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Measuring interoception from infancy to childhood: A scoping review☆

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ABSTRACT

Background: Interoception is the ability to perceive, understand, and respond to internal bodily signals. Despite its importance, our knowledge of interoceptive abilities in the early stages of development remains limited. Delays or atypical patterns in interoceptive development may serve as early indicators of potential developmental psychopathology. Thus, assessing interoception in infancy and early childhood is essential for advancing our understanding of both typical and atypical developmental pathways.

Objective: This scoping review summarises existing evidence regarding interoception from infancy to childhood and identifies the most common methods for assessing interoception in neurotypical pediatric populations.

Design: A literature review was performed through a robust search of three scientific databases.

Results: Among 663 studies, 24 articles met the inclusion criteria. The most commonly used methods in infancy were looking-time paradigms and brain-based implicit measures, such as Heart-Evoked Potentials (HEP). Researchers predominantly used child-adapted versions of Heart Tracking Tasks (HTT) for preschool-aged children. The primary methods for investigating interoceptive abilities among school-aged children included HTTs and self-report measures. Only one study used fMRI to examine mind-body connections in childhood, while two relied on parent reports.

Conclusions: This review offers a comprehensive overview of past and current methods for measuring interoception in the literature. It highlights the strengths and limitations of existing methodologies and presents recommendations to enhance our understanding of interoception in early human development.

1. Introduction

Interoception is a multifaceted construct that encompasses the ability to perceive, understand, and respond to a wide range of signals originating within the body, such as muscular and visceral sensations, and above the body, like temperature and itch. In recent years, interoception has garnered significant attention due to its critical role in cognitive functioning and psychopathology (e.g., Khalsa et al., 2018; Murphy et al., 2017), along with its importance in maintaining homeostasis and body regulation (Craig, 2002). Much of the existing literature has predominantly centered on adult populations, but there is a growing interest in investigating interoception across various developmental stages, including infancy and childhood. Understanding interoceptive abilities early in life provides valuable insights into how the interoceptive system influences different aspects of human development, ultimately guiding interventions that support socio-emotional and cognitive growth.

Basic interoceptive abilities are thought to emerge early in life and might be influenced by early parent-infant interactions (Filippetti, 2021; Fotopoulou and Tsakiris, 2017). Indeed, infants can perceive perturbations in their bodily state, such as hunger, pain, and cold/warm temperature, and can communicate their needs to the caregivers eliciting a response to their bodily cues. If the caregiver interprets these cues correctly, they will promptly respond to match infants' demands, supporting infants' self-regulatory development (Filippetti, 2021; Fotopoulou and Tsakiris, 2017). If the caregiver misinterprets infants' cues, their response will be inappropriate, delayed, or even missing, having negative implications for interoceptive processing and child

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development, with potential consequences throughout the lifespan. Besides infancy, childhood represents another crucial period in which more mature and sophisticated interoceptive abilities develop (Koch and Pollatos, 2014a, 2014b), and possible psychopathological conditions, associated with impairments in interoception, could emerge (Brand et al., 2024). Indeed, recent studies indicate that atypical interoceptive skills during childhood are associated with a multitude of developmental issues including eating disorders (Koch and Pollatos, 2014b), internalizing symptoms (Brand et al., 2024), and emotional dysregulation (Cheung et al., 2024).

Essential for the investigation of interoception is the need to use reliable and valid measures to do so. This requires, first, a clear understanding of what interoception is. Although several definitions of interoception exist in the literature, there is a consensus to conceive it as a broad and multidimensional construct that comprises different components. Recently, a three-dimensional model of interoception was proposed (Garfinkel, 2015; Suksasilp, and Garfinkel, 2022). According to this author, there are 3 key dimensions of interoception: (1) interoceptive accuracy (IA), defined as the ability to detect accurately bodily sensations, assessed through objective measures, such as heartbeat tracking tasks (HTT); (2) interoceptive sensibility (IS), indexing the self-perceived ability to detect body signals and focus on them, typically measured with questionnaires and (3) interoceptive awareness, which refers to the metacognitive awareness of interoceptive accuracy, captured by measuring correspondence between confidence ratings and behavioural accuracy measures.

In adults, the complex and multidimensional nature of interoception has prompted the creation of diverse measures to capture its varying aspects. Interoceptive sensibility is commonly measured through self-report measures such as the MAIA (Multidimensional Assessment of Interoceptive Awareness; Mehling et al., 2012; Mehling et al., 2018), the BPQ (Body Perception Questionnaire; Porges, 1993), the BAQ (Body Awareness Questionnaire; Shields et al., 1989), and the SAQ (Self--Awareness Questionnaire; Longarzo et al., 2015). However, these questionnaires have been found to measure distinct constructs, lacking empirical convergence (Desmedt et al., 2022). Moreover, evidence suggests that the MAIA measures are better understood as reflecting adaptive interoception, which involves focused attention on bodily signals and their accurate interpretation within context, facilitating behaviours that support physiological balance. In contrast, maladaptive interoceptive processing—characterized by excessive vigilance or avoidance—can interfere with emotion regulation and is specifically measured by tools like the BPQ (Trevisan et al., 2023)

To evaluate interoceptive accuracy, researchers frequently used heart-rate tracking tasks (HTT), which are non-invasive, quick, and user-friendly methods. Common tasks include counting perceived heartbeats (Heartbeat Counting Task HCT; Schandry, 1981), tapping along with the heartbeat (Canales-Johnson et al., 2015), or matching external stimuli with the heart rate (Heartbeat Detection Task, HDT; Brener and Ring, 2016). Responsivity to the cardiac channel has also been examined through the Heartbeat Evoked Potential (HEP), a neurophysiological marker of interoceptive processing (Pollatos and Schandry, 2004; Maister et al., 2017; Coll et al., 2021). HEPs are primarily considered a measure of interoceptive accuracy. Indeed, HEPs reflect neural processing of cardiac signals and are often used to assess how well the brain tracks interoceptive signals.

However, cardioception alone should not be considered a general measure of interoceptive ability, as it does not account for sensitivity across all interoceptive channels (e.g., gastrointestinal or respiratory systems). To address this, new tasks have been developed for adults—such as those focusing on gastrointestinal, respiratory, and thermal interoceptive channels—to provide a more comprehensive, multichannel approach to studying interoception (Desmedt et al., 2023). Finally, to evaluate interoceptive awareness, researchers examined the extent to which subjective confidence in task performance predicts objective measures of heartbeat detection (e.g., heartbeat counting task, HCT). This relationship was quantified using metrics such as the area under the ROC curve (Garfinkel et al., 2015). How can interoception be measured in the early stages of development? Conducting research with developmental populations is always challenging. Infants and toddlers cannot communicate verbally like older children or adults and have short attention spans. Although older children have more advanced language skills and better attention spans, their ability to express thoughts and feelings can vary significantly and are often influenced by a desire to please adults or to fit in with peers. These challenges required researchers to find sensitive and sometimes creative approaches tailored to children's age needs and capacities to study interoception. So far, there has been limited research on interoceptive abilities in early developmental stages. Studies with non-verbal populations relied mostly on looking-times procedures and implicit measures, such as HEP (Maister et al., 2017). Despite some exceptions (Weijs et al., 2023), converging evidence supports the foundational study by Maister and colleagues (2017), which demonstrated behavioural and neural evidence of interoceptive cardiac abilities in infants during their first months of life. Research involving preschool and school-aged children has modified existing measures commonly used with adults, such as the HCT, to better accommodate children's shorter attention spans. In school-age children, HCT was shortened, while preschoolers were asked to do jumping jacks before the heartbeat detection task to enhance their ability to sense their heartbeats (Schaan et al., 2019). Additionally, new tasks have been developed for preschoolers, including the Eye-Tracking Interoceptive Accuracy Task (EIAT) (Yang et al., 2021). Besides accuracy tasks, interoceptive sensibility was also assessed in school-age children through validated self-reports, such as the MAIA_Y(Multidimensional Assessment of Interoceptive Awareness_Youth Version; Jones et al., 2021) and the SAQ_C (Self-Awareness Questionnaire_Children; Raimo et al., 2024). It is important to recognize that most interoceptive processes occur outside of conscious awareness (Khalsa et al., 2018). When these processes are consciously perceived, they are typically assessed using subjective questionnaires and objective measures (e.g., the Heartbeat Tracking Task, HTT) that require focused attention on interoceptive signals. In contrast, measuring unconscious interoceptive processing is more challenging, as it involves physiological mechanisms that function without explicit awareness. These processes can be examined using implicit measures, such as Heart Evoked Potentials (HEPs). Notably, during infancy, unconscious interoceptive processing likely predominates over conscious interoception, as the ability to recognize, interpret, and verbalize internal bodily signals emerges later in development.

However, a clear understanding and consensus on standard measures for studying interoception in early development are lacking. This scoping review aims to explore the various techniques employed to assess interoception across three developmental stages: infancy, preschool age, and school age. Specifically, we will identify all quantitative methods utilized for evaluating interoception in typically developing children from infancy through childhood, as well as their respective strengths and limitations at each stage. By providing a comprehensive mapping of the existing and emerging literature on interoception measurement, this review will offer valuable insights that can guide future research regarding the types and combinations of methods suitable for developmental populations.

2. Methods

The present scoping review is in adherence with the Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews (PRISMA-ScR; Tricco et al., 2018). To our knowledge, a comprehensive review that maps the commonly used measures to assess interoceptive abilities from infancy to childhood has not been done. This review not only highlights the strengths and limitations of the various measurement techniques but also identifies gaps in the current literature, offering a foundational resource for researchers and clinicians

seeking to understand and evaluate interoceptive abilities early in life. Scoping reviews are typically employed for exploratory purposes, making them particularly useful for shedding light on emerging areas that have not yet been extensively reviewed (Peters et al., 2015; Arksey and O'malley, 2005). They provide a broader, more inclusive overview of a topic compared to other review methods like systematic reviews, enabling a more comprehensive description of the existing evidence base (Peters et al., 2015). Given the need to thoroughly assess and investigate the literature on interoceptive assessment during developmental ages, a scoping review was the most suitable approach. We used a standard process to conduct the scoping review (Tricco et al., 2018) which includes the following steps: 1) Identify the research question, 2) identify relevant studies, 3) study selection and data extraction, 4) chart the data, 5) summarize and report the results.

2.1. Objectives

The present scoping review was carried out to provide a comprehensive picture of the available literature exploring interoception from infancy to childhood, determining the extent of the research available and mapping the most commonly used measures used in developmental populations, highlighting the strengths and weaknesses of these methods.

We identified two key questions:

1. Which tools have been used to assess interoception across various developmental stages (infancy, preschool- and school-age)?
2. What are the strengths and limitations of these measures when applied to developmental populations?

2.2. Search strategy

2.2.1. Eligibility criteria

The inclusion criteria for this scoping review were: (1) Only studies that used an explicit or implicit measure of interoception in the methodology were included; (2) Only sources in English were included; (3) Only empirical studies published in peer-reviewed journals were included. Reviews, meta-analyses, case studies, dissertations, and other items such as conference proceedings, book chapters, and commentaries were not included; (4) Papers from all years were included to map all the existing body of literature on the topic; (5) Only papers that included studies conducted with infants, preschoolers and school-age children were included (studies reporting participant mean age of higher than 12 years were excluded); (6) Only studies assessing typically developing infants and children were included. All the inclusion criteria were developed a priori and used for screening titles and abstracts during level 1 screening, and full-text articles during level 2 screening.

2.2.2. Information sources

Searches were conducted in PubMed, PsychInfo and Web of Science databases on 24/7/2024 and produced an overall 633 results. This search relied on various relevant keywords and terms such as Interoception and child, preschoolers, infants, toddlers, youth, and school-age with Boolean operators AND and OR. The primary search terms included 'Interoception' AND ('child' OR 'preschooler' OR 'infant' OR 'toddler' OR 'youth' OR 'school-age'), ensuring broad coverage of research on interoception in early stages of development. These keywords were searched in titles, abstracts, and keywords. No date limits were applied.

2.2.3. Study selection

All 663 articles were imported by Rayyan software (2022), an online screening tool. Then, 179 articles were removed from the software for being duplicates, leaving 484 articles for title and abstract screening, which involved two separate screeners. To establish consistency among reviewers, training was conducted on 5 % of the articles before starting the screening process. Inter-rater agreement for study inclusion was measured using percent agreement, and once the two reviewers achieved a threshold of over 90 %, we advanced to the next stage. All article titles and abstracts were scanned, and screeners decided whether the article was relevant based on eligibility criteria by pressing either yes, no, or maybe. Voting was blinded to avoid bias. If an article received two no votes, it was classified as an irrelevant reference and excluded from further screening. Differently, articles that received two yes or two maybe votes were moved to the next screening stage. Lastly, if an article received one no and one yes/maybe vote, then, in a separate stage, the screeners discussed and jointly decided whether to move or not the reference to the next screening round. After this voting process, the number of articles moved to the full-screen review stage was 30. However, two articles were not retrieved, leaving 28 reports for full-text screening. In this last round, the two screeners excluded 4 studies for not meeting the eligibility criteria. Specifically, 4 reports were excluded because of participants' age. Twenty-four articles were considered for data extraction. See Fig. 1 for the Prisma Flowchart for this scoping review.

3. Results

3.1. Study characteristics

Studies included in this scoping review were published between 2012 and 2024, with 18 studies published in the last 5 years. Most research was published in Germany. The review also includes research from the United Kingdom, Austria, Italy, Switzerland, China, Japan, the USA, and Australia. The mean sample size of participants used across ages varied. For infants, the sample size was $M = 54.5$ ($SD = 44.1$). For preschoolers, the sample size was $M = 50.5$ ($SD = 2.12$). In school-aged children, the sample size was $M = 351.7$ ($SD = 551.7$).

3.2. Types of study and main outcomes

Among the 24 studies that met the inclusion criteria, 4 focused on infants, 3 on preschoolers, and 17 on school-age children. To assess interoceptive abilities, different methods were used: 4 studies employed looking time procedures, 2 utilised heartbeat-evoked potentials (HEP), 1 used functional magnetic resonance imaging (fMRI), 9 relied on self-report questionnaires, 11 employed Heart Tracking tasks (HTTs), and 2 used parent-report measures. Twenty studies used a single measure of interoception while 4 studies used a combination of measures. Below, we outline the quantitative methods applied across each developmental age group (Table 1).

3.3. Infancy

Studies exploring interoceptive accuracy in non-verbal populations relied mostly on preference-looking procedures and implicit EEG measures, such as the Heartbeat Evoked Potential (HEP) or a combination of these two measures (Maister et al., 2017; Weijs et al., 2023).

3.3.1. Looking-times measures

Looking-time paradigms have enabled researchers to determine whether infants show a preference for visual stimuli presented in sync or out of sync with their heartbeat or respiration rate. Maister et al. (2017), observed that 5-month-olds looked longer at stimuli moving up and down out of sync with their heartbeat compared to those moving in sync. This study used an infant-controlled sequential-looking paradigm, in which stimuli were presented one at a time on either the left or right side of the screen. Looking times were then measured through an eye-tracker. Tünte et al. (2024) replicated this approach using both heartbeat and respiration tasks and found that infants aged 3–18 months could distinguish between external stimuli in sync or out of sync with their heartbeat. However, in Tünte et al. (2024) study, infants generally

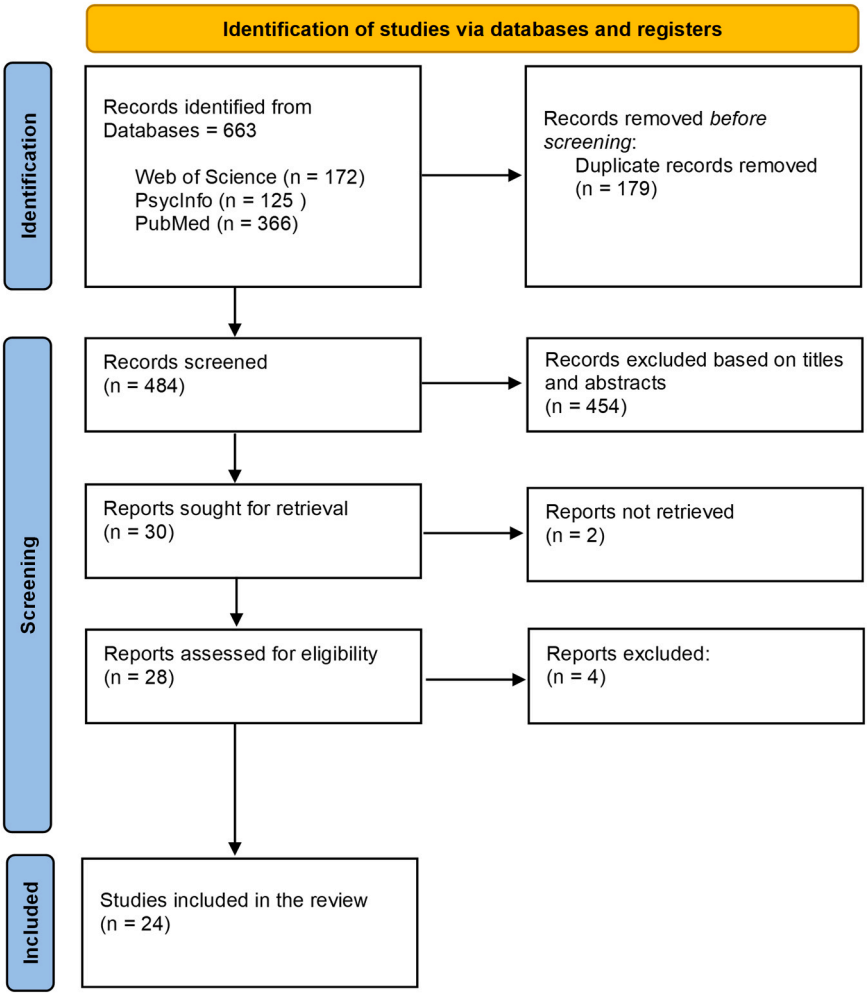

Fig. 1. Flowchart illustrating the movement of sources through the search process.

preferred synchronous stimuli over asynchronous ones, with this preference remaining stable across ages. Respiratory interoceptive sensitivity followed a similar pattern in 3- and 9-month-olds but not at 18 months. In a related study, Imafuku et al., (2023) explored interoceptive abilities in 6-month-olds using an experimenter-controlled looking time task where synchronous and asynchronous visual stimuli were presented side-by-side on a screen. Looking times were recorded using an eye-tracking system. Results showed that infants looked longer at asynchronous cardio-visual stimuli than at synchronous ones. This preference was also associated with increased eye contact and gaze/affect synchrony within the mother-infant dyad. Finally, Weijs et al. (2023) examined 5- to 7-month-olds' looking times towards visuo-cardiac (bimodal) and audiovisuocardiac (trimodal) stimuli blinking in synchrony and out-of-synchrony with their heartbeat. Stimuli were presented sequentially on the center of the screen and infants' looking times were assessed through manual coding procedures. Interestingly, this study found no visual preference for synchronous versus asynchronous stimuli (Weijs et al., 2023).

Preferential-looking time paradigms are widely and commonly used in developmental psychology, and allow researchers to capture infants' spontaneous responses to the external world, offering crucial insights into their cognitive and perceptual abilities. However, the effectiveness of this paradigm heavily depends on the task design. In studies assessing interoception, factors such as whether the observation is infant-controlled or experimenter-controlled, the presentation format of stimuli (simultaneous or sequential), the nature of the stimuli (blinking or moving up and down), the measurement technique (using an eye-tracker versus less sensitive measures such as manual coding) and the definition of asynchrony based on the infant's heart rate just before the trial (Weijs et al., 2023) or from the preceding trial (Maister et al., 2017; Tünte et al., 2024) can all lead to varying outcomes. These methodological variations can lead to inconsistent data, complicating the interpretation and comparison of findings across different studies.

3.3.2. *Heartbeat-evoked potentials (HEP)*

Interoceptive processing can be implicitly recorded through an event-related potential (ERP) time-locked to participants' heartbeats, known as the heartbeat-evoked potentials (HEP). The HEP serves as a neurophysiological marker of cardiac processing, typically observed, in adults, over frontocentral and parietal brain regions within the 250–600 ms time window following the cardiac R-wave (Coll et al., 2021). Infant studies have examined HEP modulations in response to emotional and neutral facial expressions, or during synchronous and asynchronous self-related recordings (Maister et al., 2017; Weijs et al., 2023). However, findings in this area are mixed. Maister et al. (2017), who analyzed infants' HEP over frontal, central and parietal areas in a 50–300 ms time window after the R wave, found that infants as young as 5 months displayed larger HEP in response to negative expressions compared to positive or neutral faces. Additionally, infants' ability to visually differentiate between synchronous and asynchronous cardio-visual stimuli positively correlated with HEP (Maister et al., 2017). Conversely, Weijs et al. (2023) did not observe this relationship in 5- to 7-month-olds and found no association between HEP and infant temperament. They also reported no modulation of HEP by emotional or

Table 1
Summary table of included studies in the scoping review (HEPs = Heartbeat Evoked Potentials; HCT = Heart Counting Task; JJP = Jumping Jack Paradigm; EIAT = Eye-Tracking Interoceptive Accuracy Task; MAIA_Y = Multidimensional Assessment of Interoceptive Awareness for Youth; SAQ = Self-Awareness Questionnaire; SAQ_C = Self-Awareness Questionnaire for Children; CQIA-2 = Caregiver Questionnaire for Interoceptive Awareness; IAS = Interoceptive Accuracy Scale; cvSDT = Cardiovascular Signal Detection Task; IAQ = Interoceptive Awareness Questionnaire; THISQ = Three-Domain Interoceptive Sensations Questionnaire).

Author	Year	Title	Country	Aim of the study	Participant age	Sample size	Methods to measure interoception	Key findings
Infancy								
Maister, Tang & Tsakiris	2017	Neurobehavioral evidence of interoceptive sensitivity in early infancy	United Kingdom	Explore interoceptive abilities in 5-month-old.	M = 5.10 months (0.29) Range = n. a	N = 29	Cardio-visual preferential looking task; HEPs	Infants preferred stimuli out of sync with their heartbeat. Such preference was positively correlated with HEPs.
Weijs, Daum, & Lenggenhager	2023	Cardiac interoception in infants: Behavioral and neurophysiological measures in various emotional and self-related contexts.	Switzerland	Investigate interoception and its link to emotion and self-awareness in infants aged 5–7 months.	M = 186 days (15) Range = 5–7 months	N = 42	Cardio-visual preferential looking task; HEPs	No preference toward either asynchronous or synchronous stimuli was found. No differences were observed in the HEP across emotional or self-related contexts, nor did the HEP correlate with infant temperament or the individual differences in looking time.
Imafuku, Yoshimoto, & Hiraki	2023	Infants' interoception is associated with eye contact in dyadic social interactions.	Japan	Elucidate the relationship between interoception and social behavior in infants and mothers.	M = 200.26 days (16.89)	N = 27	Cardio-visual preferential looking task	Infants looked a asynchronous cardio-visual stimuli longer than synchronous cardio-visual stimuli. Looking time toward asynchronous cardio-visual stimuli was positively correlated with infant–mother gaze and affect synchrony.
Tünte, Hoehl, Wunderwald, Bullinger, Boyadziheva, Maister, … & Kayhan	2024	Respiratory and cardiac interoceptive sensitivity in the first two years of life	Austria	Assess Respiratory and Cardiac Interoceptive accuracy in 3-, 9-, and 18-month-olds.	M (3 mo) = 113.53 days (7.82) M (9 mo) = 301.63 days (10.5) M (18) = 576.65 days (14.4)	N (3 mo) = 40 N (9 mo) = 52 N (18 mo) = 28	Cardio-visual and Respiration-visual Preferential looking tasks	For cardiac interoceptive accuracy, stable evidence across ages was found with infants preferring synchronous stimuli to their heartbeat. For respiratory domain, a similar pattern was found only for 3- and 9-month-olds.
Preschoolers								
Schaan, Schulz, Nuraydin, Bergert, Hilger Rach & Hechler	2019	Interoceptive accuracy, emotion recognition, and emotion regulation in preschool children.	Germany	Testing a novel paradigm (JJP) in preschool age to measure Interoceptive accuracy and its relation to emotion regulation and recognition.	M = 4.86 y (0.68) Range = 4–6 y	N = 49	JJP	Interoceptive accuracy increased with age, was unrelated to emotion recognition, and marginally associated with emotion regulation
Opdensteinen, Schaan, Pohl, Schulz, Domes, & Hechler	2021	Interoception in preschoolers: New insights into its assessment and	Germany	Tested an adapted version of the JJP in preschoolers and its relation to emotion	EXP: 1 M = 4.93 y (0.73) Range 4–6 y Exp 2: M= 4.81 y (0.75) Range 4–6 y	Exp 1 = 40 Exp 2 = 31	JJP	Weak relation between IA and emotion regulation. Higher cortisol following acute

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Country	Aim of the study	Participant age	Sample size	Methods to measure interoception	Key findings
		relations to emotion regulation and stress.		regulation(EXP 1) and stress (EXP 2).				stress induction was related to reduced IA.
Yang, Zhou, Wei, Wan, Wang, Wang, … & Chan	2021	Multidimensional interoception and autistic traits across life stages: evidence from a novel eye-tracking task.	China	Assess the relation between IA assess through a novel eye-tracker paradigm and autistic traits in three age groups (EXP 2)	EXP 2: M (Preschooolers) = 5.33 (n.a) Range = 4–6 M (Adolescents) = 13.1 (n.a) Range = 12–16 M (Adults) = 31.7 (n.a) Range = 23–54	Exp 2: N (Preschoolers) = 52 N (Adolescents) = 50 N (Adults) = 50	EIAT	An increase in interoceptive abilities from preschool age to adolescence was followed by a decline of IA with age afterwards. Limited relations with autistic traits were found
School-age								
Schmitz, Blechert, Krämer, Asbrand & Tuschen-Caffier	2012	Biased perception and interpretation of bodily anxiety symptoms in childhood social anxiety	Germany	Evaluate differences in perception and interpretation of bodily anxiety symptoms during social stress in a High Social Anxiety (HSA) and Low Social Anxiety (LSA) group of children.	M (HSA) = 11.1 (0.76) M (LSA) = 11.0 (0.83) Range = 10–12 y	N (HSA) = 20 N (LSA) = 20	HCT; Rating of perceived Heart Rate intensity at the end of the social-stress task.	HSA children perceived their heart rate as higher than LSA children during the social stress task, despite having similar actual heart rates and comparable IA abilities.
Koch & Pollatos	2014	Cardiac sensitivity in children: sex differences and its relationship to parameters of emotional processing.	Germany	Assess a child-friendly HCT in children and its relation to gender, body mass index (BMI), Heart-rate variability and emotional experience.	M = 8.39 y (0.94) Range = 6–11 y	N = 1350	HCT	Independently of BMI, boys showed higher IA than girls. IA is weakly but positively related to emotional intelligence and adaptability.
Koch & Pollatos	2014	Interoceptive sensitivity, body weight and eating behavior in children: a prospective study.	Germany	Shed light on the relations between IS, body weight and eating behaviours in two timepoints (T1 and T2), one year apart	M (T1) = 8.38 y (0.95) M (T2) = 9.13 y (0.93) Range = 6–11 y	N (T1) = 1657 N (T2) = 1610	HCT	Only in overweight children eating behavior were predictive for later IS. There was no direct relation between IS and body mass index
Georgiou, Matthias, Kobel, Kettner, Dreyhaupt, Steinacker, & Pollatos	2015	Interaction of physical activity and interoception in children	Germany	Investigate the interaction between IS and physical activity	M = 9.72 y (0.58) Range = 9–11 y	N = 49	HCT	Children with higher IS performed better in the physical performance task.
Eley, Gregory, Clark, & Ehlers	2017	Feeling anxious: a twin study of panic/somatic ratings, anxiety sensitivity and heartbeat perception in children	United Kingdom	Examine genetic and environmental influences on childhood anxiety sensitivity (AS), IA, and panic/somatic ratings in children.	M = 8 y (n.a) Range = 8,2–8,11 y	N (Group 1, Twins) = 247 N (Group 2, Control) = 53	HCT	Significant correlations between panic/somatic ratings, AS and HCT. Heritability estimates were modest for the panic/somatic scale, and moderate for both for AS and HCT.
Klabunde, Juszczak, Jordan, Baker, Bruno, Carrion, & Reiss	2019	Functional neuroanatomy of interoceptive processing in children and adolescents: a pilot study.	USA	Examine IA in children with fMRI.	M = 11.09 years (3.56) Range = 6–16 y	N = 11	fMRI during HCT	Children activated regions similar to those in adults, including the left insula, cuneus, inferior parietal lobule, and prefrontal cortex during the HCT.
Murphy, Cheesman, Gregory, Lau, Ehlers, Catmur, … & Eley	2019	Estimating the stability of heartbeat counting in middle childhood: A twin study	United Kingdom	Estimated the magnitude of genetic and environmental influences on HCT across two years (age	M (T1)= 8.47 y (0.18) Range = 8–10 y M (T2)= n.a	N (Group 1, Twins) = 247 N (Group 2, Control) = 53	HCT	Correlation between heartbeat counting at Time point 1 and Time point 2. Variation in

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Country	Aim of the study	Participant age	Sample size	Methods to measure interoception	Key findings
				8–10) and its relation to health meaures.				heartbeat counting at each time-point is influenced primarly by the non-shared environment. No significant relationship between heartbeat counting and anxiety, depression, sleep problems or emotion recognition was observed.
Jones, Silas, Todd, Stewart, Acree, Coulson, & Mehling	2021	Exploring the Multidimensional Assessment of Interoceptive Awareness in youth aged 7–17 years.	United Kingdom	Adapt the MAIA questionnaire for children and adolescents.	Children: Range 7–10 y Adolescents: Range 11–17 y	Children: N = 212 Adolescents: N = 217	MAIA_Y	The eight-factor structure of the MAIA_Y is acceptable with younger participants. Good levels of internal consistency of the majority of scales.
Raimo, Di Vita, Boccia, Iona, Cropano, Gaita … & Palermo	2021	The body across the lifespan: on the relation between interoceptive sensibility and high-order body representations	Italy	Explore the association between body representation and interoceptive sensibility cross-sectionally in 5 different age groups across lifespan.	Group 1: Range = 7–8 y Group 2: Range = 9–10 y Group 3: Range = 18–40 y Group 4: Range = 41–60 y Group 5: Range = > 60 y	Group 1: N = 65 Group 2: N = 37 Group 3: N = 50 Group 4: N = 50 Group 5: N = 37	SAQ; SAQ_C	The SAQ score moderates the relationship between age and Body representation.
Wengrovius, Zick, Beltz, Wentz, Ulrich, & Robinson	2022	Relations among parent-reported physical activity and interoception in children.	USA	Explore the relations between phisical activity (PA) and interoceptive sensibility	M = 6 y (1.7) Range = 3–10 y	N = 122	CQIA−2 (modified version)	Higher PA levels were positively associated with higher interoceptive sensibility.
Bishop, Brown, & Yu	2023	The relationship between school-age children's interoceptive awareness and executive functioning: An exploratory study	Australia	Testing the relationship between children's IS and executive functioning.	M = 10 y (n.a) Range = 8–12	N = 30	MAIA_Y	Significant and predictive relationship between children's IS and some aspects of executive functioning
Pollatos, Mönkemöller, Groppe, & Elsner	2023	eroceptive accuracy is associated with benefits in decision making in children	Germany	Explore the relation between interoceptive accuracy and decision making (Iowa Gambling Task (IGT) and Delay-Gift Task) at2 time points (T1 and T2) (approximately 1 year apart)	M (T1) = 8.4 y (0.95) M (T2) = 9.1 y (0.92) Range = 6–11 y	N (T1) = 1446 N (T2) = 1454	HCT	Children with higher interoceptive accuracy performed better in decision-making tasks at T2.
Grist, Brown, Yu, & Clark	2023	An exploration of the association between sensory processing and interoceptive awareness in neurotypical school-aged children	Australia	Exploration of the association between Sensory processing and Interoceptive sensibility.	M = 9 y (n.a.) Range = 8–12 y	N = 33	MAIA_Y, IAQ, THISQ	Positive predictive relationships were found between sensory processing and interoceptive awareness variables.
Brand, Lang, Bellinghausen, Witthöft & Jungmann	2024	Interoceptive accuracy in children aged 8–13 and their parents: implications for mental health	Germany	Investigate the connection of IS and IA with dimensions of psychopathology, including internalizing, externalizing, and somatoform symptomatology.	M = 10.6 y (1.6) Range = 8–13 y	N = 37	HCT, cvSDT; IAS	Negative relationship between children's self-reported interoceptive accuracy (IAQ) and internalizing symptomatology reported by their parents

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Country	Aim of the study	Participant age	Sample size	Methods to measure interoception	Key findings
Cheung, Brown, Yu & Cheung	2024	The relationship between school-age Children's self-reported perceptions of their interoceptive awareness and emotional regulation: an exploratory study	Australia	Relationship Between children's IS and Emotional Regulation.	M = 10.49 y (1.00) Range = 9–12 y	N = 25	MAIA_Y	Significant correlations between MAIA_Y and emotional regulation, and academic self-regulation.
Clark, Brown, & Yu	2024	A comparison of child-reported and parent-reported interoceptive awareness in typically developing school-aged children.	Australia	Comparisons of interoceptive sensibility across gender and between child- and parent-reports.	M = 9.78 y (1.23)	N = 27	MAIA_Y (self and parent report)	Parents reported higher scores for the MAIA-y Emotional Awareness subscale compared to their children.
Raimo, Iona, Di Vita, Boccia, Torchia, Canino, … & Palermo	2024	The interoceptive sensibility in middle childhood: the Italian validation of the Self-Awareness Questionnaire.	Italy	Validate the Self-Awareness questionnaire with children.	M = 9.89 y (2.04) Range = 7–13 y	N = 239	SAQ_C	SAQ-C is a reliable and valid tool to assess IS in childhood. IS increases with age.

self-related contexts.

Electroencephalography (EEG) is a relatively inexpensive neuroimaging technique that captures electrical signals by placing electrodes on the scalp of the individual. One of the key advantages of EEG is its remarkable temporal resolution, allowing researchers to measure neural activity with millisecond precision. In the context of infant research, EEG is a highly versatile and non-invasive methodology, enabling researchers to measure cortical activity in response to a variety of stimuli. As such, EEG is a valuable complement to behavioural assessment of interoception during the first years of life. However, it is important to note that EEG signals in developmental populations, can be noisy due to external factors like muscle artifacts or eye movements. Also, the findings illustrated above, show that no uniform way of analyzing EEG data was adopted. Also, differences in the paradigm and the stimuli duration could have affected divergent results across studies.

3.4. Preschoolers

Studies exploring interoceptive accuracy in preschoolers commonly employed a newly developed Jumping Jack Paradigm (JJP) and the HDT, with some modifications to facilitate young children's ability to sense their heartbeat.

3.4.1. Heart tracking tasks

To measure interoceptive accuracy in children, Schaan et al. (2019) developed the Jumping Jack Paradigm (JJP) by asking children aged 4–6 years to perform jumping jacks (JJ) for 10 seconds to create a physiological activation that facilitates heartbeat perception. Before and after jumping jacks, children were asked to estimate their heart rate in a 30-second time interval by selecting 1 out of 4 circles of various sizes rather than counting beats. This novel paradigm demonstrated that interoceptive accuracy improved with age and showed no connection to emotion recognition, with only a marginal link to emotion regulation (Schaan et al., 2019). Opdensteinen et al. (2021) adapted Schaan et al.'s (2019) task in which 4–6-year-old children performed jumping jacks for three trials of 15, 20, and 25 seconds each instead of a single trial. Then, children estimated their HR before and after JJ on five different-sized circles instead of four, as in Schaan et al. (2019). This adapted task revealed that higher cortisol reactivity after a stressor correlated with lower interoceptive accuracy, along with a marginal positive relationship between interoceptive accuracy and emotion regulation (Opdensteinen et al. (2021).

Yang et al. (2021) used a novel paradigm, named Eye-Tracking Interoceptive Accuracy Task (EIAT) to shed light on the developmental trajectory of interoception across different age groups (preschoolers, adolescents and adults) and its relation to autistic traits. In this task, participants were asked to find and fixate on a rabbit bouncing in sync with their heartbeat while ignoring another out-of-sync rabbit. Results showed an inverted U-shaped developmental trajectory in interoceptive accuracy, with an increase in interoceptive abilities from preschool age (aged 4–6 years) to adolescence (12–16 years) followed by a decline with age afterwards (23–54 years). However, limited relations with autistic traits were found (Yang et al., 2021).

HTTs are non-invasive, user-friendly, and affordable tools suitable for a broad range of participants. These tasks enable researchers to directly measure interoceptive accuracy across different ages and among both typical and atypical populations. However, a key limitation is their vulnerability to guessing strategies. Instead of accurately sensing their heartbeats, individuals may estimate based on assumptions about average heart rates, though younger children may lack this prior knowledge, which needs further study to confirm. Another limitation is that HTTs are influenced by factors such as attention levels, anxiety, and environmental conditions (e.g., noisy settings). Without controlling for these variables, results may not reflect children's true interoceptive abilities.

3.5. School-age children

Studies involving school-aged children have used interoceptive accuracy measures—adapting versions of the HCT specifically for younger participants—as well as interoceptive sensibility assessments, which rely on self-reported or parent-reported questionnaires. One study relied on both sensibility and accuracy measures (Brand et al., 2024). One study employed fMRI (Functional magnetic resonance imaging) measure to scan brain activity during interoception tasks (Klabunde et al., 2019).

3.5.1. Heart tracking tasks

Most studies examining interoceptive accuracy in school-aged children have used a modified version of Schandry's (1981) HCT proposed by Koch and Pollatos (2014a). In this task, children aged 6–11 began with a 10-second training period, followed by three intervals of 15, 20, and 18 seconds during which children were asked to count their perceived heartbeats. Accuracy scores are typically calculated by

comparing the counted and the objective measure of heartbeats. Researchers explored age and gender differences in interoceptive accuracy in a large sample of children between 6 and 11 years as well as the relationship between cardiac accuracy, body mass index (BMI), heart rate variability (HRV), and emotional experience. Results revealed that boys, regardless of body mass index, were more accurate in heartbeat perception than girls, though no link was found between cardiac accuracy and heart rate variability (HRV). In addition, there was a positive association between cardiac accuracy and emotional intelligence. Koch and Pollatos (2014b) also explored whether 6- to 11-year-old children's interoceptive accuracy was related to disordered eating behavior and weight issues in two time-points with 1-year distance. The primary findings indicated that eating behavior in overweight children—but not in those of average weight—predicted interoceptive sensitivity at a later age, suggesting a potential link between interoception and eating disorders. Additionally, there was no direct association between interoceptive accuracy and children's body mass index. Several other studies employed Koch and Pollatos' (2014) child-adapted version of the HCT. For example, Pollatos et al. (2023) found that in 6- to 11-year-olds tested in 2 time points (T1 and T2) one year apart, interoceptive accuracy was linked to decision-making abilities; children with higher interoceptive accuracy performed better on a child-friendly version of the Iowa Gambling Task (IGT) and delayed gratification longer in a Delay-Gift Task only in the second time point. Additionally, Georgiou et al. (2015) noted that accurate perception of bodily signals in the HCT correlated with better physical performance and daily activity levels.

Brand et al. (2024) expanded this approach by using a 3-trial HCT (25 s, 35 s, 45 s) (preceded by a short practice session) in which children were asked to count felt heartbeats alongside the Cardiovascular Signal Detection Task (cvSDT; Pohl et al., 2021). In the cvSDT, children (aged 8–13 years) and mothers sensed their heartbeats during varying intervals determined by heart rate and then completed a two-alternative choice task where they chose between their objective heartbeat range or an alternative option. Brand and colleagues found no association between accuracy measures (HCT or cvSDT) and children's psychopathology, such as internalizing, externalizing, and somatoform symptomatology. Similarly, Schmitz et al. (2012) evaluated the perception of and concern about heart rate visibility, actual heart rate, and subjective anxiety during public speaking in two groups of children aged 10–12: high-socially-anxious (HAS) and low-socially-anxious (LSA). During the task, a non-veridical heart rate feedback tone could be heard only by the participant (private condition) or by both the participant and observers (public condition). Following the social stress task, interoceptive accuracy was measured using a 3-trial HCT (25 s, 35 s, 45 s). Results indicated HSA children perceived their heart rate as higher than LSA children in both private and public conditions, despite having similar actual heart rates and comparable interoceptive accuracy. Finally, a couple of twin studies explored the influences of genetic and environmental factors on Interoceptive accuracy during childhood (Eley et al., 2007; Murphy et al., 2019). These studies employed an HCT in which each child completed three trials lasting 25, 35, and 45 seconds, preceded by a 10-second practice trial. After each trial, the child reported the number of heartbeats they had counted. Results showed that at 8 years of age panic/somatic ratings correlated with both anxiety sensitivity (AS) and HCT error scores. The genetic influence was modest for the panic/somatic scale and moderate for both AS and HCT (Eley et al., 2007). Murphy et al. (2019) twin study explored HCT stability across two years in 8/10-year-olds and its relations with health measures. Results indicated moderate stability of HCT across ages. Non-shared environmental factors contributed most to such stability but no association was found between HCT and mental health measures (anxiety, depression, sleep problems) or emotion recognition (Murphy et al., 2019).

As previously mentioned, HCTs are accessible, non-invasive tools for measuring interoceptive accuracy across various age groups and populations. However, they are prone to guessing, especially in older participants, who can use their previous knowledge about resting heart rate to guide their responses. To overcome this limit, researchers developed new tasks, such as the cvSDT, which reduces the likelihood of random guessing, enhancing its reliability as a tool for assessing interoceptive ability. Is also important to mention that variations in the instruction provided to the participant (i.e., vague or unclear; not explicitly discouraging guessing) could result in variability in responses not reflecting true interoceptive abilities. Desmedt et al. (2018) proposed that participants should be explicitly instructed to report only the heartbeats they feel, avoiding the use of strategies to estimate or guess the number of heartbeats. Instructions should be adapted to suit younger participants' comprehension abilities and reported in the study.

3.5.2. *fMRI*

Klabunde et al. (2019) investigated the neural basis of interoceptive processing in children and adolescents using fMRI. Participants completed three conditions, pressing a button to indicate when they detected their heartbeat, a tone, or their heartbeat while ignoring a tone. Results revealed that children as young as 6 years old activated regions similar to those in adults, including the left insula, cuneus, inferior parietal lobule, and prefrontal cortex, particularly when comparing heartbeat and tone detection conditions. Age was also associated with increased activation in the anterior cingulate cortex, orbitofrontal cortex, and mid-inferior frontal gyri.

fMRI (functional Magnetic Resonance Imaging) is a non-invasive tool with high spatial resolution that offers valuable information on specific brain regions involved in cognitive and perceptual developmental processes. However, using fMRI in developmental populations is complex. The difficulty for children to remain still for long periods can lead to motion artifacts impacting data quality. In addition, the confined space and loud noise of the MRI scanner could cause distress and anxiety in the child influencing the perception of bodily signals.

3.5.3. *Self-report measures*

Currently, only two questionnaires assessing interoceptive sensitivity have been adapted and validated for school-aged children. The Multidimensional Assessment of Interoceptive Awareness for Youth (MAIA_Y; Jones et al., 2021), is a 32-items tool created and validated in youth aged 7–17 years to assess interoceptive awareness that captures eight different scales: Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body-Listening and Trusting. The Self-Awareness Questionnaire for Children (SAQ_C; Raimo et al., 2024), is a child-adapted version of the SAQ (Longarzo et al., 2015), validated on a sample of children ranging from 7 to 13 years, that evaluates the natural tendency to self-report a broad spectrum of bodily sensations using a bifactorial structure (i.e., somatosensory and visceral sensations). This study showed that the ability to perceive internal bodily signals improves with age.

The MAIA questionnaire has been the most widely used tool for exploring interoceptive awareness in children. Through this self-report measure, Bishop et al. (2023) explored the relationship between interoceptive awareness and children's executive functioning (EF), as reported by parents. Findings revealed positive associations between MAIA_Y scores and EF components like emotional and Cognitive Regulation. Cheung et al. (2024) also used the MAIA_Y to investigate a relationship between interoceptive sensibility and self-regulation in 9- to 12-year-old children. The authors discovered associations between children's interoceptive awareness and some aspects of their self-regulatory abilities. Raimo et al. (2021) employed the SAQ_C to measure interoception across the lifespan and its relation to body representations (BR). Results showed that SAQ_C score significantly moderated the association between age and BR, being the ability to mentally represent one's body parts negatively affected by higher interoceptive sensibility levels in childhood (7–8 and 9–10 years) and late adulthood (over 60 years).

Several studies investigating interoception sensibility in school-age

children used measures that have not yet been formally validated. For example, to explore associations between interoceptive abilities and sensory processing in children aged 8–12, Grist et al. (2023) used the validated MAIA_Y, as well as two non-validated measures: the Interoceptive Awareness Questionnaire (IAQ; Van den Bergh et al., 2012) and the Three-Domain Interoceptive Sensations Questionnaire (THISQ; Vlemincx et al., 2023). The IAQ is a standardized self-report assessment consisting of 19 questions that focus on two aspects of bodily awareness: awareness of neutral bodily sensations and attention to unpleasant bodily sensations. The THISQ is an 18-item self-report that focuses on the perception of neutral sensations resulting from three bodily channels: the respiratory, cardiac, and gastroesophageal channels. Grist et al. (2023) found that increased interoceptive sensibility was associated with increased sensory processing in children. In addition to the HCT and the cvSDT interoceptive accuracy measures, Brand et al. (2024) also used a child-adapted version of the Interoceptive Accuracy Scale (IAS; Murphy et al., 2019) to assess children's sensibility to bodily signals (e.g., heartbeat, hunger, body temperature), though this adaptation has not yet been validated for children. They found a negative correlation between children's IAS scores and parent-reported internalizing symptoms in children, as well as a positive correlation between children's and their parents' IAS scores.

Questionnaires are particularly useful for studying the development of interoception. Indeed, child reports can offer a unique view of their perceptions of bodily signals, which may be challenging to observe from an external perspective. This research often involves large sample sizes that benefit from longitudinal data collection. As outlined in the study cited above, despite the importance of self-reports, only a couple of questionnaires have been formally validated for children (SAQ_C; MAIA_Y). Self-reports also show some limitations. Children's cognitive and language development impacts their capacity to provide accurate reports, often leading to inconsistencies, particularly in younger age groups. Additionally, child reports are susceptible to external influences, such as question phrasing, or the desire to give socially acceptable answers, which can distort their responses. While questionnaires are a valuable tool, they are most effective when used alongside other measures to provide a fuller picture of interoceptive abilities.

3.5.4. Parent-report measures

Two studies have employed parent-reported measures to assess children's interoceptive sensibility, though these tools have yet to undergo formal validation. Clark et al. (2024) investigated age-related differences in interoceptive awareness by administering both self- and parent-report versions of the MAIA_Y, with parents completing an adapted version from a third-person perspective. While no differences were found between boys' and girls' self-reported interoceptive awareness, divergent results emerged between parent-reported and self-reported interoceptive awareness. Wengrovius et al. (2022) examined the link between physical activity (PA) and interoceptive awareness in children aged 3–10 using a modified version of a non-validated measure named Caregiver Questionnaire for Interoceptive Awareness (CQIA-2) (Mahler, 2016). They found that higher PA levels were positively associated with increased sensitivity to emotional and physical energy states.

A distinct advantage of using parent-report questionnaires is their ability to capture a caregiver's perspective on the child's interoceptive abilities. Furthermore, these questionnaires are an attractive tool for identifying developmental delays, as they are efficient, user-friendly, and cost-effective. Although parent reports are essential for assessing interoception in developmental populations, no questionnaires have yet been formally validated for this purpose. There are also some limitations to caregiver-reported questionnaires. For example, they may be subjective and not fully reflect the child's true capabilities in perceiving and responding to bodily signals.

3.6. Discussion

This scoping review, following an extensive literature mapping, analysed 24 studies conducted between 2012 and 2024. Measurement approaches varied according to age group: behavioural (LTP) and neurophysiological tasks (HEP) requiring non-verbal responses were key for pre-verbal populations, while self-report questionnaires and HTT that require verbal responses were more commonly used in childhood. All infant studies employed looking-time paradigms, with two studies combining behavioural and brain-based methods (e.g., HEP). Most research focused on cardiac sensitivity, and one study examined infants' ability to align external stimuli with both heart rate and breathing patterns. In preschoolers, interoceptive abilities were assessed primarily through adapted HTT procedures tailored to heart rate awareness and to suit young children's shorter attention spans. Among the three studies on preschoolers, two used the JJP, and one utilised the EIAT to measure heart rate accuracy. For school-age children, self-report measures were mostly used to quantify interoceptive sensibility and HCTs to measure heart rate accuracy. Only 2 studies used parent reports to assess children's sensibility to bodily signals. Furthermore, only one study incorporated neuroimaging measures, using fMRI. One study combined both accuracy and sensibility measures in childhood.

3.7. Limitations

Scoping reviews present several limitations. First of all, they are broad in scope, which helps provide a comprehensive overview of the literature. However, this approach can make it challenging to capture all relevant information about interoceptive abilities during development. Indeed, some excluded papers may have assessed aspects of interoception without specifically linking them to interoceptive abilities. Moreover, this review included typically developing children and excluded studies involving atypical populations (i.e., Autism spectrum Disorder, ASD; Attention-deficit/hyperactivity disorder, ADHD) that could offer some additional interesting insights on the methods used to explore interoception during development. Also, our search strategy incorporated different terms commonly used to describe interoception and developmental population, although there may be other relevant terms that were not included. Despite searching across three multidisciplinary databases (PubMed, PsychInfo and Web of Science), the overall approach may have been more oriented toward health and science-related fields. Additional scoping reviews could have been identified by searching other bibliographic databases. Lastly, our review considered articles published only in English. As a result, we may have missed some relevant studies.

4. Conclusion

This scoping review aimed to provide a thorough overview of the most common methods for measuring interoception, examining their strengths and limitations in each developmental stage. So far, little is known about interoceptive abilities in developmental populations, however, in the last five years, we have witnessed an increased interest in the origins and development of the ability to sense and interpret body signals. This review allowed us to identify gaps in the literature and provide some recommendations for researchers interested in exploring interoceptive abilities in developmental populations.

Methods for measuring interoception in the early stages of human development should be carefully chosen depending on the research aim and the age group under investigation. Studies examining interoception in infancy reveal significant procedural differences. In looking-time paradigms, some studies (e.g., Maister et al., 2017; Tünte et al., 2024) employed infant-controlled stimulus presentation, while others relied on experimenter-controlled setups (Imafuku et al., 2023; Weijs et al., 2023). Visual stimuli were presented either sequentially (Maister et al., 2017; Tünte et al. (2024) or simultaneously (Imafuku et al., 2023), with

looking times recorded through either eye-tracking or the less sensitive method of manual coding (Weijs et al., 2023). Definitions of asynchrony varied as well, with some studies using the heart rate from the preceding trial (Maister et al., 2017) and others relying on the infant's heart rate just before the trial (Weijs et al., 2023). For EEG measures, study designs need to be simple and engaging to gather sufficient artifact-free data, and careful attention must be given to EEG signal preprocessing to avoid procedural inconsistencies in infant EEG studies, such as the use of ICA (Independent Component Analysis) (Maister et al., 2017) or manual procedures (Weijs et al., 2023) to remove artifacts from the EEG recordings. Standardized methodological procedures are needed to allow cross-study comparisons in infancy.

Studies investigating interoception in preschool and school-age children have mostly used child-adapted heart rate accuracy tasks and self-/parent-report measures of interoceptive sensibility. A common issue with heart rate tracking tasks (HTTs) is that interoceptive skills may not be essential to complete them, as participants can simply guess based on beliefs about resting heart rates (Brener and Ring, 2016). However, guessing strategies may primarily affect older individuals, as preschoolers and young children are unlikely to have prior knowledge of resting heart rates. Future studies should examine this assumption. Also, researchers developed new measures to overcome these limitations minimizing the likelihood of random guessing such as the cvSDT (Brand et al., 2024). In relation to self- and parent-report measures, a key issue is that some studies have used questionnaires lacking formal validation. Given the young age of participants, it is essential to ensure these questionnaires are reliable, accurate, and age-appropriate. Although a few self-report measures have been validated for children (e.g., SAQ_C, MAIA_Y), there is a notable lack of validated parent-report tools. Parent reports can provide unique insights into a child's interoceptive development, offering context-rich information that complements self-reports or direct assessments, particularly for younger children. Overall, only one study in childhood used neuroimaging measures (i.e., fMRI) to study interoception. A multi-method approach to interoceptive processing that includes measuring brain activity, physiological responses, and behavioural assessments could deepen our understanding of the origins and development of brain-body connections. Applying complementary measures of interoceptive processing offers an appealing yet challenging way to strengthen the robustness of research in infants and children, providing essential insights that individual measures alone may not capture. Also, future studies may combine interoceptive accuracy tasks with measures of interoceptive awareness (Desmedt et al., 2018), evaluating children's ability to recognize whether they are making accurate or inaccurate interoceptive decisions, based on their interoceptive behavioural performance.

This scoping review reveals that most studies assessing interoception accuracy in children have primarily relied on the cardiac channel. Only Tünte et al. (2024) considered multiple interoceptive channels (cardiac and respiratory) in infancy, observing differing results across modalities. This aligns with adult research (Desmedt et al., 2023), which suggests that cardioception alone is not a comprehensive measure of interoceptive ability, as it overlooks sensitivity across various interoceptive channels. Future research should address this gap by developing tasks for pediatric populations that target multiple interoceptive channels. In heart tracking tasks, incorporating a control condition is also crucial to determine whether children's performance reflects true interoceptive accuracy rather than general cognitive or attentional processes. One commonly used control is the Tone Discrimination Task, where participants count externally presented auditory tones (Legrand et al., 2022). This control condition could help to account for attentional and numerical processing factors that are unrelated to interoceptive awareness. Further, exploring the relations between the gut-brain interaction and interoception early in life holds great promise for improving health outcomes, particularly in areas like gastrointestinal disorders which are often linked to psychiatric symptoms, such as mood and affect disorders (Karaivazoglou et al., 2024). Recent research indicates that subtle interoceptive signals from the gut, including those generated by intestinal microbes, may play a role in shaping emotional functions and responses (Mayer, 2011).

Furthermore, longitudinal research is needed. Longitudinal studies are crucial for understanding interoception, as they allow researchers to observe how interoceptive abilities evolve over time. In addition, longitudinal approaches could help to gain insight into the long-term effects of early environmental, genetic, and social influences on interoceptive development, offering a more comprehensive perspective than cross-sectional studies alone can provide. So far, only a few studies have employed a longitudinal design in the early years of development. Tünte et al. (2024) conducted a longitudinal study to examine the development of interoceptive abilities in infants between 9 and 18 months old. Their findings showed no evidence of change in cardiac or respiratory interoceptive perception across this age range. In addition, a study with school-age children suggests that the link between interoceptive accuracy and decision-making abilities may be stronger in a second measurement point (when children were between 7 and 11 years old) compared to one year earlier (Pollatos et al., 2023). Further, eating behaviour predicts interoceptive sensibility at a one-year later time-point in 6–11-year-old overweight children (Koch and Pollatos, 2014). Finally, one study explored genetic and environmental factors influencing the stability of HCT in two time periods 2 years in distance (Murphy et al., 2019). However, all of these studies with school-age children used a broad age range within a longitudinal design with only two data collection points spaced one or two years apart. Future research could gain valuable insights by exploring the developmental trajectory of interoception and its association with other domains of human development over a more extended period.

Recent theoretical perspectives suggest that early parent-infant interactions may play a crucial role in shaping interoceptive abilities (Filippetti, 2021; Fotopoulou and Tsakiris, 2017). From birth, infants can perceive bodily perturbations such as hunger, pain, and temperature changes, communicating their needs to caregivers, who, in turn, help regulate their internal states. This dynamic highlights the infant's reliance on caregivers for maintaining homeostasis. However, the mechanisms underlying the development of interoceptive processing across the lifespan remain a topic of ongoing debate. In adulthood, interoceptive processing is often explained through prediction error minimization, as proposed in the predictive coding framework (Barrett and Simmons, 2015). This model suggests that the brain interprets sensory inputs based on prior experiences, constantly evaluating and updating these inputs to maintain a stable internal state. Despite its relevance, much of the theoretical work on interoception is based on research with adults, with limited empirical evidence from early developmental stages. Our review highlights this gap, emphasizing the need for further research to explore how interoceptive abilities emerge and evolve throughout childhood.

Given the critical role of interoception in children's health and well-being, expanding its assessment in clinical practice is essential (Khalsa et al., 2018). However, research on interoceptive interventions for children remains scarce, underscoring the urgent need for age-appropriate, evidence-based strategies that enhance interoceptive awareness and self-regulation. Strengthening these capacities could support children's emotional, cognitive, and physiological development. Moreover, emerging technologies such as biofeedback and virtual reality (Schoeller et al., 2022) present promising opportunities to facilitate interoceptive growth in both clinical and educational settings. To establish their effectiveness, rigorous randomized trials are needed to assess the diagnostic and therapeutic value of these interventions.

By mapping existing assessment tools and methodologies, this scoping review provides valuable guidance for future research. It identifies inconsistencies and underdeveloped approaches, highlighting areas where refinement is needed to improve the reliability, accessibility, and validity of interoceptive assessments, particularly in clinical settings. Developing age-appropriate methods that accurately capture

interoception's complexity in infancy and childhood is crucial for identifying early indicators of both typical and atypical developmental trajectories. This, in turn, enables timely preventive interventions that promote healthy child development. Ultimately, advancing research in this field will drive more targeted and effective clinical interventions, improving outcomes for children experiencing interoceptive dysfunction.

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