitive domains. Whilst investigating the impact of individual differences in the processing of others' interoceptive expressions is beyond the remit of the current thesis, providing evidence of the existence of these is crucial in paving the way for future research. Crucially, this thesis provides the first investigation of the potential correlates of individual differences in the processing of others' interoceptive expressions. Previous research has demonstrated that emotional and interoceptive processing appear closely related (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013b; Gendron & Barrett, 2009; James, 1894; Lange, 1885; Schachter & Singer, 1962), as do the processing of one's own and others' emotions (Bird & Viding, 2014; Grynberg et al., 2012; Heaton et al., 2012; Jongen et al., 2014; Luminet et al., 2021). Whether the processing of one's own and others' interoceptive states are also associated, however, remained to be seen. This thesis, therefore, investigated individual differences in the processing of others' interoceptive expressions in the context of self-reported interoceptive processing. Surprisingly, however, limited evidence for a relationship between self-reported interoceptive processing and the processing of others' interoceptive expressions was found, Self-reported interoceptive abilities were not found to be associated with memory for or attention to others' interoceptive expressions. Relatedly, no memory or attention advantage was seen for interoceptive expressions over action postures. A more nuanced picture, however, seems to exist for recognition accuracy, assessed using two distinct paradigms in Studies One and Two.

The paradigms employed in Studies One and Two utilised identical interoceptive state stimuli taken from the ISSI database (Biotti et al., 2021), with the exception of one state being removed in Study Two, with the main difference between these paradigms being the available response options. Study One presented participants with multiple interoceptive labels, requiring participants to differentiate between interoceptive states. Although there were also options for 'running' and 'animal', these were easily distinguished (with performance at ceiling level) and included as a control task to ensure findings were not driven by individual differences in factors such as attention to the stimuli or the ability to perform the alternative forced choice task. In this task, therefore, participants viewed interoceptive expressions, knowing that an interoceptive state was being experienced, and were tasked with discriminating between multiple expressions, some of which are expressed very dissimilarly (e.g., itch and nausea), and others of which shared postural cues (e.g., satiety and nausea, where hands were often placed on the abdomen). In contrast, Study Two provided two valid labels to describe the image, with one being interoceptive and one simply describing the actor's actions, assessing the tendency to interpret another's actions as indicative of an interoceptive state. In this task, therefore, participants were not required to distinguish between various types of interoceptive change; instead, the task assessed participants' tendency to believe that an individual's actions were driven by interoceptive changes. Where Study One found no relationship between the recognition of others' interoceptive expressions and self-reported interoceptive processing, Study Two observed a significant association between self-reported interoceptive accuracy and labelling propensity score; participants who reported increased precision in the perception of their own interoceptive states also had a higher tendency to select interoceptive labels to describe others' interoceptive expressions. Both the tendency to interpret another's actions as indicative of interoceptive states and the ability to distinguish between multiple interoceptive expressions are likely to contribute to one's accuracy identifying interoceptive signals in others. It is therefore clear that further research is needed to assess both aspects of processing and their relationship with self-reported interoceptive abilities in the same individuals. Indeed, whether the tendency to infer interoceptive states from actions and the ability to distinguish between interoceptive states are related is also of interest.

Perhaps even more pertinently, however, these findings demonstrate the importance of methodology and the use of response labels in experimental design. It is well documented that even in paradigms with identical stimuli, changes to response labels can alter reported relationships between variables (Alwin & Krosnick, 1991; Braitman et al., 2015; Krosnick et al., 2002). As seen in the current thesis, the modification of response options led to different conclusions concerning the relationship between the processing of interoceptive states in oneself and others. The findings from Studies One and Two, therefore, highlight the importance of carefully considering the role of methodology and response options when interpretating findings. A number of issues are of relevance to the current thesis. Firstly, these studies were designed to assess two distinct aspects of interoceptive expression recognition, and response options were carefully selected in order to allow for their separation. While this is advantageous in terms of experimental rigour and enabling specific investigation of distinct aspects of interoceptive expression processing, it may not reflect real world performance well, especially if one's tendency to interpret actions as interoceptive and one's ability to distinguish between interoceptive expressions are either related or interact with each other. Secondly, it is possible that if alternative response options were utilised (for example if only state labels that tend to be confused, such as nausea and satiety, were available for these stimuli in Study One) this would have a substantial impact on participants' performance, and potentially its relationship with self-reported interoceptive abilities. This issue is not specific to the current studies; both the ambiguity of stimuli and the number of and perceived validity of available response options are likely to have affected findings in the existing emotion recognition literature and, thus, should always be taken into consideration when interpreting findings.

Whilst the hypotheses presented in this thesis have sound theoretical reasoning, as no relationship was reported between self-reported interoceptive processing and recognition of, attention to and memory for others' interoceptive expressions it is worth noting that these hypotheses may, in fact, be unsupported by future research. If so, this would suggest that the processing of others' interoceptive states is unrealted to the ability to perceive these states in one's own body. In other words, an understanding of one's own internal states is not required to process others' internal states. A finding such as this would contradict much of what is currently understood aboutthe role of one's own internal states in processing those of others (Bird & Viding, 2014). Howerever, it may be sufficient to learn about others' expressions through verbal labels, or one's own interoceptive abilities may be utilised in childhood to inform learning about interoceptive expressions, but not contribute 'on-line' to interoceptive expression recognition once learning has occurred. As these are the first investigations of their kind, furture research is needed to further delineate the relationships between the processing of one's own and others' interoceptive states. As it seems likely that some understanding of one's own internal states is required to understand others, research should focus on investigating the relationship between the processing of one's own and others' interoceptive states in early development and those with profound interoceptive difficulties (for a detailed discussion of potential future research directions see Section 8.3). Nonetheless, this thesis does provide evidence for a relationship between self-reported interoceptive processing and the propensity to assign interoceptive labels to others' interoceptive expressions, suggesting that further work utilising a range of methodologies to allow additional relationships to be uncovered should they exist, is warranted.

Beyond investigating the impact of self-reported interoceptive processing on the processing of others' interoceptive expressions, this thesis also explored individual differences in the context of gender. While conflicting findings are reported on the influence of gender on the processing of one's own interoceptive states, actor and participant gender were consistently related to individual differences in the processing of others' interoceptive expressions. In line with the emotion literature (Abbruzzese et al., 2019; Olderbak et al., 2019; Sullivan et al., 2017; Thompson & Voyer, 2014), women appear to display superior recognition of others' interoceptive expressions, despite male and female participants exhibiting similar tendencies to select interoceptive, over action, labels to describe interoceptive expressions. Interestingly, a recent meta-analysis revealed that women perform significantly worse than men on objective behavioural tasks in both the cardiac and respiratory domains (Prentice & Murphy, 2022). It is, therefore, unlikely that the relationship between participant gender and recognition of others' interoceptive states can be explained by individual differences in interoceptive processing in the self. Rather, it is likely that the superior performance exhibited by women is explained by differences in the socialisation experience of males and females (Prentice et al., 2022). Irrespective of participant gender, the current thesis also found that women's depictions of internal states are more likely to be distinguished accurately from other interoceptive states, but less likely to be labelled as interoceptive (as opposed to being labelled as actions) than those posed by men. This finding further supports research which suggests that internal states are more commonly interpreted as interoceptive (rather than, for example, as emotional) in males than females (Prentice & Murphy, 2022), whilst suggesting that these differences cannot be explained by poorer state depictions by females. Again, these findings may therefore be attributed to social expectations relating to gender. Interestingly, there are multiple societal expectations which might lead to preconceptions in the interpretation of others' interoceptive state displays. It is plausible that there is an expectation for men to be physically stronger, or less affected by physical changes in their body, therefore, any postural or expressional cues associated with the experience of an interoceptive state may be considered to be associated with extreme hunger, nausea, or breathlessness, for example. On the other hand, women may be considered more affected by physical changes in their body and, therefore, their interoceptive expressions may be less likely to be relied upon, or thought to be indicative of less intense interoceptive experiences. If this is the case, cues associated with interoceptive states in men would be more likely to be labelled as interoceptive than in women. Alternatively, it is possible that it is adaptive to identify subtle interoceptive cues in men as, if indicative of ill-health or reduced strength, historically this may have leaft them less able to fulfil assigned societal roles (e.g., hunting or fighting), negatively impacting the group. Future work should aim to investigate the extent to which preconceptions about males' and females' internal experiences (for example their emotional responsiveness, susceptibility to illness, and pain thresholds) predict interpretation of their interoceptive expressions.

The finding that male and female interoceptive expressions tend to be interpreted differently supports existing literature (Fivush et al., 2000.; Kuebli & Fivush, 1992; Mascaro et al., 2017; Prentice et al., 2022) and has important implications for both social interactions and medical care. Indeed, failure of medical professionals to interpret physical symptoms correctly in males, or to attribute behavioural symptoms to internal changes in females, would potentially lead to misdiagnosis and inappropriate treatment approaches. While further research is required to determine the likelihood of these outcomes, it is possible that medical professionals would benefit from training on the potential effects of patient gender on the manifestation of physical symptoms of illness.

Age also appears related to state labelling, such that increasing age is related to a decreased tendency to interpret others' actions as being indicative of interoceptive change. As this tendency does not appear to be related to changes in self-reported interoceptive processing, this relationship might be explained by reduced social contact leading to decreased sensitivity to others' interoceptive states, similar to that reported with the perception of others' emotions (Lambrecht et al., 2012; Ruffman et al., 2008). Older adults display lower cognitive empathy (Beadle & Vega, 2019), often manifesting as difficulties understanding others' thoughts and feelings, and perhaps in turn increasing the tendency to label others' interoceptive expressions as actions. As with emotion (Gross, 2002; Schutte et al., 2007), the recognition of interoceptive states is presumably important for a range of mental health and cognitive outcomes, as well as in the provision of appropriate care and building relationships. Perhaps the importance of building social relationships decreases with age, however, making inferences about others' interoceptive states less crucial for older adults. Nonetheless, older age is a key risk factor in the development of a range of mental and physical health conditions, including Parkinson's (Reeve et al., 2014), dementia (McCullagh et al., 2001), and cardiovascular disease (Leritz et al., 2011). As older adults are likely to spend time with others of a similar age, these individuals are at a higher risk of experiencing interoceptive changes associated with ill-health. Relatedly, older adults often display difficulties in verbalising their feelings (Khalsa et al., 2009; Murphy et al., 2017; Yorkston et al., 2010), meaning the accurate detection and interpretation of others' interoceptive expressions is likely to play a key role in determining others' internal states. Whilst the importance of processing others' interoceptive expressions may become less important in the context of building social relationship in older age; in the context of providing or identifying the need for adequate care for others, it is likely to become paramount. Future research is, therefore, required to investigate age-related changes in the processing of others' interoceptive expressions, with a particular focus on the explanations for and impact of any change in processing.

Beyond findings relating to the perception of others' interoceptive states, the current thesis also reports a series of findings on self-reported interoceptive processing. First and foremost, once interpretation questions have been included alongside the Interoceptive Accuracy Scale (IAS; Murphy et al., 2019a, 2020) and Interoceptive Attention Scale (IATS; Gabriele et al., 2022), no relationship was found between these measures, supporting the conceptual distinction between interoceptive accuracy and attention (Gabriele et al., 2022; Murphy et al., 2019a; Murphy et al., 2020a; Suksasilp & Garfinkel, 2022). This finding is particularly compelling considering the IAS and IATS are matched perfectly in terms of the interoceptive signals they enquire about. In line with this distinction, in the current thesis, females tended to report increased attention to interoceptive states when compared to males, despite reporting similar levels of interoceptive accuracy. This is in line with previous findings (Grabauskaite et al., 2017) and has implications for physical and mental health outcomes. For example, increased interoceptive attention may lead females may be more likely to seek medical help for physical symptoms than males (Owens, 2008), and high levels of interoceptive attention have been associated with anxiety (Anderson & Hope, 2009; Palser et al., 2018), with differences in interoceptive attention potentially partially explaining the increased prevalence of anxiety in females relative to males (Angst & Dobler-Mikola, 1985; Bruce et al., 2005; McLean et al., 2011; Regier et al., 1990). Interestingly, a recent meta-analysis found that women perform significantly worse than men on objective behavioural tasks in both the cardiac and respiratory domains (Prentice & Murphy, 2022). The contrast between this finding and the current finding of no gender differences in self-reported interoception may be due to differences in interoceptive accuracy across different interoceptive signal channels (Ferentzi et al., 2018), but also raises questions concerning the level of metacognitive insight that females have into their interoceptive abilities. Research specifically comparing interoceptive insight in males and females, across a range of interoceptive signal channels, remains a priority for future research.

This thesis also reports an inverse relationship between self-reported interoceptive attention and age, again whilst self-reported interoceptive accuracy was unrelated to developmental changes. If this is the case, changes in interoceptive attention could be explained by the changes in mental and physical health seen in older age, such as the increased risk of Parkinson's disease (Reeve et al., 2014), dementia (McCullagh et al., 2001), and cardiovascular disease (Leritz et al., 2011). An increased risk of deteriorating health could lead to decreased interoceptive attention as a compensatory mechanism to reduce health-related anxiety. In contrast to the finding that self-reported interoceptive accuracy was unrelated to age, previous research suggests that ageing is associated with decreased objective interoceptive accuracy, at least in the cardiac domain (Khalsa et al., 2009; Murphy et al., 2018c). Again, it is therefore possible that both interoceptive attention and accuracy decline in older adulthood, but that metacognitive insight into one's interoceptive accuracy also decreases with age. Taken together, these findings suggest that both females and older adults may pay a disproportionate amount of attention to internal bodily signals, relative to the precision with which they can detect them. Replication using objective measures of interoceptive accuracy and attention is a clear priority for future research, as is investigation of the extent to which age and gender affect interoceptive, for both attention and accuracy.

8.3 General limitations and future directions

While limitations relating to individual studies are discussed in detail in the relevant chapter, some general limitations and related future research directions are worth highlighting here. To begin, one main aim of this thesis was to investigate the impact of development on the processing of others' interoceptive expressions and its relationship with the processing of these states in one's own body. Whilst this was achieved in older participants, due to COVID-19 restrictions it was not possible to recruit a sample spanning from early childhood to adolescence. The developmental changes associated with the processing of others' interoceptive expressions in childhood and early adolescence, therefore, remain to be seen. Where emotion is concerned, while sensitivity to changes in emotional expressions continue to be seen throughout adolescence, basic emotion recognition is thought to mature by 11 years of age, with a distinct developmental trajectory for each emotion (Chronaki et al., 2015; Lawrence et al., 2015; Rogers et al., 2012; Thomas et al., 2007). It is, therefore, likely that the perception of interoceptive expressions develop at a similar rate, with distinct trajectories for each internal state. Although not reported in the current thesis, it seems theoretically plausible that some understanding of one's own interoceptive states is necessary in learning to recognise these states in others. Perhaps one's own interoceptive processing only predicts the processing of others' interoceptive expressions in the early stages of development. During later stages of development, as assessed in this thesis, individuals may come to rely more on cues from others' verbal descriptions of their feelings, or third-party observers' descriptions. Individuals may learn the cues associated with interoceptive expressions when these are accompanied by objective descriptions of internal states, such as interaction partners stating that they are tired or in pain whilst expressing this non-verbally. Of course, in order to fully characterise the trajectory of interoceptive state recognition and the mechanisms which lead to individual differences in processing, further research is needed. Experimental methods, such as manipulating one's interoceptive accuracy through false feedback, brain stimulation, or training, and assessing the impact of these manipulations on the processing of others' interoceptive expressions, would help to establish causal relationships. Longitudinal investigations which assess the processing of one's own interoceptive states and others' interoceptive expressions are also key. If, for example, improvements in the processing of one's own interoceptive states closely precede improved processing of others' interoceptive expressions, this may suggest a causal role of one's own interoceptive abilities in the processing of others' interoceptive states.

A further limitation concerns the fact that the studies in this thesis rely on self-report measures of interoception. Crucially, self-report measures can be delivered online, therefore adhering to COVID-19 restrictions in place at the time of testing. Besides this, self-report measures of interoception are useful for assessing responses to a range of interoceptive states, and for capturing the day-to-day interoceptive experiences of individuals outside the laboratory. Given the utility of self-report measures of interoception, there are a range of questionnaires designed to capture interoceptive processing which have been widely used in the literature. Nonethless, they are limited as they do not distinguish between interoceptive accuracy, attention, and the frequency with which internal bodily signals occur (see Desmendt et al., 2022 for a review). Throughout studies 1 - 4, however, this thesis utilised the IAS (Murphy et al., 2019a, 2020) and IATS (Gabriele et al., 2022) which appear to overcome these issues by asking participants to report on the accuracy with which they can perceive, or the amount of attention they pay to, interoceptive signals in isolation. Of course, as with any questionnaire, there is still the chance that wording is incorrectly interpreted, an issue which is particularly petinent when designing a measure of interoceptive attention. The IATS asks participants how much they agree with statements such as, 'Most of the time my attention is focussed on whether my heart is beating fast.' Of course, for most individuals it is unlikely that 'most' of their time is spent focused on this singular bodily signal, however, a statement such as this allows the full spectrum of responses to be captured. The IAS and IATS also mitigate issues with interpretation through the inclusion of interpretation questions, utilised throughout studies 2 to 4, with participants who incorrectly interpreted the questionnaire removed from analysis. Once utilised, this thesis reports no correlation between the two measures, further supporting both the validity of the questionnaires and the distincition between interoceptive accuracy and attention. It is worth noting, however, that the correlation with objective measures is relatively small (Murphy et al., 2020a), and interoceptive insight varies across individuals (Forkmann et al., 2016; Garfinkel et al., 2015), meaning self-report measures are more valid in some individuals than in others.

Beyond this, there is also evidence that interoceptive processing fractionates, with ability to perceive interoceptive signals from one channel (e.g., cardiac) not necessarily relating to the ability to perceive signals from another channel (e.g., respiratory; Ferentzi et al., 2018). When measured using questionnaires, however, items assessing multiple channels tend to load onto a single factor, namely self-reported interoceptive accuracy or attention. This discrepancy might suggest that there are nuances in interoceptive processing which are not captured by self-report methods, with individuals failing to identify bodily states that they can process more or less accurately. Alternatively, discrepancies between performance on objective tasks could be driven by highly varying methodologies across intreroceptive channels; it will only be possible to draw reliable conclusions about fractionating interoceptive abilities once a carefully controlled battery of tasks is utilised with well matched task requirements and response options. Future research should, therefore, aim to employ both objective and self-report measures of interoceptive accuracy and attention, across a range of bodily axes, when assessing the relationship between the processing of one's own and others' interoceptive states. Notably, recent advancements in the field of interoception now allow for the measurement of heartbeats remotely, through remote photoplethysmography, using either a computer webcam (Lernia et al., 2022), or the camera on an iPhone (Plans et al., 2021). It is worth noting, however, that remote employment of the Heartbeat Counting Task (HCT; Dale & Anderson, 1978; Schandry, 1981) is subject to the same limitations as outlined in Chapter 1.3. In fact, many of these limitations are likely to be amplified due to the lack of control associated with online research. As objective measures of interoceptive are also not matched on response type, trail methodology, or difficulty across domains, careful consideration is needed when selecting an appropriate objective measure of both interoceptive accuracy and attention to ensure validity of the employed measure and the concurrent conclusions. Nonetheless, given that self-report measures are not highly correlated with objective measures (Murphy et al., 2020a), particularly for some individuals (Forkmann et al., 2016; Garfinkel et al., 2015), a stronger relationship between the processing of one's own and others' interoceptive expressions might be found should objective measures be employed.

Despite the limitations associated with relying solely on self-report measures of interoception, both the IAS and IATS were found to have good reliability across all studies in this thesis. Relatively low variance in scores on the IAS was observed, however, with most individuals self-reporting reasonable ability to detect their internal bodily signals. As was speculated in the case of early development, some understanding of one's own internal states is presumably necessary in learning to process others' interoceptive expressions, but it is possible that a relationship between the processing of one's own and others' internal states is only observed when samples include individuals with marked difficulties in interoceptive accuracy. Interoceptive atypicalities are common in a range of clinical conditions, such as autism spectrum disorder (ASD; Garfinkel, Tiley, et al., 2016; Hatfield et al., 2019; Mul et al., 2018; Nicholson et al., 2019), depression (Aaronson et al., 2017; Dunn, Stefanovitch, et al., 2010; Furman et al., 2013b), feeding and eating disorders (Pollatos et al., 2008), and alcohol and substance abuse (Jakubczyk et al., 2019; Naqvi & Bechara, 2010; Paulus & Stewart, 2014). The current thesis also demonstrated reduced self-reported interoceptive accuracy in children with MUS and TS. Indeed, interoceptive atypicalities have been proposed to be a key predictor of psychopathology (Murphy et al., 2017), potentially representing the 'P-Factor' (a general vulnerability to developing and maintaining psychiatric symptoms; Brewer et al., 2021). If it is the case that marked interoceptive atypicalities are associated with reduced processing of others' interoceptive expressions, this is likely to exacerbate many of the social and communication difficulties already experienced by those with clinical disorders (American Psychiatric Association, 2013; Kupferberg et al., 2016; Treasure et al., 2012). It is worth noting, however, that interoceptive and emotional atypicalities are not universal within clinical groups, with individual differences existing just as they do in the general population. In fact, where emotion is concerned, co-occurring alexithymia has been found to explain many of the social and communication difficulties previously thought to be caused by psychological conditions themselves (Brewer et al., 2015; Cook et al., 2013; Gil et al., 2009). Quantifying individual differences in the processing of one's own and others' interoceptive states in clinical groups is, therefore, a clear priority for future research, with implications for diagnosis and treatment of psychological and neurodevelopmental conditions. Understanding the role of interoceptive difficulties in contributing to the development, maintenance or manifestation of different clinical conditions is essential for clinicians when completing assessment procedures, in order to conduct case formulation appropriately, and form hypotheses about potential causes of clients' difficulties. Similarly, the effectiveness of different treatment approaches may vary as a function of individuals' interoceptive abilities, making assessment of these abilities crucial when making treatment plans.

Beyond measures of self-reported interoception, the current thesis assessed the processing of others' interoceptive expressions using stimuli from the ISSI database. The ISSI database is particularly useful as it contains matched images of the same actors posing a series of control actions e.g., walking, running, washing hands. These control images were utilised in Studies 1, 3 and 4, to ensure that if a relationship had been found between the processing of one's own and others' interocepitve states, this was specific to interoceptive expressions, rather than the ability to discriminate between categories of visual postures more generally. Whilst no relationship between the processing of one's own and others' interoceptive states was reported in these studies, the use of control postures still rules out the influence of domain general processes such as, motivation, general intelligence and social experience. Nonetheless, no direct measures of broader individual differences were taken throughout studies 1 to 4. Indeed, given that interoceptive processing appears linked to a range of cognitive abilities and mental and physical health outcomes (Barrett, 2014; Damasio, 1998; Dunn et al., 2010; Garfinkel et al., 2013a; Gendron & Feldman Barrett, 2009; Herbert et al., 2007b; Kandasamy et al., 2016; Matthias et al., 2009; Pollatos & Schandry, 2008; Seth, 2013; Werner et al., 2009; Werner et al., 2010), future research should certainly look to investigate the impact of broader individual differences on the processing of others' interoceptive expressions. It is important to note that these investigations would still benefit from the use of the conservative controls, either provided in the ISSI database or otherwise, to ensure that any relationship is specific to interoceptive expressions. One other potential control would be the use of artistic or cartoon figures, rather than the use of real posed individuals.

As mentioned, the ISSI is composed of static images of actors posing a series of interoceptive states, rather than depicting genuinely elicited interoceptive expressions. This mirrors the vast majority of research on the recognition of emotions, which typically utilises posed expressions from widely used stimulus databases (Ekman, 1976; Langner et al., 2010; Lundqvist et al., 1998; Tottenham et al., 2009). Notably, whilst naturalistically elicited cues are typically seen as more valid, deliberately posed communicative emotional expressions are also used in real world interactions, in order to communicate one's internal states to others (Frith, 2009). Nonetheless, there are differences in the cues associated with posed and naturalistically induced emotions (Schmidt et al., 2006a; Schmidt et al., 2006b; Sowden et al., 2021; Valstar et al., 2006), and the same is likely true of interoceptive expressions. Investigations using the ISSI stimuli can, therefore, only be applied to instances where interoceptive states are signalled using communicative gestures and cannot inform investigations into how interoceptive states are signalled naturalistically. Without stimuli depicting naturalistically induced interoceptive states, it remains to be seen whether one’s own interoceptive abilities are associated with the recognition of others’ spontaneous interoceptive expressions. The development of a stimulus set depicting genuinely elicited interoceptive expressions is, therefore, a target for future research. Not only would these stimuli facilitate investigations into the relationship between the processing of interoceptive states in oneself and others, but they would also allow for assessment of the similarities in and differences between posed and spontaneously elicited interoceptive expressions. The recording of interoceptive expressions (both posed and spontaneous) in future research would also allow for investigations into the potential relationship between one’s own interoceptive accuracy and attention and the expression of these states. It is possible, as has been seen in the emotion literature, that difficulties interpreting one’s own internal states would lead one to produce atypical, and perhaps less recognisable, expressions of these states (Brewer et al., 2016; Guha et al., 2018; Trevisan et al., 2018). If this is the case, the issues individuals face with expressing their own emotions are likely to be compounded by the fact that others may also struggle to recognise their emotional expressions. Investigating the relationship between the processing of one’s own interoceptive states and the expression of these states to others is, therefore, a clear direction for future research.

Potential differences in the depiction of posed and naturalistic interoceptive expressions aside, the current thesis only investigated the perception of interoceptive states from static visual stimuli. Of course, in real world interactions, cues to others’ interoceptive states are available through multiple perceptual modalities (e.g., body postures, body movements, and vocalisations). It is, therefore, necessary for future research to determine whether any difficulties recognising interoceptive states are due to a modality-specific perceptual encoding impairment or a modality-general categorisation impairment. Indeed, emotion recognition research has demonstrated that the ability to recognise emotion from faces is likely to generalise to bodies and auditory signals (Lewis et al., 2016; Schlegel et al., 2012). Interoceptive expression recognition may, therefore, also be characterised as a modality-general ability. Notably, however, some psychological disorder symptoms may lead to impairments in specific modalities, for example in those with atypical visual or auditory perception, or those with atypical perception of biological motion such as many autistic individuals (Dakin & Frith, 2005; Kaiser & Shiffrar, 2009; O'Connor, 2012). For these individuals, recognition of others' interoceptive expressions from one modality is likely to be compromised, whilst in naturalistic settings, when multiple cues are available, overall processing may be relatively spared. To investigate this, stimulus sets depicting the motion (e.g., using point light displays and videos) and auditory cues associated with interoceptive states are required. Similarly, to the ISSI, these stimulus sets should depict as many internal states as possible allowing for the assessment of interoceptive expression processing across interoceptive signal channels (e.g., hunger, nausea, temperature, and breathlessness) and perceptual modalities (e.g., facial, bodily, and vocal cues). Relatedly, the current thesis investigated each domain of processing in isolation (e.g., recognition of interoceptive expressions, attention to and memory for interoceptive expressions, and the tendency to assign interoceptive labels to others' actions), which did not allow for analysis of the potential relationships between these abilities. Investigation of attention and memory biases in the processing of others' interoceptive expressions within the same individuals, for example, would provide further evidence on whether atypicalities in early processing (e.g. attention) are related to subsequent atypicalities in later processing (e.g. memory). As well as investigating the association between attention and memory biases in the processing of interoceptive expressions, the relationship between interpretation of and attention to others' interoceptive expressions is of particular interest. If, for instance, an individual tends to interpret interoceptive expressions as actions, this may negate any attentional bias associated with the processing of others' interoceptive expressions. Together, these investigations will determine whether difficulties recognising interoceptive states, where observed, are due to a modality-specific perceptual encoding impairment, or a modality-general categorisation impairment, whether recognition of others' interoceptive states is a unitary ability or fractionates across different internal signals, and whether processing in one cognitive domain relates to that in another (e.g., attention to and memory for interoceptive expressions).

As well as enabling investigations into the processing of others' interoceptive expressions across a variety of modalities, the creation of stimulus sets depicting internal states using a range of modalities may also allow for more sensitive tests of processing. For example, the creation of point light displays would leave only motion signals on which to base interpretation of the interoceptive expression. Tasks which utilised these stimuli may, therefore, be more sensitive measures of interoceptive processing than those which utilised the current ISSI stimuli. Of course, there are also methods which could be utilised with the existing ISSI stimuli to make the processing of interoceptive expressions more challenging. The ISSI is composed of multiple depictions of each internal state, which vary in recognisability. As this was the first investigation of its kind, the best depictions were selected for use in the studies of this thesis, however, to make tasks more difficult stimuli which are less recognisable could be selected. All state lables were also presented, when interoceptive expression recognition was assessed in Study 1. If, however, only state labels that tend to be confused, such as nausea and satiety, were available for these stimuli, this would likely have a substantial impact on participants' performance, and potentially its relationship with self-reported interoceptive abilities. Beyond response-option manipulations, there are also other well-established techniques which have been widely used in the emotion literature, such as the so-called bubbles technique (Gosselin & Schyns, 2001). The bubbles technique involves placing a mask over the stimuli with randomly selected Gaussian windows (hereafter called 'bubbles'). Accordingly, only the parts of the stimuli which appear in the bubbles are visible, therefore, making tests of processing interoceptive expressions more sensitive. Perhaps even more importantly, however, this technique would also reveal which parts of the stimuli (e.g., postural cues or facial expressions) are vital in making correct internal state judgements which is an interesting direction for future research.

Besides future directions which address the limitations of this thesis, there are several outstanding questions which, although beyond the remit of the current thesis, should be addressed by future research. Primarily, throughout this thesis hypotheses and potential implications of a deficit in the processing of others' interoceptive expressions have been informed by the existing literature on emotion recognition. Given the close relationship between emotional and interoceptive processing in oneself (Barrett, 2017; Critchley & Nagai, 2012; Damasio, 1998; Garfinkel et al., 2013b; Gendron & Barrett, 2009; James, 1894; Lange, 1885; Schachter & Singer, 1962), it is theoretically likely that the processing of others' emotional and interoceptive expressions would be closely related, particularly if the hypotheses in this thesis are supported. The exact mechanism by which this might occur is debateable and may vary from individual from individual. In example, an individual who struggles to process their interoceptive states is likely to experience similar difficulties processing their emotions (Brewer et al., 2016; Gaggero et al., 2021; Murphy et al., 2018; Zamariola, et al., 2018) which, in turn, is likely to lead to reduced processing of others' emotions (Luminet et al., 2021). On the other hand, the processing of others' emotions and interoceptive states may be directly linked, both being a form of social perception. Yet, empirical work testing this hypothesis is limited to research exploring the perception of pain alongside other emotions. Simon and colleagues (2007) reported similar accuracy in the perception of pain compared to other emotions (e.g., happy, sadness, disgust, and anger) from one-second video clips. Pain, however, received significantly higher arousal and unpleasantness ratings than other emotions. Similar findings were reported when rating emotions and painful body postures from static images (Walsh et al., 2014). Alexithymia also appears to be similarly related to recognition of others' pain expressions as it is to recognition of other emotional expressions (Brewer et al., 2015). As pain contains both sensory and affective components (Fernandez & Turk, 1992), future research is needed which assesses the processing of interoceptive and emotional states, depicted by the same actors, across various cognitive domains. These investigations should unveil whether these are distinct abilities or encompassed by one another. Importantly, as this research is yet to be undertaken, the current thesis does not make assumptions regarding the distinction between emotions and interoceptive states. While these have been discussed separately in the existing literature, it is notable that traditionally 'interoceptive' and 'emotional' states share many features, and it is arguable that interoceptive states could in fact be conceptualised as emotions themselves, depending on one's definition of 'emotion'. For example, the majority of interoceptive states have both a valence and arousal level, which would allow them to be plotted within the Circumplex model of emotion (Russell, 1980). If future work goes on to suggest that the processing of interoceptive states is an extension of emotion expression processing, the current thesis will have paved the way for utilising a broader set of states when assessing these abilities, and prompted research into the processing of emotions, beyond the six basic emotions, and some more complex emotions, typically studied in the literature thus far.

Future research should also explicitly test the relationship between processing of others' emotional and interoceptive expressions, to determine whether recognition of, attention to, and memory for others' emotions predicts processing of others' interoceptive expressions in the same cognitive domain. These findings will elucidate whether a bias in the processing of interoceptive expressions is accompanied by a similar bias in the processing of emotions, for example, providing crucial insight into whether the mechanisms for emotional and interoceptive expression processing are similar. If they are, training in one domain may lead to improvements in the other, which may be especially useful in individuals who struggle with social perception. Relatedly, based upon the importance of the processing of others' emotions in mental health and cognitive outcomes (Gross, 2002; Hu et al., 2014; Kret & Ploeger, 2015;

Parker et al., 2004; Schutte et al., 2007), this thesis consistently ascribes a similar role for the processing of interoceptive expressions. Yet, it is currently unknown whether individual differences in recognition of others' interoceptive states contribute to differences in social communication, empathy, or building relationships, for example. Future research should aim to characterise the impact of individual differences in the processing of others' interoceptive expressions on other cognitive, mental health and social factors.

Whilst the importance of processing others' interoceptive expressions for social communication is currently unconfirmed, as interoceptive cues are often related to health and physical wellbeing, the processing of these is almost certainly involved in one's ability to care for others; if one does not interpret others' interoceptive cues correctly, this is likely to impede one's ability to provide appropriate care or medical attention. Accordingly, the recognition of interoceptive expressions is particularly important for those in a position of care (e.g., medical professionals, carers, and parents). The importance of recognising others' interoceptive expressions is, of course, exacerbated, if the observed individual has poor understanding of their interoceptive states themselves, or struggles to communicate, for example in young children (e.g., Feldman, 2019; Schaan et al., 2019), older adults (Khalsa et al., 2009; Murphy et al., 2017; Yorkston et al., 2010), or clinical groups where interoceptive or communication difficulties are common, such as in autism spectrum disorder (American Psychiatric Association, 2013; Garfinkel et al., 2016; Hatfield et al., 2017; Mul et al., 2018; Nicholson et al., 2019). Given the importance of recognising the cues associated with interoceptive states for those in a position of care, future research should also aim to develop training paradigms which improve recognition of others' interoceptive expressions. Of course, if one's own interoceptive processing is related to the processing of others' interoceptive expressions, it follows that training individuals to process their own states may lead to improvements in the processing of others' interoceptive expressions. As the current thesis did not find conclusive evidence of this relationship, however, specific expression recognition training paradigms could instead be designed, for example providing accuracy feedback alongside a recognition paradigm, or explicitly identifying relevant and salient features of interoceptive expressions.

It is worth noting that if expression recognition training is to be implemented, it is first important to assess the universality of interoceptive expressions, as expression training is contingent on the assumption that interoceptive expressions are consistent across individuals, such that training an individual to recognise the cues associated with an interoceptive expression in one individual will generalise to all individuals. There is much debate concerning the universality of emotional expressions. Whilst early work argued for universality in emotional expressions (Ekman et al., 1971), further research has demonstrated that there are, in fact, cultural differences in emotional expressions (e.g., Mandal & Ambady, 2004). One might, therefore, expect that there would also be cultural differences in the expression of interoceptive states. Further supporting the existence of cultural variation, are reports of variations in the processing of one's own interoceptive states between Western and non-Western cultures (Ma-Kellmans, 2014). On the one hand, non-Western cultures consistently display increased focus on interoceptive sensations, whilst on the other hand exhibit decreased interoceptive accuracy in laboratory tests. These findings point to a complex effect of culture on the processing of one's own interoceptive states, which, if the hypotheses laid out in this thesis are proven correct, may suggest a similarly complex relationship between culture and the expression of interoceptive states. Indeed, if cultural differences are observed in interoceptive expressions this would limit the applicability of expression training.

Beyond the impact of cultural differences, mental health and neurodevelopemental conditions may also lead to differnces in the expression of interoceptive states. In example, communication difficulties experienced by individuals with conditions such as autism are often attributed to difficulties recognising their neurotypical interaction partners' emotions and mental states (Harms et al., 2010), however, contemporary research highlights that this explanation fails to consider the bi-directional nature of social interactions (Keating & Cook, 2020). Indeed, it is equally plausible that interaction difficulties are explained by neurotypical individuals' difficulties recognising the states of their autistic interaction partner. Consistent with this idea, evidence suggests that autistic individuals express emotional states differently, leading to poorer recognition by neurotypical individuals (Brewer et al., 2016; Guha et al., 2018; Trevisan et al., 2018), although some argue that differences in spontaneous facial expressions may be explained by co-occurring alexithymia (Trevisan et al., 2016). Importantly, however, the differences in autistic expressions appear to be idiosyncratic rather than systematic and shared by all autistic individuals (Brewer et al., 2016). It is, therefore, likely that autistic individuals (and perhaps those with other neurodevelopmental or psychological conditions) also express interoceptive states differently to neurotypical individuals, and these differences may be unique to each individual. As those with social communication difficulties, such as autistic individuals, are most likely to experience difficulties verbalising their internal states (American Psychiatric Association, 2013; Garfinkel et al., 2016; Hatfield et al., 2017;

Mul et al., 2018; Nicholson et al., 2019), future research should aim to investigate the degree to which interoceptive expressions vary, or contain common features, in neurotypical individuals and clinical populations. These findings will then inform training procedures aimed at improving the recognition of others' interoceptive expressions, in turn allowing for the provision of better care and potentially improving social communication.

8.5 Conclusions

The current thesis aimed to provide the first comprehensive assessment of the processing of others' interoceptive expressions, as well as investigating individual differences in state recognition in relation to one's self-reported interoceptive processing, age, and gender. Whilst it appears that individuals can successfully infer another's state from static visual images and have a greater tendency to assign interoceptive, over action, labels to others' interoceptive expressions, no attention or memory biases were observed in the processing of interoceptive postures, when compared to actions, contrasting with the well-documented salience of emotional stimuli (Yiend, 2010). Given the importance of processing others' interoceptive expressions in certain situations (e.g., when another person is unwell), future research should aim to investigate under which circumstances these expressions elicit salience. Similarly, no relationship was observed between self-reported processing of one's own internal states and the recognition of others' interoceptive expressions, or attention to, or memory for, others' interoceptive state displays. Nonetheless, tendency to assign interoceptive labels to others' interoceptive expressions was positively related to self-reported interoceptive accuracy, such that as individuals reported higher accuracy in the processing of their own interoceptive states, they were more likely to interpret others' actions as indicative of interoceptive signals. Age also appears to be related to the labelling of others' interoceptive expressions, such that as age increased, the tendency to assign interoceptive labels decreased. Interestingly, this effect did not appear to be explained by changes in self-reported interoceptive accuracy. This thesis also found that females were more accurate at recognising others' interceptive states than males. Relatedly, women's actions were less likely to be interpreted as being driven by interoceptive changes, despite their interoceptive expressions being recognised more accurately amongst a series of interoceptive states. It seems, therefore, that one's own interoceptive processing, age, and gender, are associated to some extent with the processing of others' interoceptive expressions, and that features of the observed individual, such as gender, also alter the way in which interoceptive expressions are perceived. To further delineate these relationships, future research should investigate the processing of others' interoceptive expressions across multiple modalities, throughout development, and in clinical groups with known interoceptive atypicalities. Future work should also aim to determine the impact of individual differences in interoceptive state recognition on other cognitive, social, and mental health outcomes, such as social perception, communication, empathy, relationship quality, and psychopathology. These findings are likely to have applications in the real world, particularly in terms of their potential to inform training in recognition of others' interoceptive expressions for medical professionals and others with caregiving roles, leading in turn to improved care. They also highlight the need to assess interoceptive abilities in clinical settings, to support diagnosis and tailor treatment approaches to individuals' needs. Finally, future work on the relationship between interoceptive expression recognition and social skills may lead to innovative ways to improve the quality of social interactions and relationships in those with social difficulties, potentially improving psychological wellbeing.

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Appendices

Appendix A. Child-Adapted Interoceptive Accuracy Scale.

Interoceptive accuracy scale: Child Adaptation

Written below are some sentences about how well you can feel things **inside your body**. Please read these sentences and use the scale to tell us whether they fit with you. If you think the statement fits you completely, please circle strongly agree. If you don't think it fits you at all, please circle strongly disagree.
It is very important that you only tell us how well you can feel what's **inside** your body without using signs from **outside** of your body. For example, if you can only tell your heart is beating fast by feeling your heartbeat with your hands, this would **not** count as correctly feeling when your heart is beating quickly.

I am always correct at feeling…

1. When my heart is beating quickly
2. When I am hungry
3. When I am breathing quickly
4. When I am thirsty
5. When I need to have a wee
6. When I need to have a poo
7. When I taste new flavours
8. When I am going to vomit (be sick)
9. When I am going to sneeze
10. When I am going to cough
11. When I am hot or cold
12. When I am going to fart
13. When I am going to burp
14. When my muscles are tired or sore
15. When I am going to get a bruise
16. When I am in pain
17. When I don't have any energy
18. When someone is touching me in a nice way
19. When something is going to be ticklish
20. When something is going to be itchy

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

Appendix B. Child-Adapted Interoceptive Attention Scale.

<u>Interoceptive attention scale: Child Adaptation</u>

Written below are some sentences about how much you pay attention to (think about) feelings **inside your body**. Please read these sentences and use the scale to tell us whether they fit with you. If you think the statement fits you completely, please choose **strongly agree**. If you don't think it fits you at all, please choose **strongly disagree**. When you answer each question, try to think about how you feel most of the time, rather than at certain times. These questions are **not** about how **good** you are at telling how your body feels. Instead they are about how much you **think about** or **pay attention to** the feelings. So if you spend a lot of time **thinking about** how quickly your heart is beating, you would choose 'agree' or 'strongly agree' – it doesn't matter if you are right or wrong about what your heart is doing. You should only tell us how much you pay attention to things you feel **inside** your body without using signs from **outside** of your body. If a question asks you about how often you notice your heartbeat, you should answer about times that you notice it from inside your body, not when you notice it by feeling it from the outside (like using your hands to touch your wrist or chest).

1. Most of the time I pay attention to if my heart is beating fast
2. Most of the time I pay attention to if I am hungry
3. Most of the time I pay attention to if I am breathing fast
4. Most of the time I pay attention to if I am thirsty
5. Most of the time I pay attention to if I need to have a wee
6. Most of the time I pay attention to if I need to have a poo
7. Most of the time when I am eating, I pay attention to different flavours I can taste
8. Most of the time I pay attention to if I need to vomit (be sick)
9. Most of the time I pay attention to if I need to sneeze
10. Most of the time I pay attention to if I need to cough
11. Most of the time I pay attention to if I feel hot or cold
12. Most of the time I pay attention to if I need to fart
13. Most of the time I pay attention to if I need to burp
14. Most of the time I pay attention to if my muscles are tired or sore
15. Most of the time I pay attention to if I am in pain after I get hurt
16. Most of the time I pay attention to if I am in pain (when I didn't get hurt by something)
17. Most of the time I pay attention to how much energy I have
18. Most of the time when someone is touching me, I pay attention to if they are touching me in a nice way
19. Most of the time I pay attention to if something feels ticklish
20. Most of the time I pay attention to if my body feels itchy

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

Appendix C. Child-Adapted Porges Body Perception Questionnaire

I: Awareness

Imagine how aware you are of your body processes. Draw a circle around the answer that sounds most like you. Answer how often you feel the things below:

Most of the time I am aware of (notice) myself:

1. **Swallowing a lot**
   Never Occasionally Sometimes Usually Always
2. **Ringing in my ears**
   Never Occasionally Sometimes Usually Always
3. **A need to cough to clear my throat**
   Never Occasionally Sometimes Usually Always
4. **My body swaying when I am standing**
   Never Occasionally Sometimes Usually Always
5. **My mouth being dry**
   Never Occasionally Sometimes Usually Always
6. **How fast I am breathing**
   Never Occasionally Sometimes Usually Always
7. **Watery eyes**
   Never Occasionally Sometimes Usually Always
8. **My skin itching**
   Never Occasionally Sometimes Usually Always
9. **Noises in my stomach after I've eaten**
   Never Occasionally Sometimes Usually Always
10. **Tired or painful eyes**
    Never Occasionally Sometimes Usually Always
11. **An ache in my neck or back**
    Never Occasionally Sometimes Usually Always
12. **Swelling in my body or parts of my body**
    Never Occasionally Sometimes Usually Always
13. **Need to go to the toilet (wee)**
    Never Occasionally Sometimes Usually Always
14. **Shaky hands**
    Never Occasionally Sometimes Usually Always

15. **Need to go to the toilet (poo)**

Never Occasionally Sometimes Usually Always

16. **An ache in my arms or legs**

Never Occasionally Sometimes Usually Always

17. **A swollen tummy**

Never Occasionally Sometimes Usually Always

18. **An ache in my face**

Never Occasionally Sometimes Usually Always

19. **Goose bumps**

Never Occasionally Sometimes Usually Always

20. **Twitchy face**

Never Occasionally Sometimes Usually Always

21. **Really tired**

Never Occasionally Sometimes Usually Always

22. **Tummy pain**

Never Occasionally Sometimes Usually Always

23. **Fluttery eyes**

Never Occasionally Sometimes Usually Always

24. **Sweaty hands**

Never Occasionally Sometimes Usually Always

25. **Sweaty forehead**

Never Occasionally Sometimes Usually Always

26. **Being clumsy and bumping into people**

Never Occasionally Sometimes Usually Always

27. **Shaky lips**

Never Occasionally Sometimes Usually Always

28. **Sweaty armpits**

Never Occasionally Sometimes Usually Always

29. **Prickly skin, tingly skin, or numb skin**

Never Occasionally Sometimes Usually Always

30. **A hot or cold face or ears**

Never Occasionally Sometimes Usually Always

31. **Grinding my teeth**

Never Occasionally Sometimes Usually Always

32. **Can't be still**

Never Occasionally Sometimes Usually Always

33. **My eyes moving**

Never Occasionally Sometimes Usually Always

34. **Itchy nose**

Never Occasionally Sometimes Usually Always

35. **The hair on the back of my neck standing up**

Never Occasionally Sometimes Usually Always

36. **Needing a rest**

Never Occasionally Sometimes Usually Always

37. **Can't focus**

Never Occasionally Sometimes Usually Always

38. **How hard my heart is beating**

Never Occasionally Sometimes Usually Always

39. **Feeling like I can't go to the toilet (poo) when I try**

Never Occasionally Sometimes Usually Always

Scale: Always (5), Usually (4), Sometimes (3), Occasionally (2), Never (1).

Appendix D. Interoceptive Accuracy Scale.

<u>Interoceptive accuracy scale: Adult Version</u>

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 non-affectionately
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), Strongly Disagree (1)

Appendix E. Interoceptive Attention Scale.

<u>Interoceptive attention scale: Adult Version</u>

Below are several statements regarding how much attention you pay to specific bodily sensations. Please rate on the scale how much attention you think you pay to each specific sensation. Think about how you feel during most situations in your daily life, rather than at a specific point in time. For example, if you often think about your heart beating, feeling hungry or needing the toilet then you would rate your attention to these sensations as high. In contrast, if you don't often think about your heart rate, how hungry you are or whether you need the toilet then you would rate your attention to these sensations as low.
Please only rate how much **attention** you pay to these sensations **regardless of how well you think you can perceive them**. For example, if you often feel you need the toilet but when you go to the toilet you realise you don't need to you should still rate your attention to this signal as high. Do not worry about how often you think the sensation is **truly** happening inside your body – we would like to know how much of the time you pay attention to these sensations.
The questions ask about your attention to feelings coming from **inside** your body. For example, if the question asks about temperature, it is referring to sensations you notice internally without using your hand to feel how warm your skin is, and if it asks about your heartbeat, it is referring to feelings you notice inside your body without taking your pulse.

1. Most of the time my attention is focused on whether my heart is beating fast
2. Most of the time my attention is focused on whether I am hungry
3. Most of the time my attention is focused on whether I am breathing fast
4. Most of the time my attention is focused on whether I am thirsty or dehydrated
5. Most of the time my attention is focused on whether I need to urinate
6. Most of the time my attention is focused on whether I need to defecate
7. Most of the time when I am eating, my attention is focused on different tastes
8. Most of the time my attention is focused on whether I am nauseated or need to vomit
9. Most of the time my attention is focused on whether I need to sneeze
10. Most of the time my attention is focused on whether I need to cough
11. Most of the time my attention is focused on the temperature of my body (feeling hot or cold)
12. Most of the time my attention is focused on whether I am sexually aroused
13. Most of the time my attention is focused on whether I need to pass wind
14. Most of the time my attention is focused on whether I need to burp
15. Most of the time my attention is focused on whether my muscles are tired or sore
16. Most of the time my attention is focused on whether I am in pain after I am hurt or injured
17. Most of the time my attention is focused on whether I am in pain (that is not caused by injury)
18. Most of the time my attention is focused on whether my blood sugar is low
19. Most of the time when someone is touching me, my attention is focused on whether it is pleasant/affectionate
20. Most of the time my attention is focused on whether touch or materials feel ticklish on my body
21. Most of the time my attention is focused on whether my body feels itchy

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

Appendix F: Interpretation Questions for Interoceptive Accuracy and Interoceptive Attention Scale.

Questions:

1. ***IATS:*** In this questionnaire we asked you to tell us how much attention you pay to specific bodily sensations. While you were completing the questionnaire, what did you think the term ‘attention’ meant in this context? Please select one option that best describes your interpretation of the questionnaire.

2. ***IAS***: In this questionnaire we asked you to tell us how accurately you can perceive specific bodily sensations. While you were completing the questionnaire, what did you think the term ‘accuracy’ meant in this context? Please select one option that best describes your interpretation of the questionnaire.

Response options for all questions:

a) How much attention you pay to these sensations (e.g. how much they occupy your thoughts/mind/ how much you think about these sensations/ how much you monitor whether these signals are occurring or not (regardless of how well you can perceive them or how often they occur).

b) How accurate you are at perceiving these sensations (e.g. how good you are at feeling/detecting them when they occur/ how well you can tell them apart from other sensations when they occur/ how precise you are at sensing them (regardless of how much you monitor them or how often they occur).

c) How often (frequently) or intensely these sensations actually occur in your body (e.g. how often your body is objectively cold/ how often your muscles are objectively tired (regardless of how much you monitor them or how good you are at perceiving them).

d) None of the above. Please tell us….