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# A scoping review on ambulatory stress assessment methods for young children and babies

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**Abstract**

**Introduction:** Repeated exposure to stress in the first years of life yields the risk of major health consequences and developmental delay. In order to detect critical exposure to stress, methods that allow for assessment in natural settings need to be established. At present, ambulatory assessment of stress within this target group mainly focuses on observation, caregiver report or cry detection. Physiological signals can serve as reliable indicators for stress. However, up till now, assessing stress by means of physiological signals is oftentimes conducted in clinical settings. In order to get an insight into current practice, physiological signals that qualify for ambulatory assessment, environments in which stress assessment is implemented and technological devices for assessment are explored. **Methods:** A scoping review was conducted by exploring the databases Web of Science, Scopus and Science Direct. The concepts “ambulatory assessment”, “physiological stress”, and “children” served as the basis for the search. **Results:** In total, 12 studies that matched the search criteria have been selected after a thorough literature search. Heart rate was identified as the most prevalent physiological signal and most effective in detecting a stress response. Based on respiratory sinus arrhythmia, a stress response was effectively detected in four out of six studies. The remaining physiological signals, heart rate variability, respiration and skin conductance did not show effectiveness in assessing stress in more than one study. It got apparent that ambulatory stress assessment in infants is mainly conducted in laboratory settings and lacks implementation in the natural environment. Here, studies aimed at understanding underlying physiological process and factors that increase or decrease stress. Studies targeting children with neurodevelopmental disorders either aimed at assessing challenging behaviour episodes or validating a tool in order to allow integration into daily life. Thus, among this population integration into the natural environment was identified to be more progressed. With regard to the implemented technology, rather traditional methods were used for infants such as electrodes and electrocardiogram. The remaining devices displayed higher innovation as they were more adapted to being used by a child in their daily life. **Discussion:** Considering the results it got apparent that research on ambulatory physiological stress assessment in infants still relies on rather traditional methods. Even though the necessity of stress assessment in infants has been widely recognized, implementation into daily life still seems to lack. It could be observed that research targeting children with neurodevelopmental disorders is more innovative and oriented towards implementation into natural environments. Finally, an advice for target users entails that heart rate as a physiological should be considered when designing devices in the future. Respiratory sinus arrhythmia is partly recommended as the effectiveness of the signal was only fully established in four out of six studies. Especially among infants, the devices in this study turned out to be impractical for longer use by infants. Therefore, development of an ambulatory tool that does not constrain the child in its natural environment would be an asset to the field.

*Keywords:* Physiological stress, Babies and young children, Ambulatory assessment, Neurodevelopmental disorders

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**Stress in the first years of life**

Exposure to stress in the first years of life has been shown to impact development of infants and young children tremendously (D'Agata et al., 2018). This period is characterized by significant development of the brain (Seehagen, Schneider, Rudolph, Ernst & Zmyj, 2015). Within the first six months, most neurons that constitute the brain are created. This development imposes an increased vulnerability onto the brain (Thompson, 2001). From birth to approximately seven years old, children go through major developmental stages including sensorimotor development and cognitive development. During this time, any obstacles may impact development negatively (Berk, 2013). Whereas, a safe and caring environment represents a prerequisite for healthy development, factors threatening these conditions such as maternal stress, abuse, neglect, pain or malnourishment leading to acute or chronic stress have lifetime consequences (Seehagen, Schneider, Rudolph, Ernst & Zmyj, 2015).

The function of stress has been studied for decades with one ascertainment being that stress serves the simple purpose of survival and the stress response preparing an organism for action when being confronted with threatening situations (Nesse & Young, 2000). However, repeated or even chronic stress comes along with major health issues. These include limited cognitive development, emotion regulation difficulties, hormone imbalance or lower intelligence. Moreover, exposure to stress at a young age influences the ability to cope with stressors later in life (Bates, Salsberry & Ford, 2017). In order to get an insight into how stress can be reliably assessed in young children, the concepts and underlying mechanisms require further clarification.

**Conceptualisations of stress and its consequences**

The term stress is associated with different constructs. Stress can be separated into physiological stress and psychological stress. Psychological stress refers to the cognitive appraisal to a stressor and requires higher order cognitive and emotional components (Kovács, Miklós & Bali, 2005). According to Figueroa-Franhanel (2014), psychological stress is typically assessed by means of observation, self-report or interviews. These methods seem not to be appropriate for young children since the developmental stage of very young children does not allow for cognitive appraisal of a situation. Moreover, young children may display difficulties in reporting their own condition which yields the risk of less reliable outcomes (Bates, Salsberry & Ford 2017). Therefore, this research will focus on physiological stress.

A stressor can be defined as a "*Real or perceived challenge to an organism's ability to meet its real or perceived needs*" (Greenberg, Carr & Summers, 2002, p. 508). Thereby, three kinds of stress are differentiated: Acute stress, episodic acute stress and chronic stress. Acute stress refers to an acute stressor occurring over a short period of time. An acute stressor occurring more frequently refers to episodic acute stress and chronic stress is characterized by the occurrence of long-term stressors (Bakker, Pechenizkiy & Sidorova, 2011). Stressors occurring in the first years of life can be the following: Premature birth, invasive interventions, pain, lack of sleep, illness, malnourishment, abuse, neglect or stressed caregivers (Azghar & Amso, 2017; D'Agata et. al, 2019). Stressors affect the stress level with perceived high stress levels resulting in a so-called stress response.

A physiological stress response expresses through the autonomic nervous system (ANS) which is separated into two branches namely the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). In a threatening situation, the body performs physiological adaptations such as an increase in heart rate, blood pressure or respiration to prepare for a fight-or-flight response (Condon, 2018). This process can be referred to as allostasis and is initiated by the SNS. In an effort to regulate bodily functions back to normal, the PNS reduces these physiological responses. This process is called homeostasis. Physiological signals deriving from above described processes, yield information indicative for a stress experience and can thereby, serve as parameters for assessing stress (Condon, 2018; Can, Arnrich & Ersoy, 2019).

In the short run, the above-described processes are adaptive and effective in overcoming a stressful situation however, ongoing exposure to these physiological processes entail increased cardiac arousal or hypertension (Luecken & Lemery, 2004). These reactions yield an increased risk for cardiovascular diseases, organ damage, infectious diseases and cognitive impairment. Experiencing prolonged stress affects neurodevelopment and influences stress reactivity and stress regulation abilities (Bates, Salsberry & Ford, 2017). Abnormal physiological reactivity to stress represents another elicitor for further physiological and psychological health concerns in the long-term (Evans et al., 2013). According to Toller-Renfree et al. (2020), children exposed to a continuous stressful environment display a neurodevelopmental delay compared to children not exposed to continuous stress. Such developmental delays can lead to limitations of language development, working memory, learning, attention and numerous other consequences. Having the ability of recognizing and assessing maladaptive stress levels, possibly minimizes the risk of the above-mentioned health consequences.

In conclusion, a first step towards improving and maintaining health within the context of stress in young children is the recognition of a stressful experience. An obstacle that hampers estimating if a child is stressed is that they either cannot verbally express their condition or, at an older age, do so rather unreliably (Bates, Salsberry & Ford, 2017). Jones et. al. (2017) report that stress levels in infants are not necessarily represented in behaviour which makes it even more difficult to be recognized by caregivers. Here, the assessment of physiological parameters can be of help for detecting stress in children. Assessing physiological signals can be facilitated by incorporation of technological devices which will be further discussed below.

**Ambulatory stress assessment**

The integration of technology into health care has been established as a tremendous asset to the health care system and has proven to fill gaps that traditional methods could not accomplish (Aguilera, 2015). For instance, technological devices exhibit a potential which can be advantageous for assessing physiological signals indicative for a stress response. Ambulatory assessment (AA) is a term that describes methods that allow to study individuals in their natural environment (Trull & Ebner-Priemer, 2013). This represents a notable asset since AA can be deployed where traditional clinical methods are not suitable (D'Alvia et al., 2020). Data acquisition is realized by means of self-report or behavioural, physiological and biological data. In this way, AA enables the collection of momentary real-time data which reduces the risk of retrospective bias and yields potential to advert to a certain health condition (Carpenter, Wycoff & Trull, 2016).

Physiological data provided by AA methods can give indications of a stress response, variations and context. Typical physiological signals are heart rate (HR), heart rate variability (HRV), skin temperature, electro-dermal activity (EDA) or blood pressure which are typically assessed by means of sensors (Massot, Baltenneck, Gehin, Dittmar & McAdams, 2011). AA exhibits advantages compared to traditional assessment methods as it provides information on multiple parameters over a certain period of time. Since AA relies more on measurable real-time data and less on self-report it produces less bias and is also more suitable for babies and children that cannot report their condition (Carpenter, Wycoff & Trull, 2016; Bates, Salsberry & Ford 2017).

**State of the art**

Within adults, ambulatory assessment of stress has already received a considerable amount of attention. Research conducted by Wettstein, Kühne, Tschacher and La Marca (2020) explored stress levels among teachers with ambulatory methods. Physiological stress was assessed by means of the parameter HRV in the context of stress assessment among teachers. Further research developed a wearable device called EmoSense to assess stress levels in blind adults as they walk a certain route. HR, electro dermal activity and skin temperature served as physiological parameters. Based on the output, the researchers were able to identify when the participants where most stressed along the route (Massot, Baltenneck, Gehin, Dittmar & McAdams, 2011). Within the context of ambient assisted living, Salai, Vassányi and Kósa (2016) developed a HR sensor for stress detection in form of a chest belt. The measures of the chest belt were compared to a professional electrocardiogram (ECG) recorder and displayed 74,60% accuracy in detecting stress compared to the golden standard device.

Within the context of babies and young children, current methods dedicated to stress assessment that can be deployed outside of medical settings oftentimes focus on observation, self-report by caregivers or cry detection (Meggelen, 2021; Choi, Jeon, Wang & Kim, 2017). There is a wide range of wearable and wireless tools that assess and monitor physiological signals in children, however these seem not to be related to the goal of stress monitoring. The Owlet smart sock is an ambulatory device that reliably keeps track of the baby's heart rate and oxygen level and immediately reports concerning changes via an alarm and notification to the caregiver's smartphone. Another device called Mimo detects the sleeping position, sleep patterns and temperature and transmits the data in real-time to the smartphone (Hasan, 2020). Both devices are mainly dedicated to the prevention of Sudden Infant Death Syndrome (SIDS) and are typical examples for current baby monitoring devices. Devices for physiological stress assessment are oftentimes still implemented in clinical settings and require a clinician. Ten Eyck et al. (2013) have developed a construct comparable to a bed, which intends to measure stress in neonates based on physiological parameters. However, this system targets Neonatal care units and is not deployable ambulatory.

Up till now, stress assessment in babies and young children is rather rarely the focus of ambulatory devices. In an effort to advance research within this field, previous literature reviews have oftentimes focused on stress assessment tools for adults with the aim of providing information that can be transferred to the context of children (Meggelen, 2021; Choi, Jeon, Wang & Kim, 2017). It gets apparent that a variety of ambulatory devices for assessing and monitoring health states and stress are out there. However, a solid connection between ambulatory assessment and physiological stress within the context of babies and young children still seems to lack. Since existing wearable devices for babies and children are rarely focused on stress assessment, it is not clear which physiological signals are meaningful and suitable to be assessed ambulatory within this target group. Furthermore, whereas stress assessment in adults is deployed in a variety of natural environments already, it is not apparent to what extent stress assessment in babies and young children is implemented in natural environments. Within the scope of this research, natural environments refer to realword environments as part of ambulatory assessment (Trull & Ebner-Priemer, 2013). Here, a review of such methods that qualify for assessing physiological stress in babies and young children can establish clarity.

**Objective of this review**

Considering the major health consequences that arise from stress exposure especially in the first years of life, it is apparent that there is need for further exploration of how physiological stress can be ambulatory assessed within this target group. Until now, stress assessment in babies and young children has mainly been implemented within clinical settings and ambulatory devices oftentimes focus on contexts other than stress such as SIDS. With respect to the relevance of this topic, stress assessment needs to be established more accessible and ubiquitous also in non-clinical settings. In this way, concerning physiological changes indicative for stress can be identified and tackled and therefore, may prevent severe consequences. Thus, this review aims at exploring methods of physiological stress assessment in babies and young children. The review serves the purpose of informing practitioners within the child care sector about research evidence that can be of help for the development of practice for ambulatory settings. The arising research question reads as follows:

*"How is ambulatory physiological stress assessment carried out within the target group of babies and young children"?*

The research question is divided into the following sub questions:

(1) Which physiological variables are assessed to determine stress?
(2) To what extent is assessment carried out in the natural environment of the target group?
(3) Which method/technology of assessment is implemented?

## Methods

The present literature review can be further classified as a scoping review. A scoping review aims at reviewing literature concerning a given topic. More specifically, this process enables identifying types of evidence and the extent of the matter of interest as well as research gaps (Peters et al., 2015). The scoping review at hand was conducted based on the preferred reporting items for systematic reviews and meta-analyses - extension for scoping reviews (PRISMA-ScR; Tricco et. al., 2018).

### Search strategy

The relevant electronic databases for this review were Web of Science, Scopus and Science Direct. Since the topic integrates psychological, medical and technological aspects databases focusing on more than one domain were estimated as representative. Whereas all three databases cover the domains social sciences, health sciences and art & humanities, Web of Science and Scopus also provide input on natural sciences and technology. The search was performed in May 2021. The concepts "ambulatory assessment", "physiological stress", and "children" served as the basis for the constructed search string. Based on the three concepts, related search terms, the Boolean operators "AND" and "OR", brackets and truncation, the following search strings emerged:

Table 1. Search strategy

| **Search string** | |
|---|---|
| Web of Science & Science Direct | ( "ambulatory assessment" OR "wearable technology" OR "real-time monitoring" ) AND ( stress OR physiolog* ) AND ( child* OR infants ) |
| Scopus | ( ( wearable* OR ( ( ambulatory OR real-time ) W/4 ( monitor* OR assess* ) ) ) AND ( stress* OR psychophysiolog* ) AND ( child* OR infants OR toddler* OR bab* ) AND ( variab* OR measure* OR instrument ) ) |

In order to specify the dataset, certain limitations were undertaken which included: German and English language within a time frame from 2011 to 2021. This time frame was chosen to ensure inclusion of novel and up-to-date methods as well as methods that have proven as solid in the past decade. In the database Science Direct the subject areas "Psychology" as well as "Medicine and Dentistry" were selected to refine the search as the remaining subject areas were not relevant.

**Selection criteria**

Studies were selected for the review if they (1) assess stress levels in infants or young children, (2) assess at least one physiological parameter and (3) if the method is not bound to clinical settings to ensure that findings can be transferred to ambulatory settings. Moreover, as mentioned in the beginning, children go through major developmental changes in the first seven years (Berk, 2013). Therefore, it was chosen to include (4) studies targeting children up till the age of seven. Exclusion criteria entailed (1) stress assessment of parents or caretakers, (2) assessment methods that are not based on physiological parameters, (3) implementation of methods bound to clinical settings and (4) participants older than seven years.

**Data extraction**

On the basis of the Prisma-Checklist (Tricco et al., 2018), the following data was extracted: In the first step the general information of each article such as author and year of publication was recorded. Thereupon, study and participant characteristics were generated. Furthermore, method of assessment, physiological measure and environment of assessment were extracted to record how stress assessment was implemented. Lastly, the outcome of each article was noted which was related to whether the type of technology identified a stress response.

## Results

In total, 565 studies have been identified of which 476 articles were acquired through the databases (see Figure 2) and the corresponding search strings. 89 articles were generated through previous acquired articles. This strategy can be referred to as the snowballing technique (Sharma, 2017). After removal of duplicates, titles and abstracts of 542 articles were scanned. Further exclusion, resulted in 156 articles that were fully screened. Reasons for the final exclusion are displayed in the flowchart of the selection process (see Figure 2). The selection process resulted in 12 remaining studies that were included in the review.

### Study characteristics

Three studies were implemented in the United States (Bush, Caron, Blackburn &Alkon, 2016; Enlow et al., 2014; Nuske et al., 2019;) two in the United States and Germany (Ritz et al., 2012; Ritz et al., 2020), three in Italy (D'Alvia et al., 2020; Fioriello, 2020; Pittella et al., 2018) two in Canada (Cirelly & Trehub, 2020; Paret et al., 2015) one in Japan (Takahashi, Matsuda & Suzuki, 2016) and one in the Netherlands (Suurland et al., 2018). The studies were published between 2012 and 2020 (see Table 1).

### Participant characteristics

The age range of the subject's ranges from 6-months to 6-years of age. The participants of five studies were children with neurodevelopmental disorders (ND) with either Autism Spectrum Disorder (ASD) or Specific Language Disorder (SLD) (D'Alvia et al., 2020; Fioriello et al., 2020; Nuske et al., 2019; Pittella et al., 2018; Takahashi, Matsuda & Suzuki, 2016). The subjects of the remaining seven studies did not have a pre-determined condition. Sample size varied from three participants to 278 participants.

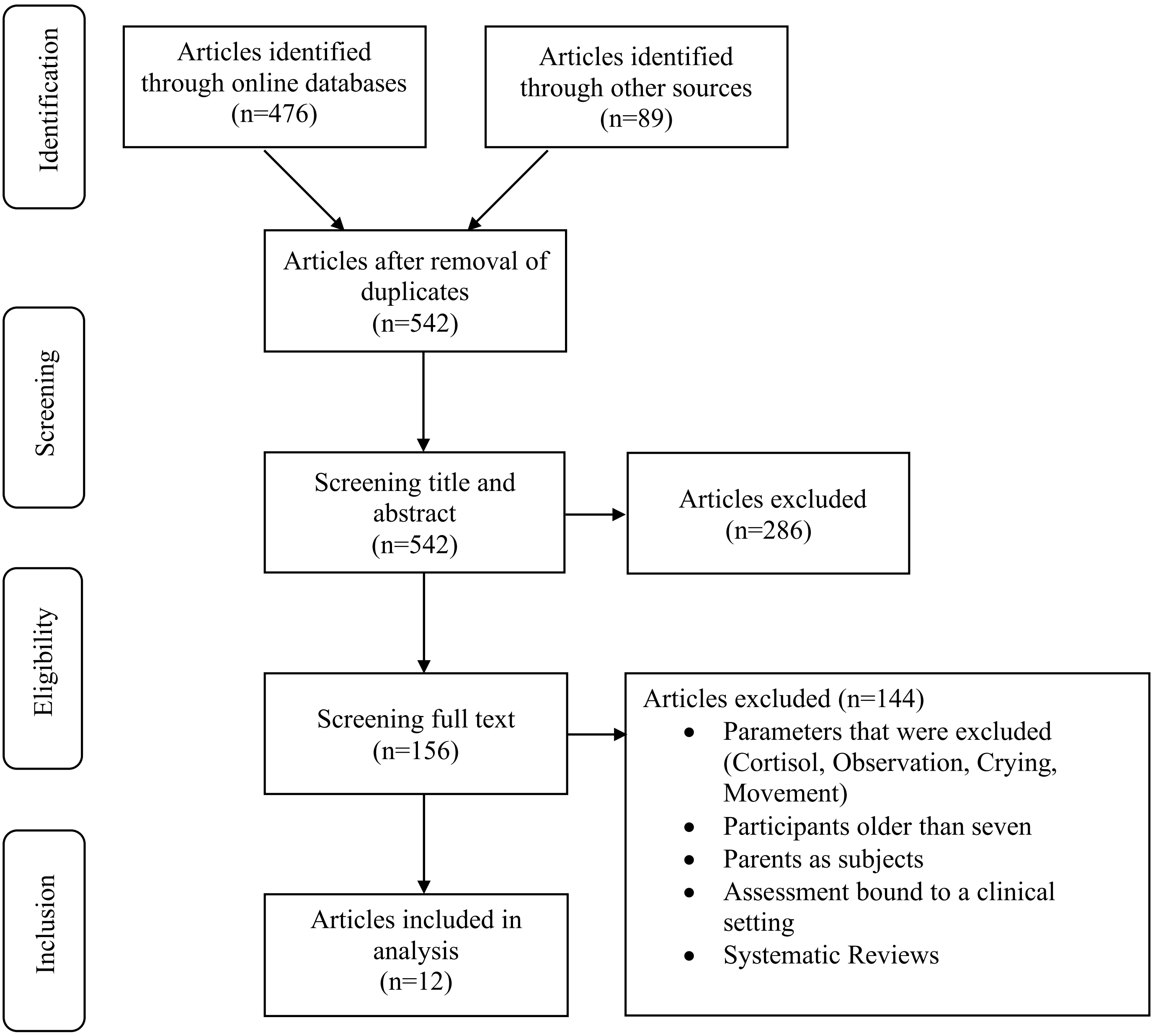


*Figure 2*. Flowchart of the selection process

**Study characteristics**

**Table 1**

*Overview of characteristics of included studies*

| | **Study characteristics** | | | | **Assessment method** | | |
|---|---|---|---|---|---|---|---|
| ***Author and year of publication*** | ***Sample size (n)*** | ***Age*** | ***Design*** | ***Method for stress assessment*** | ***Physiological measure*** | ***Environment of assessment*** | ***Outcome*** |
| Bush, Caron, Blackburn & Alkon (2016) | 133 children | 18-21 months | Experimental study | ECG Electrodes | HR, RSA | Home and laboratory setting | Under resting and challenging conditions, stress related arousal could be successfully identified by means of HR and RSA |
| Cirelli & Trehub (2020) | 140 infants | 8-10 months | Experimental study | Biopac MP160 | Skin conductance | Laboratory | Speech and singing was shown to reduce distress; Skin conductance successfully identified increase and decrease of stress related arousal |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D' Alvia et al. (2020) | 32 children | 24-60 months | Experimental study | Wireless belt sensor device | HR, RSA | Experimental set-up outside of a laboratory | Belt identified significant differences in stress related arousal based on HR measures among children with and without ND but not based on RSA |
| Enlow et al. (2014) | 35 infants | 6 months | Observational study | LifeShirt System | HR, RSA | Laboratory | Caregiving quality affects responsiveness of ANS; Increase of HR and decrease of RSA during stressful situations |
| Fioriello et al. (2020) | 24 children | 30-60 months | Experimental study | Wearable belt system | HR | Experimental set-up outside of a laboratory | HR significantly higher in children with ASD than in children with LSD; HR measures successfully identified |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | physiological reactions to stress |
| Nuske et al. (2019) | 41 children | 24-48 months | Experimental study | Biopac BioNomadix | HR, HRV | Laboratory | HR increases during stressful tasks and predicts challenging behaviour episodes in children with ND; HRV was no significant predictor in this study |
| Paret et al. (2014) | 48 | 42-48 months | Cohort Study | Biopac MP100 | HR, RSA | Laboratory | Significant increase of HR and decrease of RSA in response to a stressor |
| Pittella et al. (2018) | 10 children | 24-60 months | Experimental study | Thoracic belt system | HR | Experimental set-up in a preschool | HR as a useful indicator for a stress response |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Ritz et al. (2012) | 23 infants | 6 months | Case Study | LifeShirt System | HR, Respiration, RSA | Laboratory | RSA predicts vagal withdrawal and therefore, stress |
| Ritz et al. (2020) | 278 infants | 6 months | Cohort Study | BioRadio tool | HR, RSA | Laboratory | Increase HR and decrease of RSA during stress inducing event |
| Suurland et al. (2018) | 124 children | 5-30 months | Cohort Study | Vrije Universiteit Ambulatory monitoring system(VU-AMS) | RSA | Home | Increased SNS activity in response to an emotional challenge evident by RSA measures |
| Takahashi, Matsuda & Suzuki (2016) | 3 | 36-60 months | Experimental study | Wearable electrocardiogram integrated in clothes | HR, HRV | Therapeutic session | ECG measurements were successfully assessed in children with ASD |

ECG: Electrocardiogram; HR: Heart rate; HRV: Heart rate variability; RSA: Respiratory sinus arrhythmia; ANS: Autonomic nervous system; ND: Neurodevelopmental disorder

**Physiological variables assessed**

The physiological variables for stress assessment differ across the studies, yet certain variables are more prevalent than others. Overall, cardiac activity in terms of HR and HRV was assessed in eleven out of twelve studies. Respiration alone and in synchrony with HRV, which can be referred to as respiratory sinus arrhythmia, was assessed in six studies. Finally, skin conductance was assessed in one study. Each variable is discussed in more detail below.

***Cardiac activity***

In general, HR was assessed in ten out of twelve studies and thereby, is the most prevalent variable that was used to assess stress (see Table 1). Notably, a stress response was successfully identified across all ten studies by means of HR. Bush, Caron, Blackburn and Alkon (2016) assessed sympathetic and parasympathetic nervous system activity which they refer to as ANS reactivity. Under resting and challenging conditions (Lullaby 1, Jack in the box, Lemon juice taste, Infant cry and lullaby 2), it was intended to elicit and monitor a change in ANS activity namely HR. One challenging condition was, playing 30 seconds of an infant crying on a tablet. Results indicate that, across all conditions, ANS reactivity could be observed in all children with an increase in HR which they relate to as a physiologically observable stress response. ANS response varied across the conditions whereas on average, HR activity was highest for the condition “lemon juice taste”.

Five studies (D’Alvia et al., 2020; Fioriello et al., 2020; Nuske et al., 2019; Pittella et al., 2018; Takahashi, Matsuda & Suzuku, 2016) successfully assessed stress by means of HR, HRV or both in children with ND. D’Alvia et al. (2020), incorporated a control group consisting of children without ASD. A stress response was identified across both conditions, however children with ASD displayed significantly greater variations in HR across the implemented tasks. These findings are in line with the findings by Takahashi, Matsudi and Suzuki (2016) who detected strong variations of HR of each participant across the individual tasks. Further, Fioriello et al. (2020), identified significant higher HR measures during interactive tasks in children with ASD compared to children with SLD. Moreover, an increase in HR correlated significantly with autistic symptoms.

Additional three studies detected stress in children without a predetermined condition using the Still-Face Paradigm (SFP; Ritz et al., 2012; Ritz et al., 2020; Enlow et al., 2014). Enlow et al. (2014) describe this task as common for assessing a stress response in infants. The SFP entails three phases. The first in which the caregiver interacts with the infant, the second in which interaction is withheld and the third where the caregivers resumes the interaction. All three studies show a peak of HR during the first still face phase and an observable decrease of HR in the reunion phase. In comparison, HRV alone was considerably less associated with a stress response. Nuske et al. (2019) made use of daily stress inducing events, such as waiting for a snack, to elicit ANS reactivity. It was observed that 1% increase in HR was related to a 4 times higher likelihood of experiencing a challenging behaviour episode whereas HRV was no significant predictor of stress.

In conclusion, cardiac activity and especially HR served as a reliable physiological parameter for detection of stress. HRV did not serve as a reliable indicator for a physiological stress response. Moreover, studies targeting children with neurodevelopmental disorder displayed strong variations across the subjects and the tasks.

***Respiration and Respiratory sinus arrhythmia***

There is great overlap of assessment of cardiac activity and respiration. Respiratory sinus arrhythmia (RSA) resembles respiration related HRV and is indicative for parasympathetic activity (Yasuma & Hayano, 2004). Therefore, in response to a stressor, RSA typically declines in order to adapt to external demands (Suurland, et al., 2018). Six studies measured RSA. For instance, during phases of the above mentioned SFP, RSA could give indications when infants regulated stress (Ritz et al., 2012; Ritz et al., 2020; Enlow et al., 2014). Bush, Caron, Blackburn and Alkon (2016) measured RSA during challenging conditions and found that it varies across all conditions indicating that PNS activity changes in response to every task.

Yet, two out of the six studies that found variations in RSA and respiration did not specifically mention the variations to be the result of a stress response but rather established other parameters as the main indicator for a stress response such as HR (D’Alvia et al., 2020; Suurland et al., 2018). The remaining three studies identified a decrease in RSA in response to a stressor (Paret et al., 2014; Ritz et al., 2012; Ritz et al., 2020). In addition, Ritz et al. (2012) and Ritz et al. (2020), reported respiration rate per seconds indicating a significant increase of breaths per second during the SFP and decrease during reunion phase. Paret et al. (2014) reports that children with vagal withdrawal, which is a sign for a decrease in RSA, already displayed higher baseline RSA than children that did not display vagal withdrawal. In response to the above described IbS, RSA decreased in response to the stressor. In addition, Ritz et al. (2012) linked higher respiration to a decrease in RSA. Significant variation of RSA was shown across the individual episodes of SFP with a strong reduction of RSA during stressful episodes. Similar results emerged from the final study by Ritz et al. (2020). Thus, RSA served as an indicator for a physiological stress response in four studies. The remaining studies ascribed the detected stress related arousal to HR rather than RSA.

### *Skin Conductance*

One Study assessed stress and stress reduction by means of skin conductance (Cirelli & Trehub, 2020). Similar to previous studies, stress was elicited using the SFP which was divided into a play phase, still face phase and reunion phase. Further, it was investigated whether parental speech or singing was more effective in reducing distress. Results indicate that that levels of skin conductance response increased from the play phase to the still face phase. Notably, skin conductance kept on increasing during the reunion phase, however this was attributed to excitement rather than distress. Moreover, skin conductance during reunion was higher for older infants. Finally, songs were more effective in reducing distress than speech.

## Environment of assessment and objective

Ambulatory stress assessment was carried out in different environments across the studies. In order to present the findings, a division into toddlers, infants and a separate category for children with neurodevelopmental disorders is undertaken.

### *Toddlers*

Two studies assess stress in toddlers without a predetermined condition. According to Bush, Caron, Blackburn & Alkon (2016), individual differences in the reactivity of the ANS, determine the development of physical and mental health. Within this scope, the aforementioned study aims at understanding factors that influence the ANS within this age group. The assessment was implemented either in the laboratory or at the child's home. In comparison, Paret et al. (2014) conducted a study which was dedicated to understanding how the attachment relationship between child and caregiver affects the regulation of stress. In accordance with previous described studies, it is outlined that attachment to a caregiver affects regulation of stressors and adaption to environmental demands. Assessment of stress in this study was carried out in a laboratory setting.

### *Infants*

Five studies assessed physiological stress among infants (Cirelli & Trehub, 2020; Enlow et al. 2014; Suurland et al. 2018; Ritz et al. 2012; Ritz et al. 2020). Four out five studies were carried out in laboratory setting whereas one study by Suurland et al. (2018) was carried out during a home visit. Cirelli and Trehub (2020) hold the view that a caregiver's response to infant distress determines the type of bond that emerges and influences self-regulation abilities. Further, they argue that music additionally contributes to regulating distress. Based on these assumptions, the study investigated whether speech or singing of the caregiver to an infant reduces distress.

Similar reasoning was identified in the study conducted by Enlow et al. (2014). The importance of stress assessment in infants was substantiated based on the health and disease hypothesis which states that environmental factors that are experienced early in life influence mental and physical health later in life. Thereby, caregiving or maternal sensitivity fundamentally coins a child's stress response. Within that scope, it was investigated how maternal sensitivity influences infant's ANS reactivity using the SFP. In contrast, Suurland et al. (2018) measured stress within the context of prenatal adversity and physical aggression in toddlerhood. Thereby, states of baseline, stress and recovery were observed. Two remaining studies focused on understanding the biological processes that take place during stress exposure. The necessity of the studies was justified by arguing that exaggerated cardiovascular stress responses potentially predict psychopathology or cardiovascular diseases (Ritz et al., 2012; Ritz et al., 2020).

Conclusively, it gets apparent, that the selected studies that assess stress in infants are of rather experimental nature and mainly implemented in laboratory settings. Only one study carried out the assessment at the child's home.

***Neurodevelopmental Disorders***

Five studies assessed physiological stress in children with ND of which one study implemented the assessment in the laboratory (Nuske et al., 2019). Furthermore, three studies performed interactive tasks in an experimental setting however, outside of a laboratory such as a preschool (D'Alvia et al., 2020; Fioriello et al., 2020; Pittella et al., 2018).
Concerning the objective of the studies, there was general consensus among all studies relating to the main issue that emerges when talking about stress assessment in children with neurodevelopmental disorders. Children with ASD typically display impairment of social functioning and communication abilities (Fioriello et al., 2020; Nuske et al., 2019. Moreover, there is a lack of recognizing and understanding own emotions which aggravates assessment of stress significantly. SLD is characterized by a developmental delay of language skills. Therefore, children with SLD do not display age-appropriate abilities to express themselves (D'Alvia et al., 2020; Pittella et al., 2018).

Thus, a device that can be implemented in daily life, that is non-invasive and does not cause any pain is of importance (D'Alvia et al., 2020; Pittella et al., 2018). Results related to the assessment of physiological stress and differences among ASD and LSD are discussed in the previous section. Takahashi, Matsuda and Suzuki (2016) particularly developed a device for the purpose of detecting stress in children with ASD in therapy settings. By making the emotional states of the child recognizable for the therapist, he can act accordingly upon the demands of the child and in this way, improve therapy.

**Method of assessment**

The methods of assessment and technology that is used show great overlap with respect to data acquisition but disparity with regard to its implementation and design. Five out of twelve studies made use of ambulatory recording devices where electrodes are attached to the child's body (Bush, Caron, Blackburn & Alkon, 2016; Cirelly & Trehub, 2020; Paret at al., 2014; Suurland et al., 2018; Ritz et al. 2020). Cirelli and Trehub (2020) and Paret et al. (2014) used a Biopac MP160/Biopac MP 100 device for acquiring physiological signals. Thereby, electrodes were attached to the foot or chest. In addition, a ECG amplifier was deployed to assess cardiac data (Paret et al., 2014). The Biopac units wirelessly transmits the data to the softwares that were used for the above-mentioned studies (BioLab Software & AcqKnowledge 3.8). Another device that was implemented using a similar procedure is the Vrije Universiteit Ambulatory Monitoring System (VU-AMS) in conjunction with the VUDAMS software suite version 2.0 for data extraction. In addition to electrodes meant for ECG acquisition, Ritz et al., utilized inductance bands attached to the child's thorax and abdomen which can be referred to as the BioRadio a non-inasive ambulatory biosignal recorder. This device continuously stores data from the electrodes and inductance bands which are transmitted to a computer and evaluated by a software called VivoSense.

In comparison, D'alvia et al. (2020), Fioriello et al. (2020) and Pittella et al., (2018) made use of a wireless device in form of a belt (see Figure 3). The belt contains a 3-lead ECG, a piezoelectric plethysmograph and microcontrollers that obtain the data. Break out boards enable wireless communication and exchange of data to a computer where the information is evaluated using the software LabVIEW (D'Alvia et al. 2020; Fioriello et al. (2020).

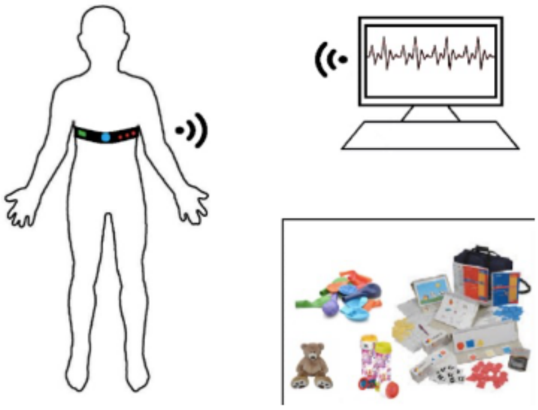

*Figure 3.* Thoratic belt displaying the ECG sensors, the piezoelectric sensor and the communication board (D'Alvia et al., 2020).

A device called LifeShirt System was used by two studies (Enlow et al. 2014; Ritz et al., 2012). The LifeShirt Sytem is a sleeveless shirt made out of Velcro with integrated inductance bands and 3-lead ECG. The raw signals are amplified, converted and stored in either an attached recorder or on a laptop. Similar methods were used by Nuske et al. (2019) and Takahashi, Matsuda and Suzuki (2016). The former made use of a vest with a sewn-in Biopac BioNomadic ECG and an accelerometer module transmitter which connected wirelessly to the Biopac MP150 receiver for exchange of data. The latter developed a smart clothing system containing an electronic module, a signal amplifier, an acceleration sensor and a monitoring system. The electrodes are integrated into the garment at the wrists. ECG and accelerometer are placed in a pocket on the front of the shirt (see Figure 4). Results indicate that this device is most accurate considering ECG measures when the activity level of the child is low.

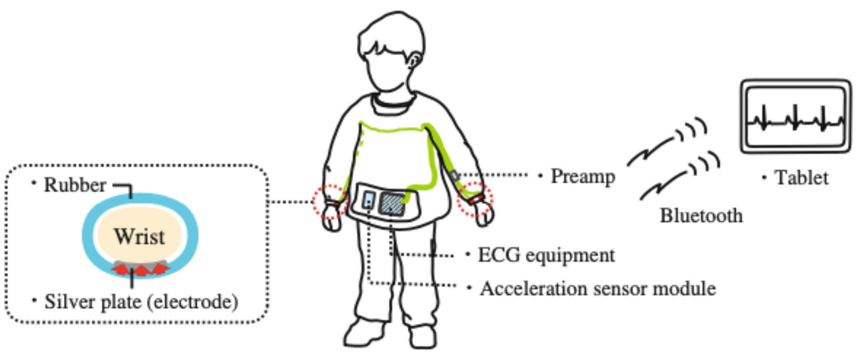


*Figure 4.* Smart clothing with integrated electrodes, ECG equipment and acceleration sensors (Takahashi, Matsuda & Suzuki, 2016).

## Discussion

The present scoping review aimed at exploring existing methods of ambulatory physiological stress assessment in babies and young children. More specifically, the main objectives were identifying physiological variables of stress, exploring to what extent stress assessment is carried out in natural environments of the target group and technological devices that assess physiological stress ambulatory. Therefore, a scoping review which included twelve studies was performed.

### Main findings

The first sub-question related to the included parameters indicative for a physiological stress response. Findings suggest HR as an effective and most prevalent signal for assessing physiological stress among the included studies. The assessment of cardiac activity is non-intrusive and not related to pain which makes assessment easy and convenient for an ambulatory tool (Hufnagel, Chambres, Bertrand & Dutheil, 2017). It was shown, that based on HR, a stress response was reliably detected in all studies that used HR. In contrast, HRV was not mentioned as a predictor for a stress response. The second most frequent used variable was respiration alone or in conjunction with HRV which refers to RSA. In four out of seven studies, a physiological stress response was detected by means of RSA. Condon (2018) reviewed biomarkers for stress and outlined that cardiac activity and respiration automatically increase in response to a stressor and are thereby, obvious physiological signals that should be considered when assessing a stress response.

Skin conductance was used in one study only which is rather surprising since skin conductance is estimated as a reliable variable for assessing stress (Taj-Eldin, Ryan, O'Flynn & Galvin, 2017; O'Haire; McKenzie, Beck & Slaughter, 2015). Even though, skin conductance provided information on physiological stress, it is questionable to what extent these findings can be generalized with regard to the effectiveness of identifying physiological stress, as it was only included in one study. A review by Hasan (2020) included several baby monitoring devices that mostly relied on the parameters body temperature, blood pressure, cardiac activity and respiration. Even though these devices are not meant for detecting stress but rather SIDS and health in general, one could assume that skin conductance might be not established well enough yet to be included within this target group.

Moreover, a review conducted by Zhu, Liu, Li, Li and Inoue (2015) introduced physiological signals crucial for health monitoring in infants that deviate from the findings of this study. Thereby, body temperature was identified as a main physiological signal for monitoring health states in infants. However, it needs to be considered that body temperature as a physiological signal was not assessed within the scope of stress assessment but rather health monitoring in infants which could be a possible explanation why body temperature was not represented in one of the included studies. The findings by Hasan (2020) and Zhu et al. (2015), outline that several physiological signals assessed by wearable devices, already serve as indicators for the health condition of infants. However, the specific focus on which of the signals are especially useful for assessing stress still seems to lack. Therefore, the present findings provide promising insights into the effectiveness of physiological signals included in this study for ambulatory stress assessment in babies and young children.

The second sub-question related to the environment in which ambulatory stress assessment is carried out within the target group. With this objective, it was anticipated to explore to what extent devices for stress assessment are implemented in the natural environment of children up till now. Six studies were implemented in laboratory settings whereas the remaining six studies where implemented either at the child's home, during a therapy session or within the scope of an experimental set-up in familiar locations such as a preschool. It got apparent, that among children with ND, implementation of stress assessment was carried out in experimental conditions, however it seemed to be more oriented towards integration into children's natural environment such as the child's home or a preschool. In line with these findings, Redd et al. (2020) outlined that monitoring physiological signals among children with ND, was mainly carried out in experimental settings in the past which inhibited its applicability into natural environments.

In contrast, among infants and toddlers without predetermined conditions, stress was assessed mainly in laboratory settings. These findings propose that devices for physiological stress assessment have not developed yet to such an extent that they are implemented in real-life settings. Zhu et al. (2015) reviewed devices that assess physiological signal for health monitoring in infants and it got apparent that in accordance with this study, integration into natural environments was still lacking. As the aforementioned study focused on health monitoring in general it could be assumed that the integration of ambulatory assessment of physiological signals in general, independent of stress, among infants is rather behind.

Finally, the third sub-question related to the used method and technology for stress assessment. Although all devices were identified as ambulatory devices, some displayed greater innovation than others. Within the context of neurodevelopment disorders, mainly devices like smart clothes and wearable belts were implemented whereas the remaining six studies made use of devices such as the BioRadio tool or VU-AMS that are bulky and attached to wires and several electrodes. Moreover, the interpretation of results requires specific software's and is rather complicated for lay people.

According to Zhu et al. (2015), assessing physiological signals by means of electrodes is a solid but rather traditional method of assessment. However, it was argued that electrodes are not suitable for a long-term monitoring as they can cause skin irritation. Moreover, attached wires hinder the infant from moving unrestricted. A more advanced method compared to traditional electrodes are textile electrodes that are more suitable to be attached to the infant's body (Zhu et al., 2015). In comparison, studies targeting children with neurodevelopmental disorders display greater innovation with regard to the technology and greater progress concerning its integration into daily life. For instance, ASD is characterized by strong variations of symptoms across the disorder which aggravates estimating the health condition of each individual. Moreover, another characteristic of the disorder is poor stress management (Taj-Eldin, Ryan, O'Flynn & Gavin, 2018). These findings outline why a device for stress assessment is necessary across this population.

Redd et al. (2020) made use of an Empatica wristband that monitors physiological signals in children with ND. Within the scope of emotion detection, this device aims at identifying difficult behavioural episodes rather than stress exclusively. Since such episodes are associated with highly stressful experiences for the child, this device may still be relevant for physiological stress assessment (Redd et al, 2020). The tool was developed based on user requirements that allow the user comfortable use in natural environments. Different from the present study, the wristband was implemented by the child and its caregiver for five days without the presence of a researcher. This represents progress with regard to implementation into daily life and usability compared to the studies of this research.

Considering these findings, the question arises why ambulatory physiological stress assessment seems to have a developmental delay for infants and toddlers without predetermined conditions. One possible explanation could be that practitioners prefer to stick to golden standard methods for stress assessment implemented in clinical settings since clinical applications possibly allow for higher accuracy (Zhu et al., 2015). This would explain why rather well-established old-fashioned devices were identified in six studies. A study conducted by Bates, Salsberry and Ford (2017), outlined the urgency of developing a tool for stress assessment in children. However, practical implications only entailed suggestions for implementation in clinical settings which raises the assumption that transference of physiological stress assessment into ambulatory settings is not taken into consideration frequently enough. Notwithstanding that the necessity of ambulatory stress assessment at a young age has been recognized by all studies, practical implementations are still rare.

**Strengths and limitations**

The study at hand displays strengths and limitations that need to be considered when making inference and interpreting results. The primary strength of this review is that, as far known, no scoping review on ambulatory physiological stress assessment tool for babies and young children has been performed yet. Therefore, the current state of the art is outlined. Considering the previously identified gap of knowledge within this field and the importance of establishing ambulatory stress assessment for children, this project contributes to advancing research further. First of all, this review identified physiological parameters that have shown to reliably assess stress ambulatory. Secondly, considering the implemented devices, information on individual features such as usability and practicality for daily use is provided. These insights can serve as a basis for the development of new innovative tools that suit the issue and the target group more.

Next to strengths, several limitations need to be taken into account. Five studies assessed stress among children with ND. This needs to be taken into consideration as children with ND possibly react to stress differently than children without ND. In line with the aforementioned assumption, a study conducted by Lydon et al. (2014) indicates that children with ASD show higher physiological reactivity to a stressor compared to a control condition. These findings elucidate how children with ASD respond to a stressor differently and more severe compared to children without ASD. Another limitation is that the scope of this review was rather small which influences the generalizability of the results. This means, that the findings of the present study do not account for a general conclusion on physiological parameters, methods and environments of ambulatory stress assessment. Furthermore, the search string is a natural limitation that comes along with literature search as is it leads to the exclusion of certain papers that could have contributed to this research as it naturally leads to exclusion of certain papers.

Another element that has limited the included studies is that only three databases were included. Yet, considering the small scope of this research project, restrictions needed to be made and three accredited databases were chosen. Within the frame of a larger research project, additional databases such as PubMed and PsychInfo could be included as the former provides references on medical matters and the latter concerns behavioural and social sciences. In combination, these databases may provide additional substantial interdisciplinary insights relevant for the topic of interest. Moreover, of the final studies included, two display a small sample size of 10 participants or less. Therefore, it is questionable to what extent these findings are representative and making inference about physiological stress assessment based on the presented parameters needs to be treated with caution. The review was conducted by one researcher only and data acquisition was not randomized which might yields the risk for selection bias. Finally, confirmation bias could have led to the selection and interpretation of information that is in line with existing beliefs of the researcher (Nickerson, 1998).

**Conclusion and direction for future research**

This research has provided information on ambulatory physiological stress assessment in babies and young children by presenting physiological parameters that are currently used, environments of stress assessment and methods or technology for assessment. One issue that particularly stands out is the gap of knowledge and lack of technological devices for assessing stress ambulatory in infants. Thereby, ambulatory stress assessment in natural environments lacks. Golden standard methods for assessment still seem to be the focus which was confirmed by the used devices as they were rather traditional and partly left room for improvement considering the suitability for infants.

Based on the findings, the following advice for stakeholders is formulated: HR and in part RSA are recommended as reliable signals for physiological stress assessment. RSA was effective in detecting a stress response in four out of six studies. Thus, further research is necessary to make a more profound statement about its suitability for assessing physiological stress. The remaining parameters, did not prominently contribute to the assessment of a stress response or where not represented well enough across the studies to allow for more specific conclusions. Moreover, current ambulatory tools especially for infant’s lack wearing comfort and restrict movement. It got apparent that comfortable wearable technology for infant’s health monitoring already exist. However, these were not implemented with the aim of assessing stress. Therefore, developing devices for ambulatory stress assessment in such a way that they do not restrict the child would be an asset to the field.

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