COGENT PSYCHOLOGY
2024, VOL. 11, NO. 1, 2348043
https://doi.org/10.1080/23311908.2024.2348043

CLINICAL PSYCHOLOGY | RESEARCH ARTICLE

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Interoceptive accuracy in children aged 8 to 13 and their parents: implications for mental health

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ABSTRACT
Objective: Interoceptive accuracy, meaning accurately detecting and discriminating internal bodily signals, has been proposed as a factor of high relevance to mental health. Nevertheless, studies focusing on the assessment of interoceptive accuracy in children are scarce.
Method: The present study addresses this gap by using questionnaire-based measures of interoceptive accuracy as well as behavioural measures such as a heartbeat counting task and a novel cardiovascular signal detection task. These instruments were used to assess interoceptive accuracy in a sample of children aged 8–13 years ($N=37$) and their parents ($N=29$), aiming to investigate its connection with dimensions of psychopathology, including internalizing, externalizing, and somatoform symptomatology. Following recent suggestions, standard frequentist analyses were complemented by results from Bayesian approaches.
Results: The findings provide evidence for a negative relationship between children's self-reported interoceptive accuracy and internalizing symptomatology reported by their parents ($\beta = -.527$). However, no evidence was found to support relationships between experimentally assessed cardiac interoceptive accuracy and psychopathological symptoms.
Conclusion: These results emphasize the importance of adopting more comprehensive measures for assessing interoceptive accuracy in research involving children. The paper addresses limitations arising from the limited sample size and potential type I error.

ARTICLE HISTORY
Received 27 December 2023
Revised 15 April 2024
Accepted 17 April 2024

KEYWORDS
Children; interoception; heartbeat detection; questionnaire; psychopathology

REVIEWING EDITOR
Daryl O'Connor, University of Leeds, United Kingdom

SUBJECTS
Psychological Science; Testing, Measurement and Assessment; Mental Health

Introduction

Interoception, a multifaceted process that has recently been described as perceiving, interpreting, and receiving signals from the body via conscious and unconscious ways (Khalsa et al., 2018) has gained considerable attention in recent years due to its apparent relevance to a wide range of physiological and psychological processes (see Brewer et al., 2021 for a review). In addition, consciously experienced facets of interoception (the subject of the present study), such as altered awareness of internal physiological changes in behavioural tasks or questionnaires, are associated with a range of mental disorders (again see Brewer et al., 2021 for a review, but also note Adams et al., 2022; Desmedt et al., 2022). Due to the assumed importance of interoception in psychopathology, some authors have referred to interoception as a higher-order factor that covaries with a number of mental disorders, commonly referred to as the 'p-factor', a concept related to, for example, the idea of a general intelligence factor (i.e. g-factor; Brewer et al., 2016; Caspi et al., 2014).

Childhood and adolescence are crucial periods for the maturation of interoceptive abilities (Li et al., 2017; May et al., 2014) and the emergence of psychopathological conditions (Kessler et al., 2005; Patel et al., 2007). There is evidence for the presence of interoceptive processing in infants as young as five months old (Maister et al., 2017), while the perception of cardiac interoceptive signals is supported by the findings from two investigations conducted with preschoolers aged 4 to 6 years (Opdensteinen et al., 2021; Schaan et al., 2019). Moreover, it seems that

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/23311908.2024.2348043.

cardiac interoceptive accuracy in children aged 6 to 11 years exhibits comparable, albeit weaker, associations with external criteria as observed in adults, suggesting a developmental aspect (Koch & Pollatos, 2014a). Regarding the development, it is postulated that caregivers play a crucial role in the maturation of children's interoceptive abilities by responding with their behaviour and verbal labelling to their children's (internal) physical changes (Brewer et al., 2021; Filippetti, 2021).

Initial proposals to clarify the various aspects of consciously experienced interoceptive processing named three dimensions, which can be distinguished depending on the measurement method used to record them (Garfinkel et al., 2015). In this model, *interoceptive sensibility* pertains to an individual's beliefs about the tendency to focus on internal signals; *interoceptive accuracy*, involves the behaviour in performance tasks to accurately perceive internal signals; and *interoceptive awareness* relates to an individual's reflection of their performance in experimental tasks. However, more recent proposals emphasise the need for a broader taxonomy of interoceptive abilities (Murphy et al., 2019). The reason for this is that common methods for operationalizing interoceptive sensibility, such as the Body Perception Questionnaire (BPQ; Porges, 1993) or confidence ratings during experimental tasks (e.g. Ehlers et al., 1995), generally do not correlate with each other and show differential relationships with performance tasks of interoceptive accuracy (e.g. Garfinkel et al., 2015). Therefore, Murphy and colleagues (2019) presented a 2 x 2 factorial model that distinguishes not only between the measurement type of consciously experienced interoceptive processes (i.e. behavioural or self-report) but also between different domains of consciously experienced interoceptive processing (i.e. interoceptive attention and accuracy). The authors claim that different measures of the same dimension are presumably related, such that interoceptive accuracy can be measured either by performance tasks or by self-report. This claim has recently been questioned as it often appears that behavioural measures and self-reports capture different dimensions of consciously experienced interoceptive processing (Suksasilp & Garfinkel, 2022).

The majority of studies in interoception research today attempt to operationalize the consciously experienced aspects of interoceptive processing primarily as cardiac interoceptive accuracy, often measured using the widely recognized Schandry Task (Schandry, 1981). In this behavioural task, participants are instructed to silently count their heartbeats over varying time intervals while concurrently monitoring the actual heart rate through electrocardiography. Few studies are addressing other dimensions of the conscious perception of internal signals, such as the perception of gastrointestinal signals, respiratory signals, or skin conductance fluctuation (Harver et al., 1993; Krautwurst et al., 2016; van Dyck et al., 2016). In the field of child and adolescent psychology, some specific tasks have been developed, that are more suitable for young individuals, such as the Jumping-Jack paradigm, the Eye-Tracking Task or adaptations of the Schandry Task (Eley et al., 2004; 2007; Herbert et al., 2012; Koch & Pollatos, 2014a, 2014b; Schaan et al., 2019; Yang, Zhou, Wei, et al., 2022). Additionally, in recent research with adults, there is an increasing tendency to employ self-assessment methods for evaluating the accuracy of perception of a wide range of bodily sensations (e.g. Brand et al., 2023; Campos et al., 2021; Lin et al., 2023; Murphy et al., 2020). Moreover, given the limitations associated with the Schandry Task (e.g. Brener & Ring, 2016), alternative cardiovascular accuracy tasks have emerged in recent years (e.g. Pohl et al., 2021). Nonetheless, it's worth highlighting that such tasks and self-assessments have not yet been widely used in studies with children. In the case of self-assessment, the available questionnaires primarily ask about a child's tendency to pay attention to bodily sensations rather than their accuracy in perceiving these sensations (e.g. Eklund et al., 2005; Jones et al., 2021). Overall, evidence regarding interoceptive processes during childhood and adolescence is sparse, and the existing literature lacks conclusive findings on the precise impact of these processes on mental health within this population.

With newer approaches of classifying psychopathology, notably the Hierarchical Taxonomy of Psychopathology (HiTOP; Kotov et al., 2017; Kotov et al., 2021), it is becoming increasingly evident that mental disorders are better conceptualized as dimensions (or dimensional) rather than discrete categories. The dimensional approach of the HiTOP model is hierarchical. At the lowest level of this hierarchy, specific signs and symptoms are described, whereas, until the top-level subfactors (e.g. *eating pathology*), spectra (e.g. *internalizing* symptomatology) and super-spectra (e.g. *emotional dysfunction*) are shown. Within the HiTOP framework, there exists the idea of a transdiagnostic factor located at the most comprehensive level (p-factor). Considering the transdiagnostic covariation observed in interoception, it could be perceived as this overarching factor (Brewer et al., 2016). However, due to the inconsistency in associations between interoception and psychopathology

(Brewer et al., 2021), alternative hypotheses should be considered (e.g. Southward et al., 2023).

Following the HiTOP model, internalizing symptomatology compromises clinical conditions characterized by distress or fear, such as depression or anxiety disorders, among others (Kotov et al., 2017). Recent conceptualizations also include somatic symptoms within a unified super-spectrum of emotional dysfunction (Kotov et al., 2021). Previous studies involving children and adolescents have found evidence for a positive correlation between cardiac interoceptive accuracy operationalized by heartbeat counting tasks and anxiety symptoms (Eley et al., 2004; 2007; Pile et al., 2018), but also no evidence for a significant association with social anxiety (Schmitz et al., 2012). Additionally, research indicates that children and adolescents experiencing chronic (abdominal) pain exhibit heightened gastric sensitivity compared to their healthy counterparts (Anderson et al., 2008; Walker et al., 2006). Externalizing symptomatology compromises behaviours associated with antisocial behaviour or conduct disorders within the HiTOP framework (Kotov et al., 2017; 2021). Specific links of externalizing symptomatology to interoception are evident in a study in which cardiac interoceptive accuracy measured with a heartbeat detection task was significantly lower in adults with attention-deficit-hyperactivity-disorder (ADHD; Kutscheidt et al., 2019; but note that these results may be attributed to variations in heart rate). Another study by Wiersema and Godefroid (2018) in turn found no group differences between adults with or without ADHD, neither in self-report nor in behavioural tasks on cardiac interoceptive accuracy. Furthermore, it was observed that children with comorbid autism-spectrum-disorder (ASD) and ADHD exhibited significantly lower cardiac interoceptive accuracy, operationalized by the Eye-Tracking Task, which is a heart rate-based behavioural measurement, compared to typically developing children (Yang, Zhou, Li, et al., 2022).

Given the limited number of studies directly investigating the connection between consciously experienced interoceptive processes and psychopathology in children, some instances suggest a potential relationship between symptoms of mental disorders and altered interoceptive accuracy in performance tasks (most commonly, this means reduced performance in heartbeat counting tasks) through the intermediary factor of alexithymia (Murphy et al., 2017; see also Brewer et al., 2016 for evidence on lower self-reported interoceptive accuracy in individuals with high alexithymia). Alexithymia, characterized by difficulties in recognizing, comprehending, and expressing emotions (Apfel & Sifneos, 1979), has been proposed as an individual marker of particularly low interoceptive accuracy (Brewer et al., 2021). Most studies on the relationship between alexithymia and psychopathology in children and adolescents align with the aforementioned findings (e.g. Karukivi et al., 2014; Rieffe et al., 2006) except in cases of internalizing symptomatology where adolescents with high alexithymia (presumably low interoceptive accuracy) reported a significantly higher presence of depressive symptoms (Honkalampi et al., 2009; Talebi Joybari, 2014).

During childhood and adolescence, young people experience many physical changes as well as changes in self-perception, which is why it is assumed that this period has a major influence on mental health in later life. However, this period (especially young adolescence) has been almost neglected in interoception research so far (Murphy et al., 2017). Hence, the present study aimed to look at the relationship between altered consciously experienced interoceptive accuracy with internalizing, externalizing, and somatoform symptomatology (according to the HiTOP model), in children aged 8 to 13 years. Therefore, Interoceptive accuracy is operationalized with a recently developed questionnaire (Murphy et al., 2020), a conventional heartbeat counting task (Schandry, 1981) and a newly introduced cardiac signal detection task (cvSDT; Pohl et al., 2021). This multi-method approach was chosen to obtain a more holistic view of the role of different aspects of consciously experienced interoceptive accuracy in mental health, rather than just picking out individual domains that may not be correlated with each other. To our knowledge, the present study is the first to conduct the cvSDT on a sample of children. Therefore, an exploratory objective is to investigate the relationship between the newly introduced cvSDT and the widely employed Schandry Task as well as self-reported interoceptive accuracy in this age group (H_1). Furthermore, given the postulated role of caregivers in the development of interoceptive abilities (Brewer et al., 2021; Filippetti, 2021), we expected a positive relationship between children and their parents in either self-reported or behavioural measured interoceptive accuracy (H_2). According to recent research on adults, utilizing questionnaires to assess interoceptive accuracy (e.g. Brand et al., 2023; Campos et al., 2021; Lin et al., 2023; Murphy et al., 2020), we expected a negative correlation between children's self-reported interoceptive accuracy with internalizing, externalizing as well as somatoform symptomatology (H_3). Due to the inconsistent findings on the role of cardiac interoceptive accuracy in psychopathology (e.g. Adams et al., 2022; Eley et al., 2004; 2007; Kutscheidt et al., 2019; Lin et al., 2023; Pile et al., 2018; Wiersema & Godefroid, 2018; Witthöft et al., 2020; Yang, Zhou, Li, et al., 2022), we aimed to exploratively examine the relationship between symptom severity and performance on behavioural measures of interoceptive accuracy in children (i.e. HCT and cvSDT; H_4).

Method

Participants

Participants were recruited from the German general population via newspaper articles, radio advertisements, flyers, and school newsletters. The study design required the involvement of one parent, with no specific parent defined, and a child aged between 8 and 13 years. Additional inclusion criteria encompassed obtaining informed consent from the participating children and their legal guardians. The socio-demographic characteristics of the sample are available in Table 1. One child and their parent had to be excluded from the data analysis because the parent did not want the child to answer certain questions due to personal reservations.

Within the defined age range, we allowed siblings to participate in the study to counteract a possible selection bias, for example, if parents decide to participate with the child who is most similar to them. In total, $n = 29$ parents and $n = 37$ children (i.e. $n = 8$ siblings) took part in the study. To obtain a larger sample, the entire data set was used for the statistical analyses. However, as this might present an imperfect solution given the non-independence of the observations, the supplementary information presents dyadic analyses between parents and children in which one sibling was randomly excluded.

Procedure

Initially, all interested parents were contacted by telephone. During a brief telephone screening, it was verified that neither children nor parents had a history of epilepsy or any type of tremor that might have interfered with electrocardiography. The study was subsequently carried out in two phases. First, participating children and parents filled out several questionnaires at home. Parents were explicitly informed that the children should answer the questions independently (i.e. same conditions for all, avoidance of bias). In the second part of the study, participants, including both children and parents, completed two tasks related to heartbeat perception, which comprised a standard heartbeat counting task (Schandry, 1981) and a newly developed cardiovascular signal detection task (cvSDT; Pohl et al., 2021). As compensation for their participation, both children and parents received 12 € per person, with the option for children to choose a cinema voucher equivalent to 12 €. The study protocol was approved by the ethics committee of the Psychological Institute.

Table 1. Socio-demographic characteristics of children and parents.

Sociodemographic variables	Parents ($n = 29$)	Children ($n = 37$)
Age[a]		
Years *M* (*SD*)	43.8 (5.4)	10.6 (1.6)
Gender[b]		
Female *N* (%)	23 (79.3)	19 (51.4)
Country of birth[c]		
Germany *N* (%)	26 (89.7)	37 (100.0)
Other *N* (%)	3 (10.2)	0 (0.0)
Children: Type of school[d]		
Primary School *N* (%)	–	11 (29.7)
Comprehensive School *N* (%)	–	14 (37.8)
Grammar School *N* (%)	–	9 (24.3)
Other *N* (%)	–	3 (8.1)
Parents: Family status		
Single *N* (%)	2 (6.9)	–
Married *N* (%)	26 (89.7)	–
Divorced *N* (%)	1 (3.4)	–
Parents: Education[e]		
Secondary School *N* (%)	5 (17.2)	–
Vocational High School *N* (%)	4 (13.8)	–
High School *N* (%)	3 (10.3)	–
University Degree *N* (%)	16 (55.2)	–
Other *N* (%)	1 (3.4)	–

Note.[a]Children age range 8 to 13 years, Parents age range 35 to 56 years; [b]Participants only reported identifying as women/girls or men/boys; [c]Other consisted of Bolivia, Netherlands, and Romania; [d]Other consisted of school forms like Waldorf and Montessori;[e]Other consisted of a private qualification.

Questionnaires

Children

The Interoceptive Accuracy Scale (IAS; Murphy et al., 2020) for children (not published and not yet validated in German) evaluates the accuracy of perceiving 20 bodily signals (e.g. *heartbeat*, *hunger*, *body temperature*; adjusted for children's comprehension). An exemplary item is phrased as follows *I am always correct at feeling when I am hungry*. Respondents rate these on a five-point scale ranging from 1 (*never*) to 5 (*most of the time*). In the current study, the IAS-C showed good internal consistency, α = .86 (evaluated according to George & Mallery, 2003).

For evaluating somatoform symptom burden, the study utilized the revised 21-item version of the German Children's Somatization Inventory (CSI; Gulewitsch et al., 2015), which is based on the original revised 24-item version introduced by Walker et al. (2009). This version of the CSI comprises 21 somatic symptoms (e.g. *headache*). Children assess the severity of each specific symptom over the past two weeks using a 5-point scale, ranging from 0 (*not at all*) to 4 (*a whole lot*). The scores for each item are summed to compute the total score, which reflects the overall intensity of somatic symptoms. In the present sample, the total score demonstrated acceptable internal consistency with α = .73.

In accordance with the recommendations of Goodman et al. (2010) the Strengths and Difficulties Questionnaire (SDQ; Goodman, 2001; Goodman et al., 1998; validated in German by Lohbeck et al., 2015) to evaluate internalizing and externalizing symptomatology in children and adolescent samples from the general population was administered. The SDQ comprises 25 items designed to capture a range of behavioral issues and prosocial tendencies. Respondents were required to indicate their responses on a 3-point Likert scale, spanning from 0 (*not true*) to 2 (*certainly true*). The alternative three-factor structure of the SDQ involves the subscales of *internalizing problems* (comprising 10 items), *externalizing problems* (comprising 10 items), and *prosocial behavior* (comprising 5 items). In line with the objectives, the analysis was focused exclusively on the internalizing and externalizing subscales, both of which demonstrated low internal consistency in the present study, $α_{Internalizing}$ = .64, $α_{Externalizing}$ = .68.

Parents

To evaluate self-reported interoceptive accuracy in the parental cohort, we utilized the Interoceptive Accuracy Scale (IAS; Murphy et al., 2020; German validation: Brand et al., 2023). This scale encompasses the same bodily sensations as the earlier-mentioned version designed for children, with the addition of an extra item that assesses the accurate perception of sexual arousal. Similarly, respondents provided their ratings to the scale's items using a five-point scale, ranging from 1 (*never*) to 5 (*most of the time*). Within our study, this scale demonstrated a good internal consistency, α = .85.

For the investigation of internalizing, externalizing, and somatic symptoms, also the parental adaptations of the SDQ and CSI instruments were administered. The parental version of the SDQ (SDQ-P; Goodman, 1997, 2001; German validation Woerner et al., 2002) was used to evaluate internalizing and externalizing symptomatology from a parental perspective and compromises the identical set of 25 items as the self-assessment version from a parental viewpoint. In the present study, both the internalizing and externalizing subscales demonstrated an acceptable to good level of internal consistency, $α_{Internalizing}$ = .71, $α_{Externalizing}$ = 80. Similarly, the parental version of the CSI (P-CSI; Gulewitsch et al., 2015) encompasses the same set of 21 somatic symptoms from an observer's perspective. In the present study, the internal consistency of the P-CSI scale was found to be low, α = .46.

Performance tasks

In the context of the heartbeat perception tasks conducted with both children and parents, an electrocardiogram (ECG) recording system from Becker Meditec in Karlsruhe, Germany, known as the Varioport system was utilized. The acquisition of biodata, sampled at a rate of 512 Hz, and the execution of the experimental tasks were carried out through a bespoke software application (created by Gerhard Mutz), known as 'uVariotest'. Electrodes were positioned at the left and right clavicles, as well as below the left costal arch.

All children and their parents engaged in a conventional heartbeat counting task (HCT) for quantifying cardiac interoceptive accuracy, commonly referred to as the Schandry Task (Schandry, 1981). Although originally designed for adults, adaptations and testing have been previously conducted for children aged 8 to 11 years (e.g. Eley et al., 2004; 2007) and 6 to 11 years (e.g. Koch & Pollatos, 2014a, 2014b). Following a brief practice session, participants were instructed to silently count perceived heartbeats in three randomized time intervals (25, 35 and 45 seconds). The instructions for the HCT were based on the original instructions (cf. Desmedt et al., 2020, p.

7), namely *The following task is designed to measure how accurately you can perceive your heartbeats. To do this, we ask you to count your heartbeats without measuring your pulse. Please also take off your watch. Now sit back, relax and count all the heartbeats you can feel as soon as you hear the sound*. The actual count of heartbeats was determined by tracking the number of R-spikes in the electrocardiogram. After automatic R-peak detection, trials were inspected visually and excluded from the analysis if the identification of all R-peaks was not possible, typically due to factors such as motion artifacts. We had to completely exclude one parent from the study due to the inability to obtain a valid ECG measurement. Interoceptive accuracy scores were determined as $1-\frac{1}{3}*\sum\left(\frac{|Measured\,Heartbeats-Counted\,Heartbeats|}{Measured\,Heartbeats}\right)$. Internal consistency for the HCT was within the acceptable range for children as well as parents, $\alpha_{children}$ = .76, $\alpha_{parents}$ = .71.

Moreover, a novel task for detecting cardiovascular signals (cvSDT; Pohl et al., 2021) was administered. The cvSDT uses the principles of signal detection theory and is, therefore, able to separate actual accuracy or sensitivity (*d*′) from response bias (*c*) of responses in cardiac behavioural tasks. Pohl and colleagues (2021) have shown that standard HCT scores may represent a mixture of accuracy and response bias, therefore it was hypothesised that the cvSDT could provide additional information in the present study. Similar to the HCT, participants were instructed to count all detected heartbeats within time intervals of varying durations, contingent on a predetermined number of heartbeats (indicated by the number of R-spikes in the ECG). The cvSDT designates five distinct interval lengths, ranging from seven to eleven heartbeats, with both the beginning and end signalled by a computer-generated tone. Subsequently, participants are presented a 2-alternative forced choice response format for each interval: (1) a range of 2 heartbeats (e.g. six to eight beats for a predefined seven-heartbeat interval) or (2) an alternative option containing either more or fewer beats. Following practice trials, participants completed the test trials, encompassing all possible combinations. The total duration of this task ranged from approximately 10 to 15 minutes for both parents and children. The computation of relevant parameters in this task followed the methodology described by Pohl and colleagues (2021): Correct responses were categorized as hits or correct rejections, while the opposite responses were classified as misses or false alarms. These values were subsequently z-transformed and used to calculate two key parameters, namely sensitivity ($d' = Z_{Hit} - Z_{FalseAlarm}$) and response bias ($c = -0.5 * [Z_{Hit} + Z_{FalseAlarm}]$).

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics Version 27.0 (IBM Corporation, 2020) and JASP (JASP Team, 2023). To examine relationships between the different measurements of interoceptive accuracy (i.e. questionnaire scores and performance task results) correlation coefficients as well as multiple regression analyses using sensitivity (*d*′), response bias (*c*) and their interaction as predictors were conducted (H_1). Furthermore, correlation coefficients were computed to examine the association between children's and parents' self-reported, and performance task-measured interoceptive accuracy (H_2). To test whether self-reported or performance task-measured interoceptive accuracy predicted psychopathology (i.e. internalizing, externalizing and somatoform symptomatology, H_3 and H_4), multiple regression analyses were calculated. Therefore, either IAS, HCT or cvSDT scores served as independent variables, while children's age and gender were used as potential covariates.

Based on recent recommendations (e.g. Kelter, 2021; Sjölander & Vansteelandt, 2019), in addition to frequentist statistics (with a significance level of α < .05) and 95% bias-corrected and accelerated bootstrap confidence intervals from 10.000 samples (Chernick 2008), results from Bayesian analyses are provided to give an insight into the likelihood of the alternative hypothesis. For Bayesian correlation analyses, a stretched beta prior of 1 and for Bayesian regression analyses, the Jeffreys-Zellner-Siow prior with a prior range of r = .354 was used (cf. Andraszewicz et al., 2015). In addition, a beta-binomial model prior with $\alpha = 1$ and $\beta = 1$ was used to avoid bias towards sparse or dense models (Bergh et al., 2021). The Bayes factors (*BF*) presented are evaluated according to the following conventions: a BF_{10} of 1–3 is considered weak evidence, a BF_{10} of 3–10 is considered moderate evidence and a BF_{10} of 10 or more is considered strong evidence towards the alternative hypothesis (Jarosz & Wiley, 2014; Nuzzo, 2017). It is argued that only models or correlations where Bayesian analysis shows at least moderate support for an existing relationship, in addition to significant *p*-values and bootstrap intervals that do not encounter zero, should be considered as potentially sufficient evidence for an existing effect (cf. Kelter, 2021).

For the interpretation of correlation coefficients, we adhere to standard conventions, where $|r| \geq .10$ is considered a small effect size, $|r| \geq .30$ signifies a medium effect size, and $|r| \geq .50$ indicates a large effect size, following Cohen's guidelines (Cohen, 1992).

Results

Relationships between different measurements of interoceptive accuracy

HCT scores in our study exhibited a range from .00 to .86, M = .38 (SD = .24) for children. We found approximately 8% of children that had been unable to count their heartbeats at all (HCT = .00). Parents' HCT scores ranged from .05. to .98, M = .64 (SD = .25). Regarding the novel cvSDT for children sensitivity scores exhibited a range from −0.23 to 1.03, M=0.40 (SD=0.32), while response bias scores varied from −1.60 to 0.85, M=−0.19 (SD=0.72). In the case of parents, sensitivity scores ranged from −0.59 to 1.95, M=0.74 (SD=0.58), and response bias scores spanned from −1.00 to 0.85, M=0.15 (SD=0.46).

To assess the impact of sensitivity, response bias, and their interplay in the novel cvSDT on cardiac interoceptive accuracy as measured by the HCT, two multiple regression analyses were conducted, the results of which are presented in Table 2. For children, no evidence was found regarding the capacity to predict HCT scores by the cvSDT scores d' and c, $F(3,32) = 1.17$, $p = .336$, $BF_{10} = 0.25$.

Beyond that, no evidence for a significant correlation between HCT scores and children's self-reported Interoceptive Accuracy, $r = .11$, $p = .502$, 95% BCa CI [–.25, .43], $BF_{10} = 0.25$, was found. The same applies to the cvSDT, where no evidence was found for a regression model to predict children's self-reported interoceptive accuracy, $F(2,32) = 0.94$, $p = .435$, $BF_{10} = 0.20$.

Similarly, a significant but weakly evidenced correlation (as indicated by the BF) between self-reported Interoceptive Accuracy and HCT scores emerged for parents, $r = .34$, $p = .049$, 95% BCa CI [.02, .68], $BF_{10} = 1.35$. Furthermore, parents' self-reported interoceptive accuracy could not be predicted by the cvSDT scores, $F(3,22) = 0.54$, $p = .660$. $BF_{10} = 0.18$.

Relationship between parental and children's interoceptive accuracy

A large and statistically significant correlation was observed between children's self-reported interoceptive accuracy and parental-reported interoceptive accuracy, $r = .63$, $p < .001$. The 95% BCa confidence interval indicates that the possible true relationship likely falls within a range from a medium to a large positive correlation, 95% CI [.41, .79]. This association is supported by a Bayes Factor of $BF_{10} = 898.75$, providing strong evidence for the existence of a correlation. A Scatterplot depicting this correlation is provided in Figure 1.

However, this pattern did not hold when assessing cardiac interoceptive accuracy through the conventional HCT, as no significant association between children's and parental scores was evident, r=–.25, p = .130, 95% BCa CI [–.56, .13], $BF_{10} = 0.56$. Furthermore, neither the sensitivity scores, $r = .11$, $p = .532$, 95% BCa CI [–.18, .41], $BF_{10} = 0.26$, nor the response bias scores, r=–.02, p = .905, 95% BCa CI [–.35, .27], BF_{10} =

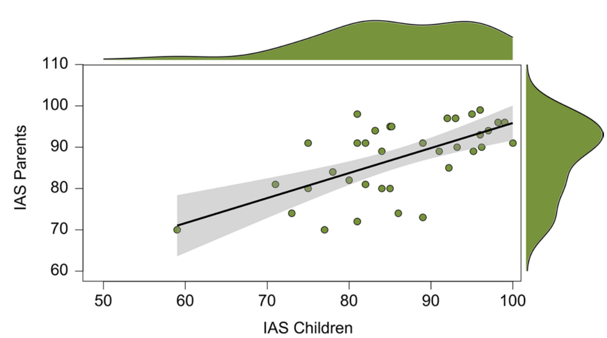

Figure 1. Scatterplot depicting the relationship between parental and children's self-reported interoceptive accuracy (r = .63).
Note. IAS: Interoceptive Accuracy Scale.

Table 2. Results of multiple linear regression analysis using the enter method for children and parental cvSDT results on the standard heartbeat counting task.

Dependent Variable	R^2 (p)	IndependentVariable	b	SE^A	[95% BCa CI]^A	β	p
Children HCT Score	.099[a](.336)	(Constant)	0.43	0.05	[0.28, 0.60]		<.001
		d'	0.11	0.11	[−0.12, 0.31]	.189[a]	.351
		c	−0.15	0.06	[−0.37, −0.03]	−.529[a]	.018
		d' x c	0.07	0.15	[−0.27, 0.45]	.103[a]	.653
Parents HCT Score	.319[a](.034)	(Constant)	0.45	0.08	[0.29, 0.57]		<.001
		d'	0.25	0.08	[−0.06, 0.81]	.566[b]	.006
		c	0.07	0.13	[−0.47, 0.49]	.132[a]	.563
		d' x c	−0.12	0.13	[−0.76, 0.04]	−.186[a]	.394

Note. HCT: Heartbeat Counting Task; [a]indicates $BF_{10}/BF_{inclusion}$ = anecdotal/weak evidence, [b]indicates $BF_{10}/BF_{inclusion}$ = moderate/substantial evidence; [A]95% CI and standard error refer to BCa bootstrap values on 10.000 samples.

0.22, in the cvSDT appeared to exhibit any discernible relationship between children and their parents.

All of the abovementioned patterns were also evident when one of the siblings was randomly removed from the dataset (see Supplementary Information S1).

Self-Reported interoceptive accuracy of children with internalizing, externalizing, and somatoform symptomatology

Table 3 shows the results of the multiple regression analyses with self-reported interoceptive accuracy as well as the age and gender of the children as independent variables and internalizing, externalizing and somatoform symptoms (either reported by the children themselves or their parents) as dependent variables. Evidence was found that children's self-reported interoceptive accuracy predicted parental-reported internalizing symptomatology, $F(3,33) = 4.20$, $p = .013$, $BF_{10} = 4.19$. Within this model, children's self-reported interoceptive accuracy negatively predicted internalizing symptomatology with a standardized regression coefficient of β = –.527. A depiction of this relationship is provided in Figure 2.

Interoceptive accuracy in performance tasks with internalizing, externalizing and somatic symptomatology

Concerning symptomatology in children, regression analyses showed no capacity for HCT scores to predict children's self-reported internalizing symptoms, $F(3,33) = 0.60$, $p = .619$, $BF_{10} = 0.14$, externalizing symptoms, $F(3,33) = 0.66$, $p = .581$, $BF_{10} = 0.15$, or somatoform symptoms, $F(3,33) = 1.45$, $p = .245$, $BF_{10} = 0.33$. Similarly, there was no evidence for HCT scores predicting internalizing, $F(3,33) = 0.08$, $p = .971$, $BF_{10} = 0.08$, externalizing, $F(3,33) = 1.19$, $p = .328$, $BF_{10} = 0.25$, or somatoform symptomatology, $F(3,33) = 0.60$, $p = .619$, $BF_{10} = 0.14$, reported by parents.

Likewise, sensitivity scores, response bias scores and their interaction in the cvSDT demonstrated no capacity to predict self-reported internalizing symptoms, $F(5,30) = 0.45$, $p = .809$, $BF_{10} = 0.06$, externalizing symptoms, $F(5,30) = 0.73$, $p = .606$, $BF_{10} = 0.09$, or somatoform symptoms, $F(5,30) = 0.95$, $p = .464$, $BF_{10} = 0.12$. This pattern extended to parental-reported internalizing, $F(5,30) = 0.78$, $p = .572$, $BF_{10} = 0.09$, externalizing, $F(5,30) = 2.17$, $p = .083$, $BF_{10} = 0.70$, and somatoform symptomatology, $F(5,30) = 0.87$, $p = .515$, $BF_{10} = 0.11$.

Discussion

The principal aim of this investigation was to respond to the call for further research to address the lack of information regarding children's interoception and psychopathology, as highlighted in the literature (e.g. Hechler, 2021; Murphy et al., 2017). Therefore, the present study explored the association between internalizing, externalizing, and somatic symptomatology and interoceptive accuracy, within a relatively understudied demographic group – children

Table 3. Results of multiple linear regression analysis using the enter method for children's self-reported interoceptive accuracy on internalizing, externalizing and somatoform symptoms.

Dependent Variable	R^2 (*p*)	IndependentVariable	*b*	SE^A	[95% BCa CI]^A	β	*p*
Self-Reported Internalizing	.173^a(.096)	(Constant)	15.91	4.84	[7.12, 26.27]		.004
		IAS Children	−0.11	0.05	[−0.22, −0.02]	−.360^a	.032
		Age	0.32	0.25	[−0.18, 0.76]	.182^a	.261
		Gender^B	−0.61	0.93	[−2.41, 1.19]	−.106^a	.514
Self-Reported Externalizing	.053^a(.610)	(Constant)	19.78	7.37	[5.29, 38.95]		.002
		IAS Children	−0.07	0.08	[−0.24, 0.05]	−.215^a	.220
		Age	−0.04	0.29	[−0.63, 0.57]	−.022^a	.897
		Gender^B	−0.30	1.03	[−2.21, 1.46]	−.048^a	.782
Self-Reported Somatoform	.178^a(.088)	(Constant)	12.25	13.37	[−13.33, 39.55]		.331
		IAS Children	−0.19	0.14	[−0.49, 0.07]	−.253^a	.125
		Age	1.53	0.64	[0.32, 2.87]	.353^a	.033
		Gender^B	−0.66	2.10	[−4.63, 3.36]	−.047^a	.772
Parental-Reported Internalizing	.276^b(.013)	(Constant)	22.22	4.99	[11.25, 30.77]		<.001
		IAS Children	−0.17	0.05	[−0.24, −0.05]	−.527^b	.001
		Age	−0.08	0.25	[-0.56, 0.34]	−.043^a	.775
		Gender^B	0.52	0.85	[−1.30, 2.49]	.090^a	.552
Parental-Reported Externalizing	.113^a(.261)	(Constant)	20.12	5.60	[9.85, 32.20]		.002
		IAS Children	−0.05	0.07	[−0.19, 0.08]	−.127^a	.451
		Age	−0.58	0.33	[−1.19, 0.02]	−.292^a	.085
		Gender^B	0.70	1.04	[−1.38, 2.77]	.108^a	.519
Parental-Reported Somatoform	.084^a(.400)	(Constant)	17.19	7.51	[2.19, 34.90]		.029
		IAS Children	−0.13	0.08	[−0.30, −0.01]	−.288^a	.103
		Age	0.19	0.41	[−0.61, 1.07]	.074^a	.639
		Gender^B	0.07	1.36	[−2.39, 2.57]	.009^a	.960

Note. IAS: Interoceptive Accuracy Scale; ^{a}indicates $BF_{10}/BF_{inclusion}$ = weak evidence, ^{b}indicates $BF_{10}/BF_{inclusion}$ = moderate evidence; ^{A}95% CI and standard error refer to BCa bootstrap values on 10.000 samples; ^{B}female = 1, male = 2.

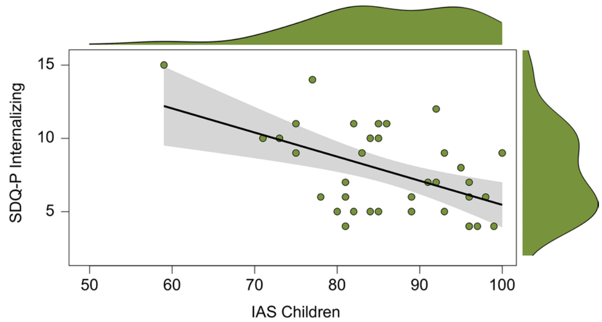

Figure 2. Scatterplot depicting the relationship between children's self-reported interoceptive accuracy and internalizing symptomatology reported by their parents (β = −.527). *Note*. SDQ-P: Strength and Difficulties Questionnaire Parental Version; IAS: Interoceptive Accuracy Scale.

aged 8 to 13 years. To achieve this goal, a multimethod approach for assessing interoceptive accuracy was utilized. This approach encompassed a recently developed self-assessment instrument (the Interoceptive Accuracy Scale; Brand et al., 2023; Campos et al., 2021; Lin et al., 2023; Murphy et al., 2020), a conventional heartbeat counting task (Schandry, 1981), complemented by a novel cardiovascular Signal Detection Task (Pohl et al., 2021). It was hypothesized that the latter task might offer certain advantages. Specifically, that it could provide additional insights regarding response tendencies, which may not be adequately captured by conventional methodologies (as discussed by Brener & Ring, 2016; Pohl et al., 2021). To construct a more comprehensive overview, parental input on the symptoms exhibited by children was additionally requested and the congruence between children's interoceptive accuracy and the assessments provided by their parents was investigated.

Supporting evidence for a negative relationship between children's self-reported interoceptive accuracy and their internalizing symptomatology, as reported by their parents, was identified. This finding is in harmony with previous research and theoretical models in adults, where self-reported interoceptive accuracy has also shown a negative correlation with depressive and anxious (i.e. internalizing) symptomatology (e.g. Brand et al., 2022; Lin et al., 2023; Paulus & Stein, 2010). However, the available data does not indicate the direction of this relationship, which may be much more complex than the simple assertion that self-reported interoceptive accuracy is a risk factor for, or an outcome of, internalizing symptomatology. Considering recommendations for the treatment of chronic pain in children (Hechler, 2021; Hechler et al., 2016), the identified correlation may serve as additional evidence supporting the notion that addressing distorted beliefs concerning bodily processes might be a potential objective in children's therapeutic interventions (e.g. employing biofeedback interventions). Given the limited body of research on the self-report dimension of interoceptive accuracy in children, this underscores the importance of developing validated questionnaires tailored for children to gain deeper insights into the impact of perceived interoceptive abilities in this population. The positive correlation between self-reported interoceptive accuracy among children and their parents provides initial insights into the capacity of children to assess their abilities in accurately perceiving bodily signals.

However, contrary to our expectations, the current study did not yield any compelling evidence of a significant association between performance on cardiac interoceptive accuracy tasks (i.e. HCT and cvSDT) and psychopathological symptoms. As noted earlier, various studies involving both children and adults have reported connections between cardiac interoceptive accuracy and psychopathological factors (e.g. Eggart et al., 2019; Eley et al., 2004; 2007; Furman et al., 2013; Pile et al., 2018; Pohl et al., 2021; Pollatos et al., 2009; Witthöft et al., 2020; Yang, Zhou, Li, et al., 2022). Nevertheless, at least for anxiety symptoms, recent meta-analytic results in adults have indicated a lack of observable associations with cardiac interoceptive accuracy (Adams et al., 2022) and have also cast doubt on the suitability of heartbeat counting tasks as reliable indicators of interoceptive abilities (e.g. Desmedt et al., 2018; 2022; Murphy, 2023). With the aforementioned results on self-assessments in mind, this underscores the necessity for further investigation into the disjunction between self-reported measures and cardiac interoceptive accuracy, extending this investigation to research conducted with children. Additionally, our results provide no evidence for any relationship between the HCT and cvSDT scores in children. As specialized tasks are already in existence for assessing cardiac interoceptive accuracy in children (e.g. Schaan et al., 2019; Yang, Zhou, Wei, et al., 2022), we advocate for future research to thoroughly investigate the applicability of the cvSDT in children. Such investigations could offer additional information regarding the reliability of widely employed methods for assessing cardiac interoception. Furthermore, there is a strong need for the inclusion of supplementary tasks aimed at assessing various interoceptive domains in research involving children (e.g. Krautwurst et al., 2016; van Dyck et al., 2016).

Limitations

It is essential to stress that the results of the present study offer initial insights that warrant careful interpretation. The project's initial planning took place in November 2019. With the emergence of the COVID-19 pandemic in March 2020 and the ensuing restrictions in Germany, which rendered laboratory assessments with children unfeasible, data collection had to be deferred. Hence, it was not possible to achieve the originally intended sample size of $N = 82$, which was required for detecting at least a medium bivariate correlation (as determined through a priori power analysis using G*Power; Faul et al., 2007; α = .05, β = .80). The constrained empirical robustness and the non-representative sample, primarily composed of children from married couples with university degrees, significantly impede the extent to which the findings can be extrapolated to the broader population. Factors such as sampling bias, akin to a 'lucky draw' scenario (Field, 2020), could have easily occurred. Despite the consistency of our results with recent research (as outlined earlier), it is essential to guard against the potential pitfalls of confirmation bias and type 1 error. Although Bayesian analysis techniques were used to gain insight into the likelihood of the presence of the hypothesized associations, not all statistical inference problems (such as a lack of sampling variability) could be resolved with the techniques used. Other multiple-test corrections, such as the Bonferroni correction, could also have been applied but were not used due to criticism of this method (e.g. Perneger, 1998). The need for replication studies and the use of larger samples is therefore beyond dispute in order to test the robustness of the effects and to rule out possible type I errors that may have occurred in the data presented.

Furthermore, it is worth noting that the majority of techniques employed for assessing interoceptive accuracy, such as the Interoceptive Accuracy Scale for Children (IAS-C) and the cardiovascular Signal Detection Task (cvSDT), have not previously been applied to samples of (young) children. Consequently, no substantiated evidence exists regarding the validity of these methods within this specific population. Additionally, our analysis revealed a notable lack of internal consistency for some of the measurements employed. Considering that these measurements have been well-established in the field of child psychology for an extended period (e.g. Goodman, 1997; Gulewitsch et al., 2015) and are known for their typically robust internal consistency, this absence may introduce additional biases into our results. Similarly, our sample exhibited a relatively low mean for the HCT, comparable to the findings in previous research (e.g. $M = 0.55$ in Koch & Pollatos, 2014b). This phenomenon could be partly due to the expected five percent of children who are presumably unable to count their heartbeats accurately (cf. Koch & Pollatos, 2014a), which aligns with number of children with HCT = .00 in our study. The presence of those may have disproportionately influenced the results in our relatively small sample. However, even when excluding these cases, our sample exhibited a mean ($M = 0.48$) that suggests a potential underperformance on the HCT. Also, we did not change the instructions of the HCT to counteract possible influences due to time estimation and knowledge, as emphasised by Desmedt and colleagues (2020). Furthermore, although we asked about possible influencing factors for the performance tasks before the study, such as epilepsy or any type of tremor, we did not collect data on the history of heart disease (e.g. arrhythmia) or the use of medications that alter autonomic function, which could further limit the validity of the performance tasks used. Consequently, future research on the cvSDT in children requires not only larger samples to provide a more comprehensive understanding of this measurement but also, comparisons with other cardiac interoceptive accuracy tasks from recent years (e.g. Schaan et al., 2019; Yang, Zhou, Wei, et al., 2022).

When considering self-assessment techniques, it is anticipated that the conventional biases, particularly relevant for children, such as extreme response bias and conformity bias, will be present. Hence, a thorough psychometric analysis of the IAS-C is strongly justified. Furthermore, we did not utilize other frequently employed self-assessment tools that center on children's propensity to attend to internal signals (e.g. Eklund et al., 2005; Jones et al., 2021). The inclusion of such assessments could have yielded additional perspectives on the differentiation of questionnaires regarding interoception in children. In addition, we did not ask the participating parents whether they were the main caregivers of the participating children, which could be another possible covariate that we could not account for.

Even though we analyzed not only children but also information given by their parents, several research questions on the influence of parental traits remain unanswered. There's still a lack of research on the origins of interoception, meaning the development of interoceptive abilities in the early years of life. This gap is characterized by limited evidence regarding interactions between children and parents and a scarcity of longitudinal studies, particularly for young children (Filippetti, 2021; Hechler, 2021; Murphy et al., 2017).

Conclusion

In summary, the current findings offer insights into the complex interplay between interoceptive accuracy and psychopathological symptoms in children aged 8 to 13 years. These results provide preliminary evidence indicating a potential negative relationship between self-reported interoceptive accuracy and internalizing symptomatology in children. However, there is no supporting evidence for a potential association between cardiac interoceptive accuracy and pathological symptoms, raising questions about the applicability of conventional heartbeat perception tasks in children, as previously observed in adult populations. Future research should concentrate on validating measures assessing self-reported interoceptive accuracy, enhancing laboratory assessments to precisely define interoceptive abilities, and conducting longitudinal studies that explore the interplay between parental and children's factors, in order to gain further insights into this understudied population.

Acknowledgments

We thank Michael Eggart for his consistent moral and scientific support. We extend our appreciation to Renée Chiara Matthes for her valuable contributions to participant recruitment. Further, we thank Johanna Kolb for her assistance with data visualization.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The dataset utilized in this study is accessible on the Open Science Framework. The permanent URL for the raw data is https://osf.io/2e3kn/.

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