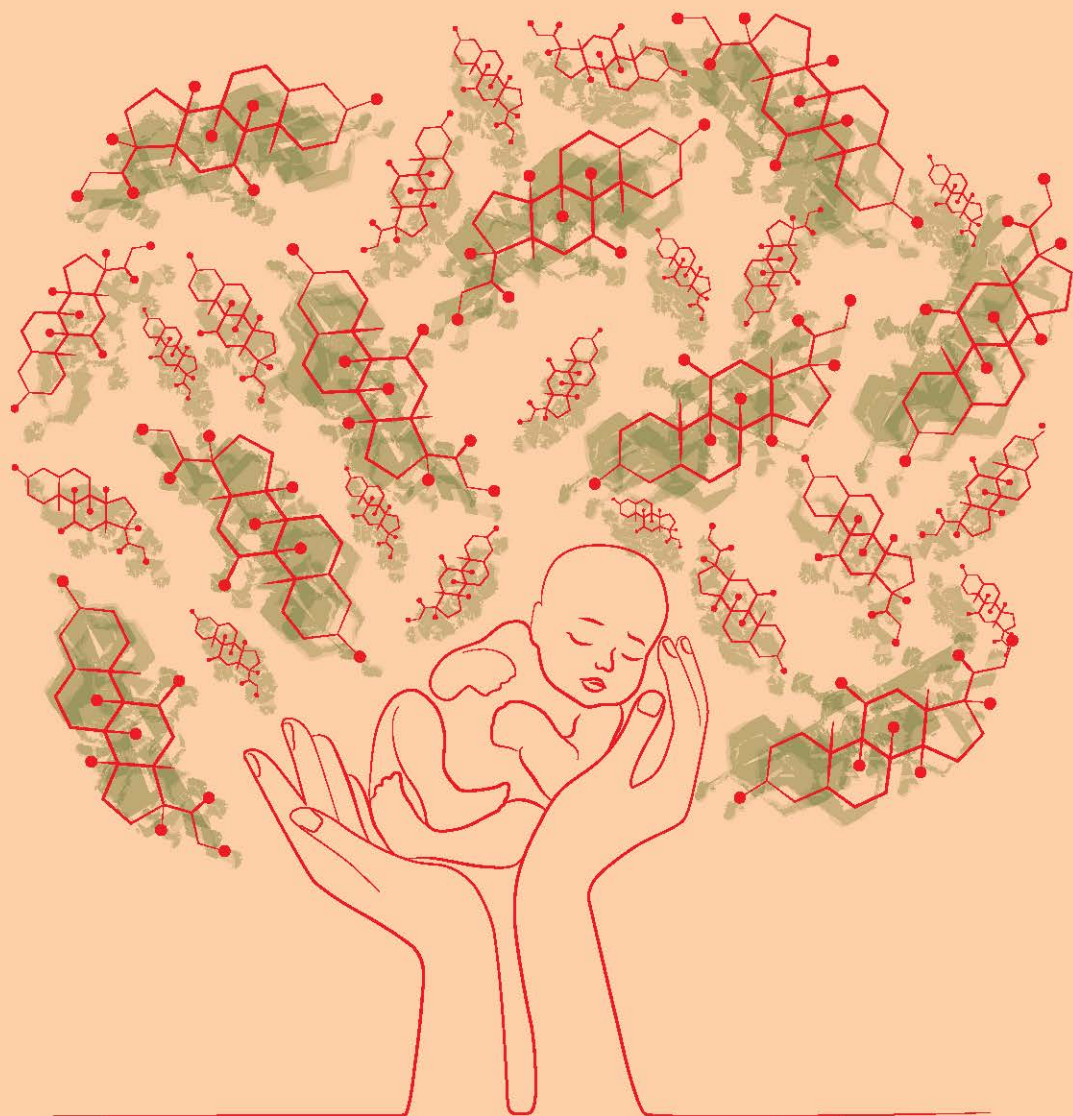


Development of regulation from infancy to adolescence

The role of early caregiving



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DEVELOPMENT OF REGULATION FROM INFANCY TO ADOLESCENCE – THE ROLE OF EARLY CAREGIVING

Nicole Rheinheimer

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**Development of regulation from infancy to adolescence
– The role of early caregiving**

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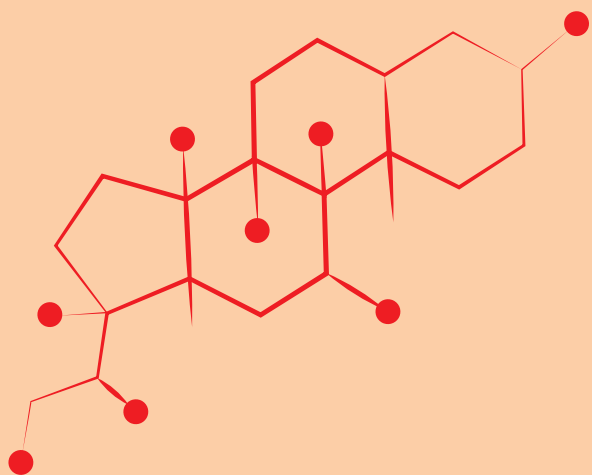
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Chapter 1

Introduction

General introduction

Self-regulation is defined as the ability to adapt physiological and behavioral states in response to internal and external demands and stressors (Beeghly et al., 2016; Nigg, 2017). This includes the regulation of physiology, such as neurobiological and circadian functioning, as well as the regulation of behavioral and emotional states, such as the ability to cope with feelings of frustration or anger, or the ability to focus on cognitive tasks (Beeghly et al., 2016). Infants are born with an immature ability to regulate, and hence highly depend on external regulation through their caregivers (Feldman, 2007, 2012; Norholt, 2020; Rattaz et al., 2022). Consequentially, early caregiving has a large impact on infants' development of regulation (Loman & Gunnar, 2010; Rattaz et al., 2022). A large body of literature has shown associations between less optimal factors of early caregiving, such as parental separation or maltreatment, with maladaptive outcomes of regulation later in life (Gruhn & Compas, 2020; Gunnar & Quevedo, 2007; Loman & Gunnar, 2010; Shonkoff & Garner, 2012; Tarullo & Gunnar, 2006). On the other hand, beneficial factors of early caregiving, such as prompt and reliable reactions to infants' cues, can positively impact the development of regulation (Albers et al., 2008; Berry et al., 2017; Kiel et al., 2024; Tsotsi et al., 2020). Identifying factors that positively affect the development of regulation can deliver important insights for future caregiving advice, for policy making, as well as for future studies on possible interventions for infants with regulatory difficulties. This thesis aims to assess the role of early caregiving in the development of children's regulation. The thesis covers three types of child regulation: physiological regulation in terms of the hypothalamic-pituitary-adrenal (HPA) axis, sleep and behavior. These types of regulation constitute the outcomes of the empirical studies of this thesis and are assessed in association with potentially beneficial factors of early caregiving, including outdoor time and increased parental proximity through infant carrying, skin-to-skin contact, and parent-infant room sharing. Furthermore, associations with early life predisposing factors for regulatory difficulties are assessed, including maternal prenatal stress and anxiety, and infant colic. The following section introduces the theoretical background on the types of regulation mentioned above, followed by a section on the assessed early life factors. The topics covered in this thesis are illustrated in Figure 1.

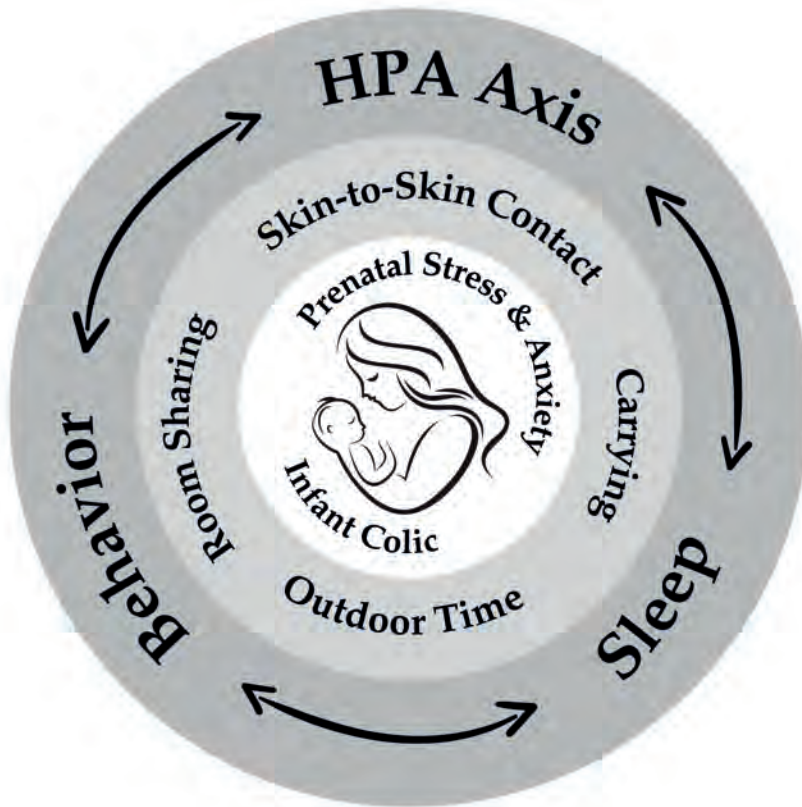


Figure 1. Overview of the types of child regulation (outer circle) assessed as outcomes of early caregiving factors (middle circle), in the light of predisposing factors for regulatory difficulties (inner circle). HPA Axis = Hypothalamic-Pituitary-Adrenal Axis

Types of regulation covered in this thesis

The **hypothalamic-pituitary-adrenal (HPA) axis** comprises the hypothalamus and pituitary gland in the brain and the adrenal glands situated on top of the kidneys. The hypothalamus releases corticotrophin-releasing hormone (CRH) and arginine vasopressin (AVP), prompting the pituitary gland to produce the adrenocorticotrophic hormone (ACTH). In turn, ACTH stimulates the adrenal cortex to release cortisol. Cortisol then inhibits the hippocampus, hypothalamus, and pituitary, regulating HPA axis activity through a negative feedback loop (Leistner & Menke, 2020; Spiga et al., 2014). In the first year of life, the HPA axis undergoes the development of a circadian rhythm,

characterized by a 24-hour cycle of cortisol production, with a peak in the morning and a gradual decrease throughout the day (de Weerth et al., 2003; Gröschl et al., 2003). Aside from this development of the circadian rhythm, already from birth onwards, cortisol is produced when infants are exposed to stressful situations (Jansen et al., 2010). This cortisol stress response is an adaptive response that mobilizes energy to aid the individual when reacting to stressors (Dickerson & Kemeny, 2004; Leistner & Menke, 2020). In a research setting, the human cortisol production is measured in a non-invasive and cost-efficient manner through the saliva. In saliva, the response to a stressor is reflected approximately 25 minutes after a stressor occurred (Dickerson & Kemeny, 2004; Jansen et al., 2010). After the stressor, the system usually recovers and cortisol concentrations decrease back to post-stressor concentrations.

Although this cortisol production is a healthy biological response to stressful situations, being confronted with too many stressors and not recovering well after each stressor may, over time, negatively impact the functioning of the HPA axis (Fogelman & Canli, 2018; Loman & Gunnar, 2010; Radley et al., 2015). Accordingly, adverse childhood experiences, such as childhood maltreatment, insensitive parenting, or social deprivation in the form of institutionalized care, are associated with a dysregulated HPA axis (Isenhour et al., 2021; Marques-Feixa et al., 2023; Murphy et al., 2022; Tarullo & Gunnar, 2006). HPA axis dysregulation, in turn, has been related to poorer physical health outcomes, including obesity, cardiovascular diseases and cancer, as well as to poorer mental health outcomes, including depression, anxiety, and increased suicide risks (Adam et al., 2017; Berardelli et al., 2020; O'Connor et al., 2020; Zajkowska et al., 2022). In young infants, parents play an important role in shielding their infants from experiencing too many stressors and in fostering recovery from stress (Hostinar et al., 2014; Kiel et al., 2024). This down-regulation from distress through the parents is crucial for young infants' development of HPA axis regulation (Hostinar et al., 2014; Loman & Gunnar, 2010). Research on factors of early caregiving that benefit the development of HPA axis regulation is therefore promising.

Closely related to the circadian rhythm and regulation is **sleep**. In early development, sleep plays a major role, such as in supporting brain development, improving memory and learning, the immune system, physical growth, and hormonal production (Beebe, 2011; Irwin & Opp, 2017; Poluektov, 2021; Vriend et al., 2015). Young infants highly rely on their caregiving

environment to regulate their sleep-wake cycle (Barry, 2021; Bathory & Tomopoulos, 2017). With increasing age, infants' sleep becomes more independent. The sleep pattern transitions from a biphasic pattern with several daily sleep and wake phases to a monophasic pattern with the majority of sleep taking place overnight (Bathory & Tomopoulos, 2017; Iglowstein et al., 2003). Roughly one-third of children and adolescents, however, are affected by sleeping problems, such as increased night waking, sleep onset delay, or short sleep durations (Carter et al., 2014; Chen et al., 2021; Cook et al., 2019; Tsao et al., 2021). Sleeping problems during childhood are burdening for children and their parents, and can negatively affect family dynamics, as well as children's and parents' physical and mental health (Bhati & Richards, 2015; Coles et al., 2022; El-Sheikh & Kelly, 2017; Lam & Lam, 2021; Matricciani et al., 2019; Miller et al., 2015; Shimizu et al., 2021; Zhou et al., 2015). Although literature commonly assumes that the emergence of sleeping problems is routed in early childhood, there is currently a lack of longitudinal research documenting this development from infancy through adolescence (Reynolds et al., 2023). Additionally, there is a lack of attention among pediatricians toward sleeping problems during well-child visits (Bathory & Tomopoulos, 2017). Research documenting the emergence and persistence of sleeping problems from early childhood into adolescence can raise awareness towards the importance of sleep development, and normative data can help to pinpoint when interventions are required (Bathory & Tomopoulos, 2017).

In close relation to physiological regulation, infants develop the ability to regulate **behavior**. Postnatally, infants heavily rely on their caregivers to regulate their emotional states, such as crying in response to daily stressors (Hofer, 1987; Norholt, 2020). With increasing age, children become more autonomous and are challenged with further demands to regulate behavioral functions, for instance during social interactions (Beeghly et al., 2016). Consequentially, toddlerhood is a time when externalizing and internalizing behaviors start to appear (Achenbach et al., 2016). Externalizing behaviors refer to outward-directed behaviors that are disruptive or impulsive, such as not being able to withhold anger towards other people (Achenbach et al., 2016). Internalizing behaviors, on the other hand, are inward-focused, including anxiety, depression, social withdrawal, and somatic issues. Furthermore, children's ability to regulate also impacts their executive functioning, which refers to a number of cognitive processes that enable goal-directed behavior, including attention, planning, working memory, and inhibitory control (Anderson, 2002; Nigg, 2017). Altogether, effective behavioral regulation is

crucial for socio-emotional interactions, future academic success, and overall mental health (Best & Miller, 2010; Hasty et al., 2023; Nigg, 2017).

Early caregiving and predisposing factors covered in this thesis

Before birth, fetal biological systems are coupled with that of their mothers, enabling constant maternal regulation (Ivanov et al., 2009; Reppert & Schwartz, 1983). The two systems are separated at birth, and in the first postnatal months, infants highly depend on external sensory cues (i.e., auditory, visual, olfactory, thermal, and tactile) in their caregiving environment to help them regulate their physiology and behavior, e.g. to down-regulate their stress (Kiel et al., 2024; Norholt, 2020). Parents make use of their behavioral repertoire to help infants to regulate their emotional states and navigate between sleep and wake states (Hofer, 1987; Kiel et al., 2024). Repeated, successful external regulation through parents, in turn, facilitates the development of infants' ability to self-regulate (Feldman, 2007, 2012; Norholt, 2020; Rattaz et al., 2022).

One way that can help parents regulate their infant's physiology and behavior may be to spend time with the infant in outdoor environments (McCormick, 2017; Moll et al., 2022). The Stress Recovery Theory (SRT) hypothesizes that being outdoors, especially in green environments, facilitates stress regulation, as humans have an innate preference for environments composed of more natural visual elements and fewer human-made stressors (i.e., television, less ventilation indoors) (Ulrich et al., 1991). Accordingly, studies found beneficial effects of exposure to outdoor green environments on adult's and older children's stress levels, mood, behavioral and socio-emotional regulation and mental health (Bowler et al., 2010; Burns et al., 2021; Corazon et al., 2019; Gidlow et al., 2016; Jones et al., 2021; Mason et al., 2022; McCormick, 2017; Moll et al., 2022; Scott et al., 2018; Taylor & Butts-Wilmsmeyer, 2020). Notably, previous studies in children have solely focused on the effects of outdoor exposure on children from toddlerhood to adolescence, who spend a large proportion of their outdoor time being physically active (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011). Note that spending time outdoors may directly affect infants, but because of the positive effects of spending time in (green) outdoor environments on adults, spending time outdoors may also indirectly affect infants through the beneficial effects on their parent.

Research in the past decades indicates that there has been a decreasing trend in outdoor time among children, and children nowadays spend less than one daily hour outdoors (Downing et al., 2022; Gao et al., 2022; Guo et al., 2013; Matz et al., 2014). Research in older children indicates that the amount of time children spend outdoors depends on child-specific characteristics, such as age and sex, parental characteristics, including socioeconomic and employment status, as well as the living environment (Aarts et al., 2010; Boxberger & Reimers, 2019; Larouche et al., 2023; Lee et al., 2021; Remmers et al., 2014; Tandon et al., 2012). To date, we know very little about the amount of **time infants spend outdoors**, as well as possible demographic characteristics that might facilitate or hinder outdoor time during infancy. Therefore, in **Chapter 2**, we first assessed frequencies and durations of outdoor walking in mother-infant dyads, as well as infant outdoor sleeping in a stationary cot or pram, and identified associations of these activities with infant, maternal and environmental sample characteristics.

Next to the distal environment, proximity to parents plays a major role in infant regulation (Kiel et al., 2024; Norholt, 2020). The exchange of appropriate, prompt, and reliable biobehavioral cues (e.g., auditory, visual, and thermal) in the first postnatal months facilitates infants' maturation of their ability to regulate autonomously (Feldman, 2012; Kiel et al., 2024). Researchers suggest that, through repeated exchange of regulatory cues, the biological and behavioral processes of caregiver and infant align. The alignment of biological processes is also called biological synchrony - a process suggested to further aid infant regulation (di Lorenzo et al., 2022; Reyna & Pickler, 2009). **Infant carrying** using a sling or chest carrier enhances physical proximity between caregiver and infant, which, in turn, may facilitate the exchange of regulatory cues (Hofer, 1987; Hostinar et al., 2014; Kiel et al., 2024). Accordingly, one study found that parents who carry their infant more often showed improved emotional responses towards infant crying and less insensitive caregiving in parental reports (Firk & Großheinrich, 2024). An experimental study additionally found that infant chest-carrying, compared to positioning the infant face-to-face in a highchair, increased maternal physical interaction and responsiveness to infant vocalizations (Little et al., 2019). Moreover, infant carrying for one daily hour over the course of three months promoted secure infant attachment between adolescent mothers and their infants (Williams & Turner, 2020). To date, no studies have assessed **the effects of being walked in a pram or carried outdoors in a green environment** on physiological and behavioral regulation of infants. In **Chapter 3**, we performed an experimental

study to assess whether being walked outdoors in a green environment, compared to staying indoors, after a naturalistic stressor in the laboratory, would facilitate infant sleep and cortisol recovery, as well as maternal mood, maternal cortisol, and mother-infant adrenocortical synchrony.

While few studies to date have focused on infant carrying, a larger body of research has assessed effects of proximity in the form of **skin-to-skin contact** (SSC) on infant physiological and behavioral regulation. Two studies in healthy full-term born infants showed that repeated SSC in the first postnatal weeks facilitated infants' sleep duration (Cooijmans et al., 2022; El Sehmawy et al., 2023). Furthermore, one study in preterm infants showed that SSC after birth immediately reduces cortisol levels of infants and mothers (Cong et al., 2015). SSC in the first postnatal weeks was also related to reduced cortisol responses to a stressor in three-month-old full-term infants (Hardin et al., 2020) and at one month corrected age in preterm infants (Mörelus et al., 2015). The study in preterm infants also found increased attunement between mothers' and infants' cortisol concentrations in the SSC group at four-months-old, which might indicate increased adrenocortical synchrony (Mörelus et al., 2015). Previous studies on the beneficial effects of SSC on cortisol regulation were largely focused on infants born preterm. In **Chapter 4** of this thesis we used a randomized-controlled trial comparing full-term infants receiving one hour of daily SSC in the first postnatal month to infants with care-as-usual (CAU). We assessed whether infants in the SSC group would show decreased cortisol reactions and improved behavioral reactions (i.e., higher responsivity and involvement, lower negative mood) during a laboratory stressor at age five weeks. Furthermore, we assessed effects on mother-infant adrenocortical synchrony, as well as the quality of the maternal caregiving behavior (i.e., sensitivity, cooperation, positive and negative regard). To date, there is also a lack of randomized-controlled trials assessing effects of SSC with children born full-term on behavioral outcomes beyond infancy. Studies following up preterm infants and infants with low birthweight who received repeated SSC found lasting effects on behavioral regulation later in childhood, including improved executive functioning (Charpak et al., 2017; Feldman et al., 2014; Ropars et al., 2018), fewer externalizing problems (e.g., hyperactivity, aggressiveness) (Charpak et al., 2017) and improved reciprocity during conversations (Feldman et al., 2014). Also, one longitudinal study on SSC with infants born full-term reported enhanced engagement and reciprocity during a mother-child conversation on emotional memories at age nine (Bigelow & Power, 2020). In **Chapter 5** of this thesis, making use of the same randomized

controlled trial as in Chapter 4, we assessed whether children who had received SSC as compared to CAU showed fewer behavioral problems (i.e. externalizing and internalizing) and improved executive functioning at age three years.

Importantly, the development of regulation depends on **predisposing factors** within the infant or in the infants' early environment. For instance, studies report associations of poor prenatal maternal mental health, such as increased stress and anxiety, with compromised offspring behavioral regulation (Graignic-Philippe et al., 2014; van den Bergh et al., 2020). However, prenatal psychosocial stress might not only heighten the risk for regulatory problems in offspring later in life, but also enhance offspring's plasticity, rendering them more responsive to early postnatal interventions (Beijers et al., 2020; Graignic-Philippe et al., 2014). Therefore, in **Chapter 5** of this thesis, we additionally explored whether infants of mothers who experienced more **prenatal stress and anxiety** benefitted more from the SSC intervention in terms of behavioral and cognitive development.

Another factor that might predispose infants to develop regulatory difficulties later in life might be **infant colic**. During infancy, colic may be considered an early manifestation of child regulatory difficulties as it is characterized by high levels of unsoothable crying and trouble sleeping (Helseth et al., 2022; Weissbluth et al., 1984). Infants are considered to have colic when they cry excessively, starting at around two weeks and peaking around six weeks postpartum (de Weerth et al., 2013; Savino, 2007; Zeevenhooven et al., 2018). Underlying causes of colic have been suggested to be inflammation, allergies, an immature nervous system, and gastrointestinal malfunctioning (Cirgin Ellett, 2003; de Weerth et al., 2013; Pärtty et al., 2017; Zeevenhooven et al., 2018). Although colic resolves around the age of three months without intervention, the condition has been suggested to be a precursor of regulatory difficulties later in life (Brett et al., 2024; Canivet et al., 2000; Galling et al., 2023; Indrio et al., 2023; Zeevenhooven et al., 2022). Existing research on the associations of infant colic with sleep development, however, is conflicting, as some studies found an association of infant colic with parental reports of increased sleeping problems and sleep disorders, reduced sleep duration, and increased night waking in children up to 10 years of age (Helseth et al., 2022; Savino et al., 2005; Ståhlberg, 1984), while other studies found no such associations (Bell et al., 2018; Canivet et al., 2000; Lehtonen et al., 1994). No studies to date have assessed associations of infant colic with sleeping

problems beyond the age of 10. In **Chapter 6** of this thesis, we assessed the association of infant colic at six weeks of age with sleeping problems from childhood through adolescence. In addition, studies suggest that parent-infant **room sharing**, as compared to solitary sleeping, might facilitate prompt and reliable regulation by parents throughout the night and, in turn, benefit the development of infants' self-regulation (Barry, 2019; Beijers & Cassidy, 2019; Tollenaar et al., 2012). We therefore also assessed whether the potential association of infant colic with increased sleeping problems might be buffered by more weeks of parent-infant room sharing in the first six months of life.

Studies used in this thesis

Outdoor survey

We performed a year-long nationwide online survey for mothers of 0-12-month-old infants in the Netherlands, aiming to assess frequencies and durations of outdoor walking and carrying in mother-infant dyads, and infant outdoor sleeping in a stationary cot or pram. We furthermore aimed to identify associations of outdoor time, with infant, maternal and environmental demographic characteristics. Initially, 1453 mothers were recruited, of which 1275 were included in the analyses. In terms of outdoor walking, collected outcome variables were mother-infant dyads' total weekly duration of walking in minutes, frequency of walking on weekdays as well as on weekends, and the frequency of using an infant carrier during walks, as well as the daily duration of carrying in hours (indoors and outdoors together). Outcome variables on infant outdoor sleeping were putting the infant outdoors to sleep (yes/no), the total weekly duration of outdoor sleeping, and the weekly frequency of outdoor sleeping. Associations of all outcome variables with a large number of infant (e.g., age, sex, health), maternal (e.g., working status, age, health), and environmental (e.g., type of home, recreational areas in walking distance, city size) demographic characteristics were assessed.

GO Baby study

The GO Baby study (*stands for Dutch: **G**ewoontes in de **O**pvoeding van **B**aby's; English: *Caregiving habits in the upbringing of babies*) is a cross-sectional quasi-randomized experimental study on the effects of outdoor pram walking and infant carrying on physiological and behavioral regulatory outcomes. In total, 101 mothers and their 0-5-month-old infants were recruited, of which 99 were included in the analyses. Upon arrival, infants were exposed to a*

mild naturalistic stressor (diaper change and mock bath) and subsequently, mother-infant dyads were randomized to one of four conditions for 30 minutes: walking in an outdoor green environment with the infant in a pram or a chest carrier, or staying indoors with the infant in a pram or a chest carrier. Mothers reported on their infants' total duration of sleeping during the condition in minutes. Maternal mood was self-reported through visual analogue vigor and affect scales before and after the conditions. Five saliva samples were collected from mothers and infants to determine cortisol concentrations following the experimental manipulations.

SKIPPY study

The SKIPPY study is a randomized-controlled trial to assess the efficacy of daily skin-to-skin Contact (SSC) in comparison to standard care across a broad spectrum of outcomes in healthy mothers and their full-term infants (Cooijmans et al., 2017). A total of 116 mother-infant dyads participated from late pregnancy through six years of age. Dyads were randomly assigned to the SSC or the care-as-usual (CAU) condition. Mothers in the SSC condition were instructed to perform at least one daily hour of uninterrupted SSC with their infants from birth until postnatal week five. Mothers in the CAU condition received neither encouragement nor discouragement regarding SSC. The study was initially designed to partially replicate the findings on maternal postnatal depressive symptoms derived from a previous long-term SSC intervention in healthy full-term infants (Bigelow et al., 2012). Consequently, maternal depressive symptoms were the primary outcome. The outcomes included in this thesis were infant cortisol and behavioral reactions, mother-infant adrenocortical synchrony, and the quality of the maternal caregiving behavior, assessed during a bathing session at five weeks postpartum. Furthermore, the current thesis includes an assessment of the long-term effects of SSC on maternal questionnaires regarding child behavioral problems and executive functioning when the child was three years old, as well as the moderation thereof by maternal reports on prenatal stress and anxiety.

BIBO study

The BIBO study (*stands for Dutch: **B**asale **I**nvloeden op de **B**aby **O**ntwikkeling; English: Basal Influences on Baby Development*) is an ongoing and prospective longitudinal cohort study. The study follows 193 healthy mothers and their children from pregnancy onwards (Beijers et al., 2010, 2013). The study primarily aims to assess connections between prenatal and early life environments and children's long-term psychobiological development. For

the outcomes reported in this thesis, data from multiple assessment waves were used, spanning from birth until 16.5 years of age. Specifically, from birth until postnatal month six, mothers filled in a daily diary, which contained an assessment of the infant's sleeping arrangements and night waking. Around infant age six weeks, mothers filled in a four-day diary regarding infants' crying and sleeping, and maternal caregiving behaviors. This diary was used to determine infant colic. Furthermore, children's sleeping problems were assessed with maternal questionnaires at ages 2.5, 6, and 10 years and child questionnaires at ages 12.5, 14, and 16.5 years.

Thesis outline

This thesis presents five empirical research projects in Chapters 2 – 6 (see Figure 2). First, **Chapter 2** assesses the time mothers in the Netherlands spend walking and carrying their infants outdoors, as well as for how much time the infant is put outdoors to sleep in a stationary cot or pram, and which infant, maternal, and environmental characteristics predict these variables, using the 'Outdoor Survey'. **Chapter 3** studies the experimental and cross-sectional effects of being walked outdoors and infant carrying on infant sleep and cortisol recovery, maternal mood and cortisol, and mother-infant adrenocortical synchrony, using the 'GO Baby study'. **Chapter 4** assesses the effects of a skin-to-skin contact intervention (RCT) on full-term infants' cortisol and behavioral reactions, mother-infant adrenocortical synchrony and the quality of the maternal caregiving behavior using the 'SKIPPY study'. Also using the 'SKIPPY study', **Chapter 5** assesses the effects of the skin-to-skin contact intervention (RCT) on full-term infants' behavior and executive functioning at age three, as well as a possible moderation of this effect through maternal prenatal stress and anxiety. Lastly, **Chapter 6** assesses associations of infant colic with sleeping problems from childhood through adolescence, and the moderating role of room sharing using the observational 'BIBO study'. Taken together, **Chapters 2-6** contribute to the overarching aim of the thesis, to assess the role of early caregiving in the development of regulation. Figure 2 displays an overview of the five empirical studies presented in this thesis. Lastly, **Chapter 7** presents a summary of the findings and a general discussion.

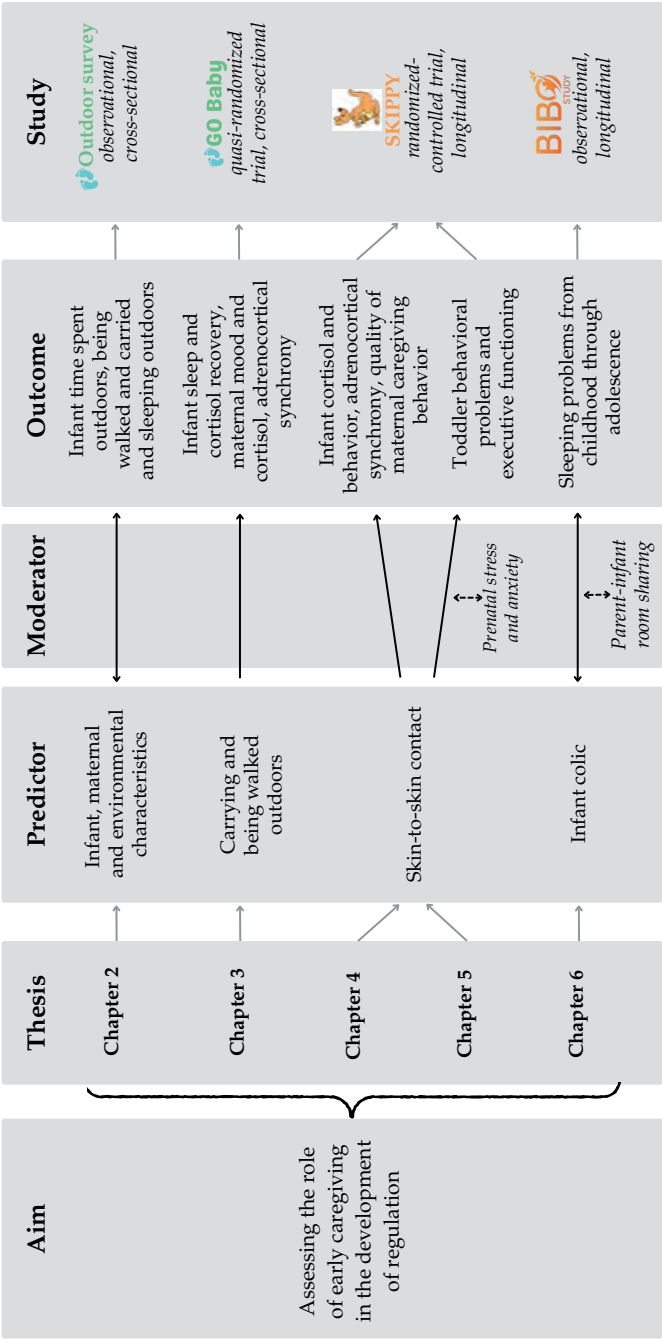


Figure 2. Overview of the research topics per chapter of the thesis. The black arrows indicate the expected direction of the effect. Arrows with two heads indicate that causality is uncertain due to the study design.

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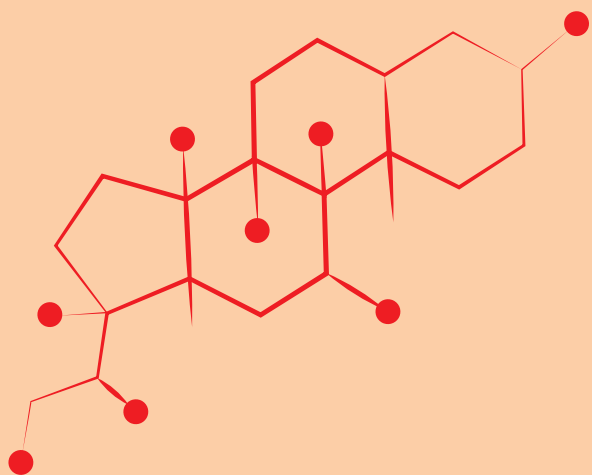
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Chapter 2

Infant care: Predictors of outdoor walking, infant carrying and infant outdoor sleeping

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Abstract

Background: Although spending time outdoors is beneficial for development, little is known about outdoor time during infancy. The aim of this study was to assess frequencies and durations of (1a) outdoor walking and carrying in mother–infant dyads and (1b) infant outdoor sleeping in a stationary cot or pram. We furthermore aimed to identify associations of (2a) outdoor walking and carrying and (2b) infant outdoor sleeping, with infant, maternal and environmental sample characteristics.

Methods: An online survey was distributed among mothers of 0- to 12-month-old infants. Initially, 1453 mothers were recruited, of which 1275 were included in the analyses. With respect to (1a) the outcomes of interest were: mother–infant dyads' total weekly duration of walking in minutes, frequency of walking on weekdays, as well as weekends, and the frequency of using an infant carrier during walks, as well as the daily duration of carrying in hours (indoors and outdoors together). With respect to (1b) the outcome variables were: placing the infant outdoors to sleep (yes/no), the total weekly duration of outdoor sleeping and the weekly frequency of outdoor sleeping. For aim 2, associations of the outcome variables with infant (i.e., age), maternal (i.e., working status) and environmental (i.e., house type) sample characteristics were assessed.

Results: Mother–infant dyads engaged in walks for a total weekly duration of 201 min, for approximately one to three walks over weekdays (Monday through Friday), as well as one to three walks on the weekend. The infant carrier was used by 22% of mothers at least half of the time during outdoor walks, and 18% reported a daily duration of infant carrying of one hour or more. Among other associations, infant and maternal enjoyment of outdoor walking correlated positively with the duration as well as the frequency of walking during weekdays and during the weekend. Furthermore, employed mothers walked for a shorter duration and less frequently on weekdays as compared to mothers on maternity leave or mothers without a paid job. The availability of nearby recreational areas correlated positively with the weekly duration and frequency of walks. The infant carrier was used more frequently during outdoor walks if more than one child lived in the household. Infant carrying during outdoor walks was also related to infant behavior at night. Roughly a third of the mothers (29%) regularly had their infant sleep outdoors for a weekly duration of four hours and a weekly frequency of approximately one to two times. Younger infants, infants of mothers with higher education

and infants living in detached houses were more likely to be placed outdoors to sleep.

Discussion: We identified associations of infant, maternal and environmental characteristics with outdoor time spent during infancy. These results lay the foundation for future research on the effects of the outdoors on child development as well as on facilitators and barriers for caregivers.

Introduction

The first year of life characterizes a sensitive period for a multitude of developmental processes, and factors in the early caregiving environment have been related to longitudinal outcomes of physical and mental health (Brett & de Weerth, 2019; Donald & Finlay, 2023; Loman & Gunnar, 2010; Vaivada et al., 2017). One factor that has been demonstrated to benefit child health and socio-emotional regulation is exposure to the outdoors (Guo et al., 2013; McCormick, 2017; Moll et al., 2022; Schutte et al., 2017; Scott et al., 2022). In the past decades, however, there has been a downward trend in the time children spend outdoors around the globe, and nowadays, children from infancy to early adolescence spend less than 15% of their wake-time outdoors (Downing et al., 2022; Gao et al., 2022; Guo et al., 2013; Matz et al., 2014). Identifying demographic characteristics that might facilitate or hinder outdoor time during infancy can deliver crucial insights for urban planning and caregiving advice, as well as for policies and interventions to facilitate outdoor exposure during infancy. Research on older children indicates that time spent outdoors depends on a number of child-specific characteristics, such as age and sex, parental characteristics, including socio-economic and employment status, as well as the living environment (Boxberger & Reimers, 2019; Chaput et al., 2018; Gao et al., 2022; Larouche et al., 2023; McCormick, 2017).

While studies in older children focus largely on active outdoor play (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011), time spent outdoors during infancy is more passive, as infants need to be taken outdoors by their caregiver, for instance, on a walk using a pram or carrier, or to sleep outdoors in a stationary cot. To date, there is a lack of studies on the frequency and duration of these outdoor activities during infancy and the demographic characteristics that might be associated with these activities. This study aimed to assess frequencies and durations of outdoor walking and carrying in

mother–infant dyads, as well as infant outdoor sleeping in a stationary cot or pram, and to identify associations of these activities with infant, maternal and environmental sample characteristics.

Infancy is a sensitive period of dramatic and rapid developmental processes, involving the immune system, brain development, gut microbiota, thermo-regulation and the stress system (Bach & Libert, 2022; Brett & de Weerth, 2019; Donald & Finlay, 2023; Loman & Gunnar, 2010). During this period, outdoor exposure might be especially beneficial, as research in older children indicates that outdoor exposure is associated with decreased risk for myopia (Guo et al., 2013; He et al., 2015), increased vitamin D levels (Absoud et al., 2011) and improved mental health (Kuo & Faber Taylor, 2004; McCormick, 2017), as well as cognitive and socio-emotional development (Cherrie et al., 2019; Hinkley et al., 2018; Larouche et al., 2016; Schutte et al., 2017; Scott et al., 2022). Furthermore, a study on young adults found positive associations of time spent outdoors in the past 24 hours with mood and gray matter volume in the brain, also after accounting for physical activity, intake of fluids, amount of spare time and the hours of sunshine (Kühn et al., 2022). Accordingly, a study assessing the area surrounding children’s residential address from birth until age 12 found positive associations of the visibility of the sky and the amount of open green space, as well as negative associations of tree cover density, with gray matter volume in areas of the brain at age 12 (Kühn et al., 2023). Another study on the residential environment found that more greenness throughout childhood was positively correlated with both gray and white matter volume at primary school age (Dadvand et al., 2018). Previous studies indicate that especially the amount of outdoor greenspace might play a role in the positive effects of the outdoors on child development. However, to date, the underlying mechanisms of the effect of the outdoors on child development are largely unknown.

Researchers suggest that the outdoors provides children with opportunities to observe, learn about and interact with their surroundings, thereby facilitating brain development (Bowler et al., 2010; Kahn, 1997). Notably, most studies on benefits of the outdoors for child development focused on older children, who spend most of their outdoor time on active play, which may account for the beneficial effects of outdoor exposure, for instance, due to increased physical exercise (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011). During infancy, outdoor time is likely to be more passive, as infants rely on caregivers to take them outdoors, for instance, on a walk using a pram. While potential

benefits of outdoor walking for infants have not been studied, pram walking has been shown to decrease postnatal depression in mothers (Armstrong & Edwards, 2004).

Furthermore, infants highly depend on proximity and responsive interactions with their caregivers (Bigelow & Williams, 2020; Feldman, 2007; Little et al., 2019; Norholt, 2020). A mode of transporting the infant in close proximity during a walk is infant carrying, by wearing a carrier or sling on the chest or on the back. Developmentalists suggest that increased proximity through infant carrying fosters an exchange of sensory cues and increases maternal responsiveness to infant vocalizations, which, in turn, is suggested to facilitate the development of stress regulation capacities (Bigelow & Williams, 2020; Feldman, 2007; Little et al., 2019; Norholt, 2020). While the benefits of infant carrying in the outdoors have not been studied to date, there is evidence of a calming effect of being carried on the cardiovascular stress response in a laboratory setting (Esposito et al., 2013), and regular infant carrying has been associated with improved mother–infant bonding (Bigelow & Williams, 2020; Williams & Turner, 2020). Furthermore, especially in Scandinavian countries, from the age of two weeks, infants are frequently placed outdoors to sleep in a stationary cot or pram in a garden or on a terrace or balcony, and this has been related to increased sleep durations (Tourula et al., 2010). While infant outdoor sleeping has been reported to be common in Scandinavia, and is also regarded as safe in cold winters (Tourula et al., 2008), no studies to date have assessed this practice in other, more temperate climate regions of Europe, and hence the prevalence is unknown to date.

Considering the potential benefits of outdoor exposure for child development, promoting outdoor activities during infancy is a promising avenue for intervention. In order to promote healthy behavior in society, the behavioral epidemiology framework states that it is crucial to first identify demographic characteristics predicting the behavior (Sallis et al., 2000). To date, there is a lack of studies on how much time infants spend on outdoor activities, such as being walked or sleeping outdoors. One study found that the greatest barrier for mothers to walk outdoors with a pram were undesirable weather conditions, neighborhood walkability, as well as a lack of time, however, this study was restricted to maternal opinions regarding postnatal exercise in the outdoors (Currie & Develin, 2002).

While there is a lack of research on outdoor activities during infancy, a large number of studies have identified child-specific, parental and environmental characteristics predicting outdoor time in older children (Boxberger & Reimers, 2019; Larouche et al., 2023; Lee et al., 2021). For instance, studies report less outdoor time in girls, in children of older age, and in children of mothers who are employed and have a higher education level (Aarts et al., 2010; Lee et al., 2021; Remmers et al., 2014; Tandon et al., 2012). Children spend more time outdoors when living in detached houses, when the neighborhood is more rural or is perceived as more safe and when there are more recreational areas around, such as parks and playgrounds (Aarts et al., 2010; Lambert et al., 2019; Matz et al., 2014, 2015; Xu et al., 2017). Furthermore, less outdoor time was reported in colder seasons (Matz et al., 2014; Nguyen et al., 2021), and especially in the past years, the COVID-19 pandemic has imposed temporary restrictions on children's time outdoors (Kanclerz et al., 2023; Liu et al., 2023).

The aim of this study was to assess (1a) the frequency and duration of outdoor walking and carrying in mother-infant dyads and (1b) the frequency and duration of infant outdoor sleeping in a stationary cot or pram in the garden or on the balcony or terrace. Aim (2) was to identify associations of (2a) outdoor walking and carrying and (2b) infant outdoor sleeping with several factors. These factors included infant characteristics: age, sex, gestational age at birth, preterm birth, having health issues, infant behavior at night and whether the infant enjoyed being walked outdoors; maternal characteristics: age, education level, employment status, working hours, having mental or physiological health issues and whether the mother enjoyed walking outdoors with the infant; and environmental characteristics: city size, availability of nearby recreational areas, housing type, number of children and adults in the household and season. The study was based on data obtained with an online survey among mothers of infants in the Netherlands.

Methods

Recruitment and participants

The ethics committee of the Faculty of Social Sciences of the Radboud University Nijmegen reviewed the study and did not have formal objections (SW2017-1303-497). The study was in accordance with the Declaration of Helsinki and preregistered (https://aspredicted.org/NTC_MJQ, accessed on 19 April, 2023). Recruitment was performed in the Dutch language and took

place online between April 2022 and April 2023 through social media, using paid ads on Instagram and Facebook (targeting mothers residing in the Netherlands), printed flyers at the Baby and Child Research Center Nijmegen (BRC) and a participant database of the BRC including mothers in the Netherlands interested in research participation. Although participation from outside of the Netherlands was not ruled out, given the recruitment strategies, it is likely that the majority of mothers resided in the Netherlands during participation. Inclusion criteria were: Dutch fluency, maternal age >18 years, infant age <53 weeks and the infant not being a twin.

In line with the exploratory and descriptive nature of this study, determining a maximum sample size was not of interest and, therefore, a priori power calculations were not required (Haile, 2023). The sample size depended on the budget available for recruitment and on recruitment continuing for a year to cover all seasons. In total, 1453 participants were recruited. From these, 176 participants were excluded, as they did not complete the survey until the first outcome variable 'frequency of walking on weekdays' (<49% of all items), and two were excluded due to providing illogical answers. Binomial logistic regressions indicated that excluded ($N = 176$) and included ($N = 1275$) participants did not differ in maternal and infant age, maternal education or whether infant or maternal health issues were reported ($p > 0.48$).

Procedure

Mothers provided informed consent and filled in an online survey (46 items; average duration of nine minutes). After survey completion, mothers could indicate whether they would like to participate in a draw to win a gift voucher worth 50 Euro with a chance of one in 50. The draw was performed by creating one random number for every 50 participants using the 'runif' function in R (R Core Team, 2021) and a total of 21 gift vouchers were distributed.

Measures

Due to a lack of existing tools and literature on outdoor time of mothers and infants, the survey was developed by the authors through repeated research group meetings and piloted among colleagues with infants. The complete survey can be found in the Supplementary materials (A). Table 1 provides a descriptive summary of all study variables.

Table 1. Descriptive statistics

Outdoor Walking and Carrying	M (SD; Range) or N (%)	Mis.
Weekly duration of outdoor walking in minutes ^a	201.28 (SD = 170; 0–1600)	46
Frequency of outdoor walking on weekdays (Monday to Friday) ^b		n/a
• (Almost) never	69 (5.41%)	
• 1–3	548 (42.98%)	
• 4–6	472 (37.02%)	
• 7–9	137 (10.75%)	
• ≥10	49 (3.84%)	
Frequency of outdoor walking on weekends (Saturday to Sunday) ^b		4
• (Almost) never	60 (4.72%)	
• 1–3	1019 (80.17%)	
• 4–6	163 (12.82%)	
• 7–9	21 (1.65%)	
• ≥10	8 (0.63%)	
Frequency of carrying the infant during outdoor walks ^b		42
• (Almost) never	498 (40.39%)	
• Sometimes	464 (37.63%)	
• Half of the time	157 (12.73%)	
• Most of the time	84 (6.81%)	
• Always	30 (2.43%)	
Daily duration of infant carrying in hours (indoors + outdoors) ^b		102
• (Almost) never	468 (39.90%)	
• <1 h	496 (42.28%)	
• 1–2 h	147 (12.53%)	
• 3–4 h	45 (3.84%)	
• 5–6 h	14 (1.19%)	
• ≥7 h	3 (0.26%)	
Satisfaction with the amount of walking ^{c,e}		71
• Satisfied	602 (50.00%)	
• Would like to walk more	598 (49.67%)	
• Would like to walk less	4 (0.33%)	
Subjective reasons for walking ^{d,e}		48
• Reaching a destination	1026 (83.62%)	
• Leisure	1012 (82.48%)	
• Maternal health	712 (58.03%)	
• Facilitating infant sleep/soothing	337 (27.47%)	
• Walking a dog	206 (16.79%)	

Table 1. Continued

Outdoor Walking and Carrying	M (SD; Range) or N (%)	Mis.
Subjective reasons against walking ^{d,e}		72
• Weather	951 (79.05%)	
• Lack of time (e.g., due to work)	535 (44.47%)	
• Easier to go by car	280 (23.28%)	
• Maternal health issues	258 (21.45%)	
• Not feeling like it	248 (20.62%)	
• Infant health issues	132 (10.97%)	
• No good walking environment	127 (10.56%)	
• Too much traffic	30 (2.49%)	
Infant outdoor sleeping		
Placing infant outdoors to sleep (yes) ^c	343 (29.42%)	109
Weekly duration of outdoor sleeping in hours ^{a,f}	4.31 (SD = 5.27; 0–39)	24
Weekly frequency of outdoor sleeping ^{b,f}		1
• <1	117 (34.21%)	
• 1–2	148 (43.27%)	
• 3–4	55 (16.08%)	
• 5–6	14 (4.09%)	
• ≥7	8 (2.34%)	
Infant characteristics		
Age in weeks ^a	23.57 (SD = 13.87; 0–52)	n/a
Sex (girl) ^c	630 (49.41%)	n/a
Gestational age at birth in weeks ^a	39.27 (SD = 1.79; 28–42)	2
Preterm (<37 weeks) ^c	77 (6.05%)	2
One or more health issues (yes) ^{c,g}	105 (8.24%)	n/a
Infant behavior at night ^b		94
• Almost never needs attention/falls asleep easily/almost never wakes up	341 (26.75%)	
• Needs attention very occasionally/wakes very occasionally	396 (33.53%)	
• Needs regular attention/sometimes wakes	334 (28.28%)	
• Needs a lot of attention/has difficulty falling asleep/wakes up often	110 (9.31%)	
Infant's enjoyment of being walked ^a	83.85 (SD = 15.95; 1–100)	66
Maternal characteristics		
Age in years ^a	31.44 (SD = 4.31; 18–50)	n/a
One or more mental health issues (yes) ^{c,g}	120 (9.41%)	n/a
One or more physical health issues (yes) ^{c,g}	229 (17.96%)	n/a

Table 1. Continued

Maternal characteristics	M (SD; Range) or N (%)	Mis.
Education level ^c		n/a
• Lower	356 (27.92%)	
• Higher	919 (72.08%)	
Employment status ^c		n/a
• Working	774 (60.71%)	
• Maternity leave	370 (29.02%)	
• No paid job	131 (10.27%)	
Weekly working hours (in employed mothers, N = 774) ^b		n/a
• 0–8	19 (2.45%)	
• 9–16	28 (3.62%)	
• 17–24	184 (23.77%)	
• 25–32	368 (47.55%)	
• 33–40	168 (21.71%)	
• >40	7 (0.90%)	
Maternal enjoyment of walking with infant ^a	84.60 (SD = 15.42; 1–100)	63
Environmental characteristics		
More than one child in household (yes) ^c	399 (31.29%)	n/a
More than one adult in household (yes) ^c	1221 (95.76%)	n/a
City size (number of citizens) ^b		n/a
• ≤5000	395 (30.98%)	
• ≤20.000	279 (21.88%)	
• ≤100.000	293 (22.98%)	
• >100.000	308 (24.16%)	
Types of recreational areas nearby ^{d,e}		n/a
• City park	625 (49.02%)	
• Green square	631 (49.49%)	
• Forest	595 (46.67%)	
• National park or nature reserve	88 (6.90%)	
• Other	100 (7.84%)	
• None	32 (2.51%)	
Sum of types of recreational areas nearby ^a	1.60 (SD = 0.98; 0–4)	n/a
House ^c		n/a
• Detached	157 (12.31%)	
• Semidetached	256 (20.08%)	
• Terraced	685 (53.73%)	
• Apartment	172 (13.49%)	
• Other	5 (0.39%)	

Table 1. Continued

Environmental characteristics	M (SD; Range) or N (%)	Mis.
Season during participation ^c		n/a
• Spring (March–May)	298 (23.37%)	
• Summer (June–August)	278 (21.80%)	
• Fall (September–November)	399 (31.29%)	
• Winter (December–February)	300 (23.53%)	

Note. *n/a*, No missing data; *Mis.*, Missing; *M*, Mean; *SD*, Standard deviation. ^a Continuous, ^b Ordinal, ^c Categorical, ^d List, ^e Not used in further analyses, ^f Includes only infants who were reported to sleep outdoors in the previous item (*N* = 343), ^g If ‘yes’ was selected, mothers were asked to provide a description of the health issues (not used in further analyses).

Outdoor walking and carrying

Mothers were asked the following questions on outdoor walking with their infant: their total weekly duration of walking in minutes with their infant and the frequency of walking with the infant on weekdays (Monday through Friday), as well as on the weekend (Saturday and Sunday), by counting all walks with a duration of at least 15 consecutive minutes. Mothers were additionally asked whether they were satisfied with the amount of walking with the infant and which subjective reasons for and against walking applied to them. Infant carrying was assessed with the following variables: the frequency of the mother using an infant carrier during outdoor walks, as well as the total daily duration of the mother carrying the infant, regardless of whether it was indoors or outdoors.

Infant outdoor sleeping

Outdoor sleeping was defined as the infant being placed outdoors in a stationary cot or pram (i.e., garden, terrace or balcony) for a nap. We did not distinguish between outdoor sleeping at home or elsewhere (e.g., at daycare) or whether it was performed by the mother or another caregiver. Outdoor sleeping was assessed with the following variables: whether the infant was placed outdoors to sleep at all (yes/no), and if the answer was ‘yes’, the total weekly duration and the weekly frequency of outdoor sleeping.

Infant, maternal and environmental sample characteristics

The following infant characteristics were collected: age in weeks, sex, gestational age at birth in weeks, preterm birth (<37 gestational weeks), having one or more health issues, infant behavior at night (how much attention the infant needs at night, how much difficulty the infant has falling asleep

and how often the infant wakes up at night) and whether the infant enjoyed being walked outdoors. Maternal characteristics collected were: age in years, education level, employment status, weekly working hours, having one or more mental health issues, having physiological health issues and whether the mother enjoyed walking outdoors with the infant. Environmental characteristics collected were: city size, sum of different types of recreational areas nearby (in walking distance), housing type, having more than one child in the household, having more than one adult in the household and the season during participation.

Analytical plan

Statistical analyses were performed in R (R Core Team, 2021) using the following packages: ggplot2 (Wickham, 2016), ggstatsplot (Patil, 2021), rcompanion (Mangiafico, 2024), car (Fox & Weisberg, 2019), aod (Lesnoff & Lancelot, 2012), Boruta (Kursa & Rudnicki, 2010), psych (Revelle, 2024), stats (R Core Team, 2021) and rstatix (Kassambara, 2023).

Preliminary analyses

The data were visually inspected and cleaned. Errors that were clearly mistakes and typos (e.g., unrealistic gestational age at birth) were replaced with missing values. Outliers on continuous outcome variables (scores greater than three times the standard deviation above or below the mean) were winsorized (Tukey, 1977). Skewed continuous outcome variables were square root transformed for the main analyses. Missing data were not imputed.

Main analyses

Aim 1: Assessing the frequency and duration of outdoor walking and carrying in mother–infant dyads, as well as of infant outdoor sleeping

For aims (1a) and (1b), we calculated descriptive statistics. For continuous outcome variables, means, standard deviations and ranges were computed. Categorical and ordinal variables were summarized by computing frequencies and percentages per response category.

Aim 2: Identifying associations of outdoor walking and carrying, as well as infant outdoor sleeping, with infant, maternal and environmental characteristics

If both the predictor and the outcome variable were continuous and normally distributed, Pearson correlations were performed, and if one of the two

variables was ordinal or non-normally distributed, Spearman correlations were used. Differences for a categorical predictor on a continuous outcome variable were assessed using Student's t-tests for normally distributed data and Mann-Whitney U tests for non-normally distributed data. More than two groups were compared using analyses of variance for normally distributed data and Kruskal-Wallis tests for non-normally distributed data. If both the predictor and the outcome variable were categorical, chi-square tests were used, and associations of continuous predictors with categorical outcome variables were assessed using binomial logistic regressions. The corresponding tables in the Results section display which statistical test was performed per analysis. Statistical significance was based on p-values. As we performed separate analyses for a large number of predictors ($N = 154$), the significance level was corrected for multiple testing through the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995) using a false discovery rate of 10%.

Additionally, for our main variables of interest, we used the Boruta algorithm in an exploratory manner (Kursa & Rudnicki, 2010) to assess the importance of all infant, maternal and environmental characteristics in predicting the following outcome variables: total weekly duration of walking, frequency of using an infant carrier during outdoor walks and whether the infant is placed outdoors to sleep at all (yes/no). Boruta is a powerful feature selection algorithm, offering a comprehensive overview of all variables relevant in predicting a response variable, regardless of multicollinearity and non-linear relationships between variables, and hence has the potential to deliver informative insights for future research (Degenhardt et al., 2019). As such, this Boruta algorithm complemented our preregistered analyses aimed at discovering factors associated with outdoor activities with the infant. As a wrapper around a random forest algorithm, Boruta creates importance scores for each variable and compares these scores to that of randomly permuted so-called 'shadow' variables. Variables receiving an importance score significantly higher than all shadow variables are labeled 'important', while items receiving significantly lower importance scores are labeled 'unimportant'. The algorithm stops when all variables are labeled or when a maximum of 20,000 predefined iterations has been reached.

Results

Preliminary analyses

The following unrealistic values were replaced with missing values: gestational age at birth below 22 weeks ($N = 2$), as live births before week 22 are rare, and total weekly duration of outdoor sleeping of more than 42 h ($N = 21$), as infants commonly nap for up to six hours during daytime (Sadeh et al., 2009). The following outliers (scores greater than three times the standard deviation above or below the mean) were winsorized (Tukey, 1977): total weekly duration of walking ($N = 24$) and total weekly duration of outdoor sleeping ($N = 8$). The variable 'total weekly duration of outdoor walking' was negatively skewed and hence square root transformed so that normality was achieved.

Main analyses

Aim 1: Assessing the frequency and duration of outdoor walking and carrying in mother–infant dyads, as well as of infant outdoor sleeping

Overall, mothers reported walking outdoors with the infant for approximately 201 min weekly ($SD = 170$). On average, mothers reported walking outdoors with their infant between one to three times throughout the week (Monday to Friday) and one to three times on the weekend (Saturday and Sunday). When walking outdoors, 22% of mothers used an infant carrier half of the time or more. Overall, 29% of infants were placed outdoors to sleep, for a mean of 4.31 h a week ($SD = 5.27$), and approximately one to two times a week. Table 1 displays the descriptive statistics for the outdoor variables, as well as for the infant, maternal and environmental characteristics.

Aim 2: Identifying associations of outdoor walking and carrying, as well as of infant outdoor sleeping, with infant, maternal and environmental characteristics

All significant results on the associations of the sample characteristics with the outcome variables after the Benjamini–Hochberg correction for multiple testing are summarized in the following sections. A complete overview of the Benjamini–Hochberg corrections can be found in the Supplementary materials (B).

Outdoor walking and carrying

All results of the analyses on the associations between infant, maternal and environmental characteristics and the outcome variables are reported in Table 2.

Infant characteristics. For infants with a greater enjoyment of being walked, we found a longer weekly duration of walking (correlation coefficient $r(\text{degrees of freedom} = 1207) = 0.22, p = 0.000, 95\%CI [0.16, 0.27]$), as well as a higher frequency of walking on weekdays ($r(1207) = 0.18, p = 0.000, 95\%CI [0.13, 0.24]$) and on weekends ($r(1207) = 0.22, p = 0.000, 95\%CI [0.16, 0.27]$). For younger infants, we found a higher frequency of walking on weekdays ($r(1273) = -0.08, p = 0.004, 95\%CI [-0.13, -0.02]$). We found a longer weekly duration of walking ($t(1225) = -2.30, d = 0.23, p = 0.022, 95\%CI [-2.77, -0.22]$) in preterm infants ($M_{\text{minutes}} = 236.13, SD = 156.42$) as compared to infants born full-term ($M_{\text{minutes}} = 194.96, SD = 154.08$). A lower gestational age at birth was associated with a higher frequency of walking on weekdays ($r(1271) = -0.07, p = 0.018, 95\%CI [-0.12, -0.01]$). We found a positive correlation of infant behavior at night with the daily duration of carrying ($r(1171) = 0.20, p = 0.000, 95\%CI [0.14, 0.25]$), as well as with the frequency of using the infant carrier during outdoor walks ($r(1179) = 0.16, p = 0.000, 95\%CI [0.10, 0.22]$). For younger infants, we also found a longer daily duration of carrying ($r(1171) = -0.14, p = 0.000, 95\%CI [-0.19, -0.08]$).

Maternal characteristics. Greater maternal enjoyment of outdoor walks was related to a longer weekly duration of walking ($r(1210) = 0.24, p = 0.000, 95\%CI [0.18, 0.29]$), as well as higher frequencies of walking on weekdays ($r(1210) = 0.20, p = 0.000, 95\%CI [0.14, 0.25]$) and on weekends ($r(1210) = 0.23, p = 0.000, 95\%CI [0.18, 0.29]$). There was also a difference for maternal education in the frequency of walking on weekdays ($U = 188,846, N = 1275, r = 0.13, p = 0.000$) and on weekends ($U = 174,236, N = 1271, r = 0.08, p = 0.004$). Higher-educated mothers reported walking approximately 'one to three times' ($Mdn = 1, M = 1.57$) with their infant on weekdays, while lower-educated mothers reported walking 'four to six times' ($Mdn = 2, M = 1.83$). Likewise, on weekends, higher-educated mothers ($Mdn = 1$, stands for 'one to three times', $M = 1.10$) reported a slightly lower frequency of walking than lower-educated mothers ($Mdn = 1, M = 1.22$). We found a shorter weekly duration of walking ($F(1227) = 8.34, \eta^2 = 0.01, p = 0.004$) in employed mothers ($M_{\text{minutes}} = 184.18, SD = 142.10$) as compared to mothers on maternity leave ($M_{\text{minutes}} = 216.64, SD = 165.89$) or mothers without a paid job ($M_{\text{minutes}} = 224.93$,

$SD = 186.19$). There was also a difference for employment status in the frequency of walking on weekdays ($\chi^2(2, N = 1275) = 17.54, \eta^2 = 0.01, p=0.000$). Employed mothers walked approximately 'one to three times' ($Mdn=1, M = 1.57$), while mothers on maternity leave ($Mdn = 2, M = 1.74$) and mothers without a paid job ($Mdn = 2, M = 1.86$) walked approximately 'four to six times' on weekdays. The association of employment status with weekly walking duration as well as walking frequency on weekdays is illustrated in Figure 1.

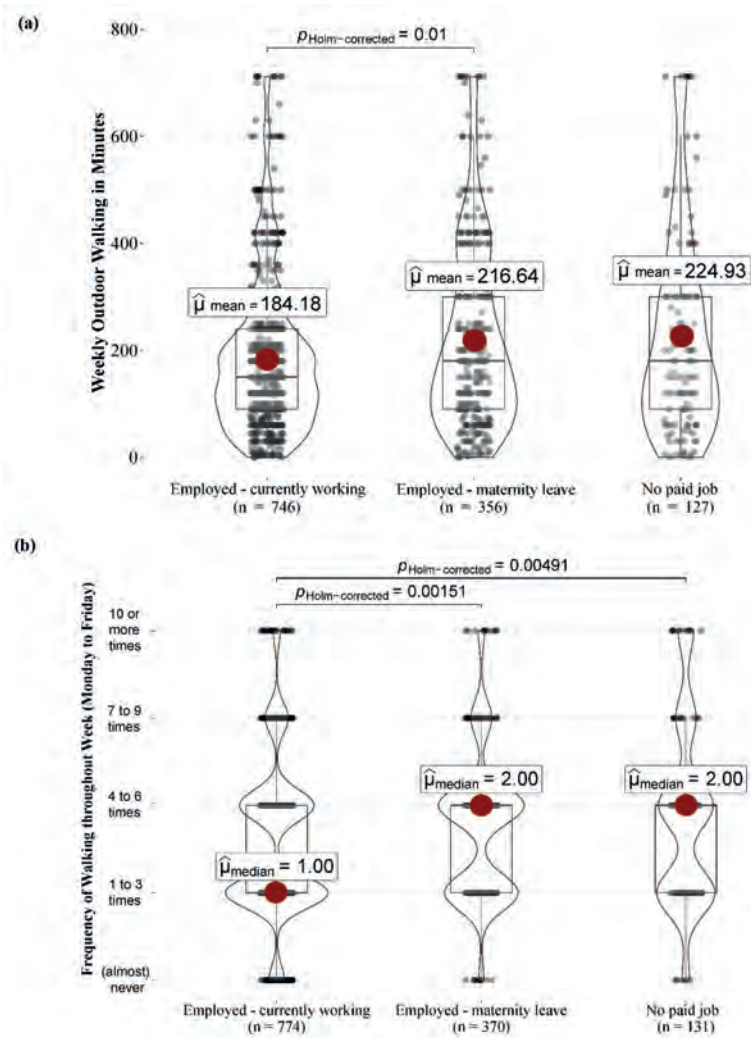


Figure 1. Violin plots on the association of employment status with (a) weekly duration of outdoor walking in minutes and (b) frequency of outdoor walking on weekdays (Monday to Friday). The width of the violin shape represents the distribution of the data, with a larger width indicating a higher frequency of scores. The red dot indicates the group mean (a) or median (b).

There was a difference in the daily duration of carrying for employment status ($\chi^2(2, N = 1173) = 20.90, \eta^2 = 0.02, p = 0.000$). Employed mothers ($Mdn = 1$, stands for 'less than one hour daily', $M = 0.74$) showed a slightly shorter daily duration of carrying than mothers on maternity leave ($Mdn = 1, M = 0.98$) and mothers without a paid job ($Mdn = 1, M = 1.13$). Higher-educated mothers ($Mdn = 1, M = 0.88$) carried the infant for a slightly longer daily duration ($U = 125,063, N = 1173, r = 0.03, p = 0.015$) compared to lower-educated mothers ($Mdn = 1, M = 0.78$). Higher-educated mothers ($Mdn = 1$, stands for 'sometimes', $M = 0.96$) also carried slightly more frequently during outdoor walks ($U = 140,097, N = 1233, r = 0.07, p = 0.022$) compared to lower-educated mothers ($Mdn = 1, M = 0.85$). A higher frequency of carrying during outdoor walks ($U = 55,673, N = 1233, r = 0.00, p = 0.005$) was reported by mothers with one or more mental health issues ($Mdn = 1, M = 1.15$) as compared to mothers without ($Mdn = 1, M = 0.91$). Mothers with one or more mental health issues ($Mdn = 1, M = 1.03$) also showed a slightly longer daily duration of carrying ($U = 53,318, N = 1173, r = 0.06, p = 0.027$) compared to mothers with no mental health issues ($Mdn = 1, M = 0.83$).

Environmental characteristics. For mother-infant dyads with more different types of recreational areas nearby, we found a longer weekly duration of walking ($r(1227) = 0.10, p = 0.000, 95\%CI [0.05, 0.16]$) and a higher frequency of walking on weekdays ($r(1273) = 0.07, p = 0.020, 95\%CI [0.01, 0.12]$) and on weekends ($r(1269) = 0.08, p = 0.007, 95\%CI [0.02, 0.13]$). There was a small difference in the weekly duration of walking for housing type ($F(1222) = 5.18, \eta^2 = 0.004, p = 0.023$). Mother-infant dyads engaged in walking for 188 min ($SD = 162$) living in detached houses, 180 min ($SD = 133$) in semidetached houses, 201 min ($SD = 158$) in terraced houses and 221 min ($SD = 164$) in apartments. We also found a difference for housing type in the frequency of walking on weekdays ($\chi^2(4, N = 1275) = 16.45, \eta^2 = 0.01, p = 0.002$). Mother-infant dyads living in detached houses walked approximately 'one to three times' ($Mdn = 1, M = 1.41$), and those in semidetached ($Mdn = 2, M = 1.66$) and terraced houses ($Mdn = 2, M = 1.66$) as well as apartments ($Mdn = 2, M = 1.78$) walked approximately 'four to six times'. A shorter weekly duration of walking ($t(1227) = 3.02, d = 0.19, p = 0.003, 95\%CI [0.35, 1.67]$) was found when there was more than one child in the household ($M_{minutes} = 181.69, SD = 152.88$) as compared to only one ($M_{minutes} = 205.11, SD = 155.18$). The frequency of walking was also lower on weekdays ($U = 188,305, N = 1275, r = 0.07, p = 0.017$) when there was more than one child in the household ($Mdn = 1, M = 1.56$) as compared to only one ($Mdn = 2, M = 1.68$).

There was a small seasonal difference in the weekly duration of walking ($F(1225) = 4.20, \eta^2 = 0.01, p = 0.006$), with 171.97 min ($SD = 138.21$) in the winter, 197.20 ($SD = 153.61$) in spring, 211.03 ($SD = 159.81$) in summer and 206.54 ($SD = 163.54$) in fall. There was also a difference for the frequency of walking on weekdays ($\chi^2(3, 1275) = 12.21, \eta^2 = 0.01, p = 0.007$), with 'one to three' in the winter ($Mdn = 1, M = 1.53$) and 'four to six' in spring ($Mdn = 2, M = 1.63$), fall ($Mdn = 2, M = 1.67$) and summer ($Mdn = 2, M = 1.73$). Likewise, there was a difference in the frequency of walking on weekends ($\chi^2(3, 1271) = 10.31, \eta^2 = 0.01, p = 0.016$), with the lowest frequency in the winter ($Mdn = 1, M = 1.07$), followed by spring ($Mdn = 1, M = 1.12$), fall ($Mdn = 1, M = 1.16$) and summer ($Mdn = 1, M = 1.16$).

A longer daily duration of carrying ($r(1171) = 0.08, p = 0.009, 95\%CI [0.02, 0.13]$) and a higher frequency of using the carrier outdoors ($r(1231) = 0.06, p = 0.028, 95\%CI [0.01, 0.12]$) were associated with more types of recreational areas nearby. More daily hours of carrying were found ($U = 135,642, N = 1173, r = 0.07, p = 0.016$) when there was more than one child in the household ($Mdn = 1, M = 0.96$) as compared to one child ($Mdn = 1, M = 0.80$), and the carrier was used more frequently on walks ($U = 149,088, N = 1232, r = 0.07, p = 0.009$) when there was more than one child in the household ($Mdn = 1, M = 1.05$) as compared to one child ($Mdn = 1, M = 0.88$). The carrier was also used more frequently on outdoor walks ($U = 23,569, N = 1233, r = 0.07, p = 0.010$) when there was more than one adult in the household ($Mdn = 1, M = 0.94$) as compared to having no other adult in the household ($Mdn = 0$, stands for '(almost) never', $M = 0.68$).

Table 2. Associations of outdoor walking and carrying with sample characteristics

Infant	Weekly Duration of Walking in Minutes^g		Frequency Walking Weekdays		Frequency Walking Weekends		Frequency Carrying Outdoors		Daily Carrying Hours (Indoors + Outdoors)	
	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>
Age	-0.04 (1227) ^a	0.168	-0.08 (1273) ^b	0.004 *	-0.03 (1269) ^b	0.308	-0.03 (1231) ^b	0.235	-0.14 (1171) ^b	0.000 *
Sex (boy/girl)	-0.76 (1227) ^c	0.447	198,899 ^e	0.485	194,613 ^e	0.109	189,372 ^e	0.916	166,958 ^e	0.358
Gestational age at birth	-0.04 (1225) ^a	0.135	-0.07 (1271) ^b	0.018 *	-0.01 (1267) ^b	0.647	0.05 (1229) ^b	0.061	0.02 (1169) ^b	0.548
Preterm (yes/no)	-2.30 (1225) ^c	0.022 *	40,382 ^e	0.052	45,078 ^e	0.707	44,438 ^e	0.697	39,236 ^e	0.942
Health issues (yes/no)	1.43 (1227) ^c	0.152	64,364 ^e	0.383	63,948 ^e	0.275	59,138 ^e	0.652	52,345 ^e	0.207
Infant behavior at night	-0.04 (1179) ^b	0.182	-0.05 (1179) ^b	0.067	-0.03 (1179) ^b	0.336	0.16 (1179) ^b	0.000 *	0.20 (1171) ^b	0.000 *
Infant enjoyment of outdoor walks	0.22 (1207) ^b	0.000 *	0.18 (1207) ^b	0.000 *	0.22 (1207) ^b	0.000 *	0.03 (1207) ^b	0.337	0.03 (1171) ^b	0.254
Maternal										
Age	-0.04 (1227) ^a	0.179	-0.06 (1273) ^b	0.033	-0.03 (1269) ^b	0.237	0.03 (1231) ^b	0.350	0.01 (1171) ^b	0.667
Education level (higher/lower)	0.38 (1227) ^c	0.707	188,846 ^e	0.000 *	174,236 ^e	0.004 *	140,097 ^e	0.022 *	125,063 ^e	0.015 *
Employment (employed/mat. leave/no paid job)	8.34 (1227) ^d	0.004 *	17.54 (2) ^f	0.000 *	1.21 (2) ^f	0.546	5.42 (2) ^f	0.067	20.90 (2) ^f	0.000 *
Weekly working hours (in employed mothers)	-0.00 (744) ^b	0.990	-0.06 (772) ^b	0.076	0.02 (770) ^b	0.572	0.02 (749) ^b	0.558	-0.03 (710) ^b	0.362
Mental health issues (yes/no)	-0.10 (1227) ^c	0.921	63,676 ^e	0.116	69,050 ^e	0.997	55,673 ^e	0.005 *	53,318 ^e	0.027 *
Physiological health issues (yes/no)	1.18 (1227) ^c	0.236	120,048 ^e	0.952	0.124862 ^e	0.112	119,016 ^e	0.156	97,485 ^e	0.186
Maternal enjoyment of walking	0.24 (1210) ^b	0.000 *	0.20 (1210) ^b	0.000 *	0.23 (1210) ^b	0.000 *	0.03 (1210) ^b	0.259	0.03 (1171) ^b	0.359

Table 2. Continued

<i>Environmental</i>	Weekly Duration of Walking in Minutes ^g		Frequency Walking Weekdays		Frequency Walking Weekends		Frequency Carrying Outdoors		Daily Carrying Hours (Indoors + Outdoors)	
	Statistic (df)	p	Statistic (df)	p	Statistic (df)	p	Statistic (df)	p	Statistic (df)	p
City size	0.06 (1227) ^b	0.037	-0.01 (1273) ^b	0.851	0.01 (1269) ^b	0.615	0.02 (1231) ^b	0.451	0.04 (1171) ^b	0.170
Types of different recreational areas nearby	0.10 (1227) ^b	0.000 *	0.07 (1273) ^b	0.020 *	0.08 (1269) ^b	0.007 *	0.06 (1231) ^b	0.028 *	0.08 (1171) ^b	0.009 *
House (detached/ semidetached/ terraced/apartment)	5.18 (1222) ^d	0.023 *	16.45 (4) ^f	0.002 *	5.97 (3) ^f	0.113	4.94 (3) ^f	0.176	8.27 (3) ^f	0.041
More than one child in household (yes/no)	3.02 (1227) ^c	0.003 *	188,305 ^e	0.017 *	180,393 ^e	0.090	149,088 ^e	0.009 *	135,642 ^e	0.016 *
More than one adult in household (yes/no)	-0.35 (1227) ^c	0.725	33,425 ^e	0.662	31,974 ^e	0.865	23,569 ^e	0.010 *	24,995 ^e	0.494
Season (spring/ summer/fall/winter)	4.20 (1225) ^d	0.006 *	12.21 (3) ^f	0.007 *	10.31 (3) ^f	0.016 *	2.75 (3) ^f	0.431	0.90 (3) ^f	0.826

Note. *df*, degrees of freedom; *Mat.leave*, Maternity leave; * *p*-values printed in bold were significant after the Benjamini-Hochberg correction. ^a Pearson correlation coefficient for continuous data, ^b Spearman's rho for ordinal or non-normally distributed residuals, ^c *T*-statistic for independent samples *t*-tests comparing two groups, ^d Cohen's *F* for analyses of variance comparing more than two groups, ^e *U* for Mann-Whitney *U* tests comparing two groups with non-normally distributed residuals, ^f χ^2 for Kruskal-Wallis test comparing more than two groups with non-normally distributed residuals, ^g Square-root-transformed and winsorized data.

Boruta results for outdoor walking and carrying

Figure 2 displays Boruta results for the weekly duration of walking. In descending importance, a longer duration was predicted by: greater maternal enjoyment of walking, employment status (most in mothers without a paid job), younger infants, greater infant enjoyment of being walked, only one child in the household, season (lowest in winter), more recreational areas in walking distance and preterm birth.

Figure 3 shows Boruta results for the frequency of using the infant carrier during outdoor walks. A higher frequency was predicted by: higher scores on infant behavior at night, younger infants, employment status (least for employed mothers), higher gestational age at birth and more than one child in the household.

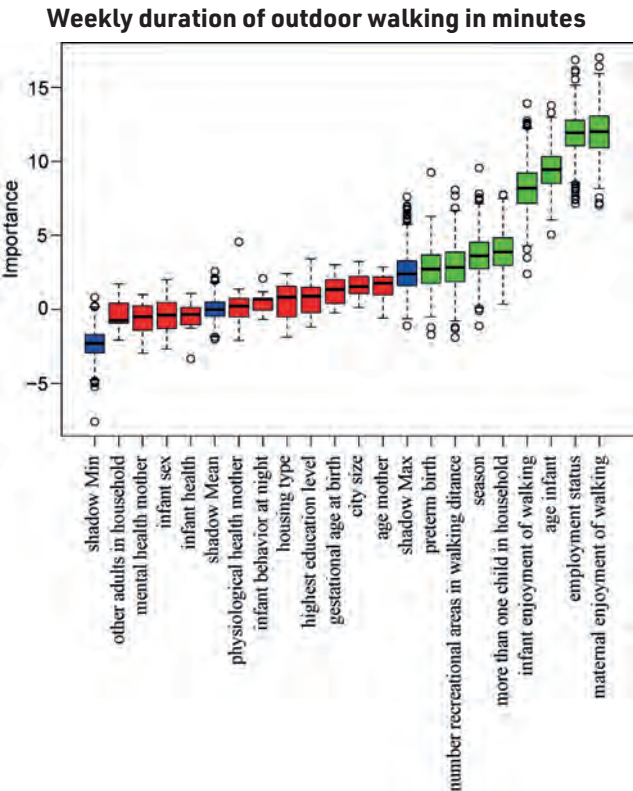


Figure 2. Boruta analysis predicting outdoor walking. Wrapped around the random forest algorithm, Boruta tests the importance of each variable against that of shadow variables created through shuffling the original variables. Green variables are classified as important, whereas red variables are unimportant. Blue variables show minimal, medium and maximal importance of the shadow variables.

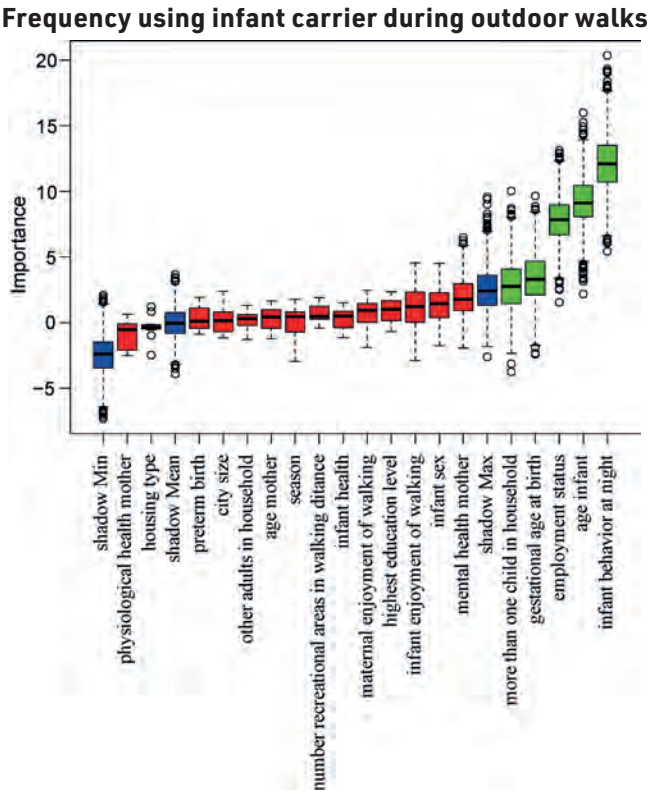


Figure 3. Boruta analysis predicting frequency of using infant carrier during outdoor walks. Wrapped around the random forest algorithm, Boruta tests the importance of each variable against that of shadow variables created through shuffling the original variables. Green variables are classified as important, whereas red variables are unimportant. Blue variables show minimal, medium and maximal importance of the shadow variables.

Infant outdoor sleeping

All results of the analyses on the associations between sample characteristics with infant outdoor sleeping are presented in Table 3. All significant findings on infant outdoor sleeping after correcting for multiple testing are summarized in the following sections.

Infant characteristics. The younger the infants, the more likely they were to be placed outdoors to sleep ($Z(1164) = 3.65$, *odds ratio (OR)* = 0.02, $p = 0.000$, 95%CI [0.01, 0.03]). Younger infant age was also associated with longer weekly durations ($r(317) = -0.14$, $p = 0.015$, 95%CI [-0.25, -0.03]) and a higher weekly frequency of outdoor sleeping ($r(340) = -0.13$, $p = 0.013$, 95%CI [-0.24, -0.03]).

Maternal characteristics. Infants of higher-educated mothers (32.51%) were more likely to be placed outdoors to sleep ($\chi^2(1, N = 1166) = 13.84$, *Cohen's* $\omega = 0.11$, $p = 0.000$) compared to infants of lower-educated mothers (21.11%). Infants of employed mothers (34.89%) were also more likely to be placed outdoors to sleep ($\chi^2(2, N = 1166) = 26.91$, *Cohen's* $\omega = 0.15$, $p = 0.000$) than those of mothers on maternity leave (22.81%) or mothers without a paid job (17.50%).

Environmental characteristics. The smaller the city, the more likely it was that infants were placed outdoors to sleep ($Z(1164) = -2.33$, $OR = -0.13$, $p = 0.020$, 95%CI $[-0.24, -0.02]$) and the longer the weekly duration of outdoor sleeping ($r(317) = -0.16$, $p = 0.004$, 95%CI $[-0.27, -0.05]$). The more types of recreational areas in walking distance, the more likely it was that infants were placed outdoors to sleep ($Z(1164) = 2.77$, $OR = 0.18$, $p = 0.006$, 95%CI $[0.05, 0.31]$). There was a difference for housing type ($\chi^2(3, N = 1166) = 37.82$, *Cohen's* $\omega = 0.18$, $p = 0.000$), with 45.21% of mothers in detached houses, 34.50% in semi-detached houses, 27.52% in terraced houses and 14.91% in apartments placing their infants outdoors to sleep. Lastly, there was a seasonal difference for the likelihood of infants being placed outdoors to sleep ($\chi^2(3, N = 1166) = 15.98$, *Cohen's* $\omega = 0.12$, $p = 0.001$), with 36.07% in the summer, 30.22% in the fall, 27.17% in the spring and 21.94% in the winter.

Table 3. Associations of infant outdoor sleeping with sample characteristics

<i>Infant</i>	Placing Infant Outdoors to Sleep		Weekly Duration Outdoor Sleeping ^f		Weekly Frequency Outdoor Sleeping	
	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>
Age	3.65 (1164) ^e	0.000*	-0.14 (317) ^a	0.015*	-0.13 (340) ^a	0.013*
Sex (boy/girl)	0.17 (1) ^d	0.683	13,795 ^b	0.181	15,032 ^b	0.604
Gestational age at birth	1.04 (1162) ^e	0.298	-0.10 (315) ^a	0.061	-0.06 (340) ^a	0.246
Preterm (yes/no)	0.60 (1) ^d	0.437	2933 ^b	0.355	3721.5 ^b	0.830
Health issues (yes/no)	1.09 (1) ^d	0.296	3892.5 ^b	0.506	4949 ^b	0.794
Infant behavior at night	0.75 (1163) ^e	0.453	-0.05 (317) ^a	0.382	-0.05 (339) ^a	0.320

Table 3. Continued

	Placing Infant Outdoors to Sleep		Weekly Duration Outdoor Sleeping^f		Weekly Frequency Outdoor Sleeping	
Maternal	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>	<i>Statistic (df)</i>	<i>p</i>
Age	2.16 (1164) ^e	0.031	0.04 (317) ^a	0.479	0.04 (340) ^a	0.408
Education level (higher/lower)	13.84 (1) ^d	0.000*	8323.5 ^b	0.479	9582 ^b	0.483
Employment (working/maternity leave/no paid job)	26.91 (2) ^d	0.000*	3.85 (2) ^c	0.146	5.93 (2) ^c	0.052
Weekly working hours (in employed mothers)	0.53 (706) ^e	0.596	0.12 (231) ^a	0.061	0.09 (245) ^a	0.170
Mental health issues (yes/no)	0.00 (1) ^d	0.999	4751 ^b	0.746	4910 ^b	0.710
Physiological health issues (yes/no)	0.03 (1) ^d	0.863	6966 ^b	0.634	8723 ^b	0.949
Environmental						
City size	-2.33 (1164) ^e	0.020*	-0.16 (317) ^a	0.004*	-0.08 (340) ^a	0.118
Types of different recreational areas nearby	2.77 (1165) ^e	0.006*	0.06 (317) ^a	0.254	0.08 (340) ^a	0.132
House (detached/ semidetached/ terraced/apartment)	37.82 (3) ^d	0.000*	9.96 (4) ^c	0.041	7.05 (04) ^c	0.133
More than one child in household (yes/no)	3.47 (1) ^d	0.063	11,331 ^b	0.738	12,196 ^b	0.151
More than one adult in household (yes/no)	1.97 (1) ^d	0.160	1928.5 ^b	0.046	1980.5 ^b	0.075
Season (spring/ summer/fall/winter)	15.98 (3) ^d	0.001*	8.10 (3) ^c	0.044	3.12 (3) ^c	0.373

Note. * *p*-values printed in bold were significant after the Benjamini-Hochberg correction.

^a Spearman's rho for ordinal data, ^b U for Mann-Whitney U tests comparing two groups with non-normally distributed residuals, ^c χ^2 for Kruskal-Wallis test comparing more than two groups with non-normally distributed residuals, ^d χ^2 for chi-square tests on categorical data, ^e Wald Z for binomial logistic regressions for continuous predictors and categorical outcome data,

^f Winsorized data.

Boruta analyses for infant outdoor sleeping

Figure 4 displays Boruta results for infant outdoor sleeping. Predictive of placing the infant outdoors to sleep were: employment status (highest in employed mothers), housing type (least in apartments), season (least in the winter), younger infants, higher scores on infant behavior at night, higher maternal education, lower gestational age at birth and smaller city size.

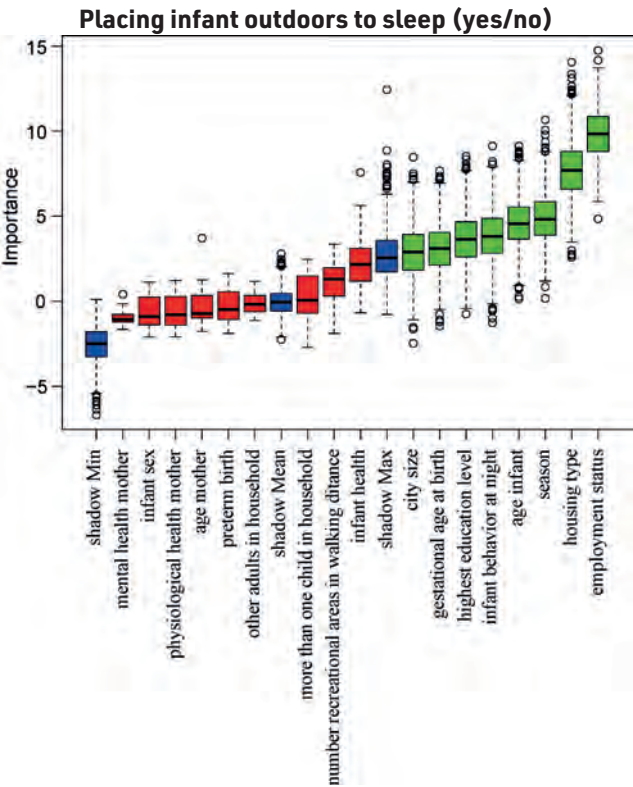


Figure 4. Boruta analysis predicting whether the infant is placed outdoors to sleep. Wrapped around the random forest algorithm, Boruta tests the importance of each variable against that of shadow variables created through shuffling the original variables. Green variables are classified as important, whereas red variables are unimportant. Blue variables show minimal, medium and maximal importance of the shadow variables.

Discussion

The first aim of the current study was to quantify how much time infants in the first year of life spend outdoors: being walked and carried and sleeping outdoors. Secondly, we investigated which infant, maternal and environmental factors were associated with time spent outdoors.

Outdoor walking

We found that mothers walked approximately 201 min weekly with their infants, and most walked one to three times on weekdays and an additional one to three times on the weekend. Half of the mothers indicated that they would like to walk more. The most commonly reported reasons for walking were to reach a destination (84% of mothers) and leisure (82% of mothers), whereas the most common reasons for not walking were the weather (79% of mothers) and a lack of time (44% of mothers).

Statistical analyses indicated that only a few infant characteristics were predictive of outdoor walking. During weekdays, younger infants were taken on walks more frequently. This might be explained by the fact that mothers are usually on maternity leave when the infant is younger, and thus the mother may have more time for walking during weekdays. We also found a longer weekly duration of outdoor walking in preterm infants, and lower gestational age at birth was associated with more walks on weekdays. Note that mothers in the Netherlands are entitled to 16 weeks of maternity leave, which can be divided between the pre- and postnatal phase. When mothers give birth before the due date, they usually have more weeks of maternity leave after birth and possibly more time to go outdoors with their infants in this period. Furthermore, infants who enjoyed outdoor walks more were taken on walks for a longer weekly duration and more frequently during weekdays, as well as during the weekend.

Likewise, greater maternal enjoyment was an important predictor for longer durations of walking and a higher frequency of walks on weekdays and on weekends. Another predictor of outdoor walking was maternal employment status. Employed mothers reported a shorter weekly duration of walking and a lower frequency of walks, particularly during weekdays, as compared to mothers on maternity leave or mothers without a paid job, possibly due to having less time. Notably, research suggests that extended maternity leave is associated with improved infant and maternal health outcomes (Jou et al., 2018). Current findings might indicate that mothers on maternity leave may

have more time for recuperative activities, such as outdoor walking with their infants, which, in turn, might improve maternal and infant health. The current findings are in accordance with previous studies on toddlers and preschoolers, where less outdoor play was reported by employed mothers (Boxberger & Reimers, 2019; Lee et al., 2021; Tandon et al., 2012). In the past decades, female education and employment rates have increased, and parents have come to rely more on childcare centers (Aisenbrey et al., 2009; Dicks et al., 2022; Hilbrecht et al., 2008). This trend might have led to decreased time outdoors for mother-infant dyads. How much time infants actually spend outdoors in childcare needs to be investigated in future studies in order to obtain a more comprehensive view of infants' total outdoor time.

Mothers with a lower education walked more frequently with their infants on weekdays as well as on weekends. This is in accordance with studies in older children reporting more outdoor time for children of parents of lower education (Aarts et al., 2010; Boxberger & Reimers, 2019; Remmers et al., 2014). The current findings might be explained by the fact that higher education increases the likelihood of workforce engagement in women (Evans & Kelley, 2008), leaving less time for outdoor walks. Indeed, post hoc analyses in our study showed that higher-educated mothers were more likely to be employed ($\chi^2(1, N = 1275) = 77.88$, *Cohen's* $\omega = 0.25$, $p = 0.000$) and worked for more hours weekly ($U = 37,024$, $N = 774$, $r = 0.25$, $p = 0.000$).

When there were more types of recreational areas within walking distance, mother-infant dyads engaged in outdoor walking for a longer duration weekly and more frequently on weekdays as well as on weekends. Likewise, previous studies reported more outdoor time in older children who lived in rural areas and areas with more greenery in the environment (Aarts et al., 2010; Lambert et al., 2019; Matz et al., 2015; Nguyen et al., 2021; Xu et al., 2017). Additionally, dyads living in apartments engaged in outdoor walking for a longer duration weekly and more frequently on weekdays than dyads living in detached houses. Future research is of interest, assessing underlying reasons for differences depending on housing type. For instance, we did not assess whether families living in detached houses might spend more time outdoors around their house (e.g., in their yard). While more outdoor walking by dyads living in apartments might be explained by mothers compensating for restricted indoor space, as well as a lack of a yard, living in apartments might also be associated with lower education, which, in turn, was also related to more outdoor walking in the current study. Also, living in an apartment may be associated with

shorter distances to shops, schools, health facilities, etc., allowing mothers to walk with their infants instead of taking the car or public transport. Having more than one child in the household was associated with a shorter weekly duration of walking and a shorter frequency of walking on weekdays, which may potentially be due to a lack of time because of increased caregiving responsibilities. Lastly, in accordance with previous studies, longer durations of outdoor walking and more frequent walks on weekdays and on weekends were found in warmer seasons (Matz et al., 2014; Nguyen et al., 2021).

Outdoor carrying

In total, 22% of mothers reported using an infant carrier for half of the time or more during outdoor walks. Infants scoring higher on infant behavior at night (how much attention the infant needs at night, how much difficulty the infant has falling asleep and how often the infant wakes up at night) were carried more often during outdoor walks. One potential explanation for this finding is that these infants have more challenges sleeping at night and that the mothers use outdoor carrying as a way of facilitating (daytime) sleep through physical contact and movement (Esposito et al., 2013; Ohmura et al., 2022). On the other hand, given the non-causal nature of the findings, the possibility that being carried outdoors more leads to changes in infant behavior at night is just as likely, for instance, through carrying facilitating more sleep during the day and hence leading to less sleep at night. In addition, a third, non-measured variable may be explaining both outdoor carrying and behavior at night. For instance, breastfeeding may lead to more waking at night to feed as well as to mothers carrying their infant more often. Additionally, most typically, developing infants wake up regularly at night (e.g., signaling the need for being fed), and need help resettling to sleep, without this being considered problematic sleeping behavior (Ball et al., 2019; Barry, 2021; Beijers et al., 2011; Schoch et al., 2020). Hence, future research is needed to disentangle the potential mechanisms underlying this finding.

Higher-educated mothers used the infant carrier more frequently for outdoor walks. Mothers having a mental health issue reported using the carrier slightly more frequently during outdoor walks than mothers without mental health issues. Again, the current study cannot assess the directionality of this association nor rule out other underlying factors not assessed in this survey. Future research assessing the association of both outdoor carrying and maternal mental health issues with infant sleeping behavior would be especially interesting to further understand underlying mechanisms. The

carrier was also used more frequently during outdoor walks when there was another adult living in the household, if there were more types of recreational areas nearby and if mothers had more than one child. These factors could be related to practical reasons for using the carrier (e.g., having free hands when walking with more children), but future hypothesis-driven research is needed to investigate this.

Outdoor sleeping

Outdoor sleeping was practiced with 29% of infants for approximately four hours a week and with a frequency of one to two times weekly. Outdoor sleeping was more likely in younger infants, and younger infants were placed outdoors more frequently and for a longer weekly duration, which might be explained by younger infants taking more naps in general (Schoch et al., 2020). Additionally, older infants are more mobile, and hence outdoor sleeping might be perceived as less practical or safe by the caregivers. In contrast, a study in Scandinavia, where outdoor sleeping is more popular, reported that most infants sleep outdoors throughout the first year of life (Tourula et al., 2008).

We found a higher likelihood of outdoor sleeping in infants of mothers with a higher level of education and in working mothers. Notably, outdoor sleeping is often practiced in Dutch childcare centers, which might explain why infants of working mothers were placed outdoors to sleep more in the current sample. Infants living in areas with more types of recreational areas nearby and infants living in apartments or terraced houses were less likely to be placed outdoors to sleep than infants living in detached houses. Accordingly, parents in Scandinavia report cigarette smoke from neighboring balconies as a concern during infant outdoor sleeping (Tourula et al., 2008). We also found that infants in larger cities were less likely to be placed outdoors to sleep and slept outdoors for fewer hours weekly. Living in a larger city might lead to less private outdoor space, as well as increased air pollution and more parental safety concerns, but these potential explanations need to be examined in future studies. Nonetheless, these findings are in accordance with studies on outdoor play in older children, where more outdoor time was reported in rural areas (Aarts et al., 2010; Lambert et al., 2019; Matz et al., 2015; Xu et al., 2017).

Lastly, infants of mothers participating in the winter were placed outdoors to sleep less often. In contrast with these findings, a survey in Scandinavian parents found −6 degrees Celsius to be the most preferred temperature for

infant outdoor sleeping (Tourula et al., 2008, 2010). The authors suggest that colder outdoor temperatures allow for more swaddling through additional layers of clothing, which restricts infants' movement and potentially increases sleep duration, as longer sleep durations were reported outdoors compared to indoors (Tourula et al., 2010). In the Netherlands, average temperatures range from +17 degrees Celsius in the summer to +3 in the winter, suggesting that outdoor sleeping is possible also in the winter.

Limitations, strengths and spin-off questions

The current study has some limitations. The observational and cross-sectional nature of the study design, as well as the non-standardized survey, restrict interpretability and preclude us from drawing conclusions on the causality of associations. In addition, we solely focused on outdoor walking and carrying performed by mothers and relied on maternal report. Also, the variable infant behavior at night was assessed through a single item collapsing all three nightly behaviors and we did not ask parents whether they perceived the infants' nightly sleeping behavior as problematic. Factors that could interact with outdoor activities (e.g., partner support, culture, perception and safety of the outdoors) were not examined in this study and may be important explanatory variables to include in future research. In addition, future studies should consider collecting more objective measures of outdoor time through the use of wearables and apps designed to register walks. Furthermore, future work should also assess outdoor time with other caregivers, such as fathers and grandparents, as well as outdoor time in childcare centers. The homogeneous nature of the sample (i.e., 73% higher education and 95% Dutch) restricts generalizability of our findings to other groups. Lastly, the current study did not assess all types of activities commonly performed with infants outdoors, such as awake time in the yard or biking with the infant, and hence does not provide an insight in the total amount of time infants spend outdoors.

Nevertheless, the current study has several strengths. This is one of the first studies in this relevant area of research and the large sample size allowed for a data-driven approach. Also, the Boruta algorithm used is a powerful tool to reveal the importance of variables, providing a comprehensive insight into demographic characteristics associated with outdoor walking, carrying and outdoor sleeping during infancy. The exploratory, data-driven approach of the current study can deliver important insights for future hypothesis-driven research. Furthermore, the study delivers crucial input for future research on interventions to facilitate outdoor activities with infants. For instance, more

than half of the mothers in this study reported walking in order to benefit their own health, supporting the idea that outdoor walking might also be of interest for interventions targeted at improving maternal postnatal health (Currie & Develin, 2002). Furthermore, maternal enjoyment of outdoor walks was one of the strongest predictors of outdoor walking with the infant. This implies that future interventions with the aim to facilitate postnatal outdoor walking may target maternal enjoyment of the activity, for instance, by facilitating group walks or making mothers aware of recreational areas suitable for enjoyable walks. Finally, the current findings on reduced outdoor walking in employed mothers during weekdays might prompt future research into the potential benefits of longer maternity leaves for mother and child.

Conclusions

This study identified associations between infant, maternal and environmental characteristics and infant time spent being walked or sleeping outdoors in the first year of life. Summarizing, more mother-infant outdoor walking was related to younger infant age, mothers without a paid job or on maternity leave and more recreational areas nearby. More outdoor sleeping was associated with younger infant age, higher maternal education and living in detached houses and smaller cities. These results lay a solid foundation for future hypothesis-driven research on the effects of the outdoors on child development as well as on facilitators and barriers for caregivers. Future studies should include other caregivers besides the mothers and assess cultural differences as well as parental perceptions of the outdoors. Ultimately, this line of work can inform advice for parents, governmental policies and urban planning related to bringing up healthy future generations.

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Supplementary material

Supplementary A: Survey on outdoor activities of mothers with infants

Part 1: Demographic data: The questionnaire starts with a number of questions about yourself and your living environment.

1.1. How old are you in years?

1.2. Where were you born?

- o Netherlands
- o Other, namely:

1.3. What is your ethnic background?

- o European
- o Turkish
- o Moroccan
- o Antillean
- o Surinamese
- o Indonesian
- o African
- o Asian
- o Latin American
- o Other, namely:

1.4. What is your highest completed level of education?

- o Primary education
- o VMBO
- o MBO
- o HAVO
- o VWO (atheneum/gymnasium)
- o HBO
- o University
- o Other, namely:

1.5. Do you currently have a paid job?

- o yes
- o no

1.5.1. Can you describe your profession below?

1.5.2. How many hours per week do you normally work?

- ☐ 0-8 hours (0-20%)
- ☐ 9-16 hours (21-40%)
- ☐ 17-24 hours (41-60%)
- ☐ 25-32 hours (61-80%)
- ☐ 33-40 hours (81-100%)
- ☐ More than 40 hours (>100%)

1.5.3. Are you currently on maternity leave?

- ☐ yes
- ☐ no

1.6. Do you currently have a permanent partner?

- ☐ yes
- ☐ no

1.7. How many people does your household consist of (including your baby)?

- ... adults (older than 18)
- ... children (younger than 18)

1.7.1. What are the ages of the children in your household?

1.8. Do you live in a:

- ☐ village (up to 5000 inhabitants)
- ☐ small city (up to 20,000 inhabitants)
- ☐ medium-sized city (up to 100,000 inhabitants)
- ☐ large city (more than 100,000 inhabitants)

1.9. What type of home do you currently live in?

- ☐ detached house
- ☐ semi-detached house
- ☐ terraced house
- ☐ apartment
- ☐ other, namely:

1.9.1. [If apartment] On which floor do you live?

- ☐ ground floor
- ☐ first floor
- ☐ second floor
- ☐ third floor
- ☐ fourth floor or higher

1.10. What types of green recreational areas are there within walking distance of your home? [Multiple options possible]

- ☐ city park
- ☐ square
- ☐ wooded or tree-rich environment
- ☐ green area with walking paths
- ☐ national park
- ☐ on the street, in the city/village
- ☐ none
- ☐ other, namely

Part 2: The following questions are about the health and well-being of you and your baby:

2.1. Do you have a physical illness/condition or complaints?

- ☐ yes, namely:
- ☐ no

2.2. Do you have mental and/or psychological complaints yourself?

- ☐ yes, namely:
- ☐ no

2.3. What was the duration of your pregnancy in days?

The following questions are about habits regarding walking outside before and during your pregnancy. By walking outside we mean a walk outside the house of at least 15 consecutive minutes.

2.4. Before your pregnancy, how often did you walk outside on average per week?

- ☐ (almost) never
- ☐ 1 to 3 times a week
- ☐ 4 to 6 times a week
- ☐ 7 to 9 times a week
- ☐ 10 times a week or more

2.5. During your pregnancy, how often did you walk outside on average per week?

- ☐ (almost) never
- ☐ 1 to 3 times a week
- ☐ 4 to 6 times a week
- ☐ 7 to 9 times a week
- ☐ 10 times a week or more

2.6. What is the sex of your baby?

- ☐ boy
- ☐ girl

2.7. Does your baby have an illness/condition or health problems?

- ☐ yes, namely:
- ☐ no

Part 2.2: Activities and habits

The following questions are about habits related to walking outside with your baby. By walking outside we mean a walk outside the house for at least 15 consecutive minutes.

During the week,...

2.8. How often do you usually walk with your baby during the week (Monday to Friday)?

- ☐ (almost) never
- ☐ 1 to 3 times a week
- ☐ 4 to 6 times a week
- ☐ 7 to 9 times a week
- ☐ 10 times a week or more

2.9. How often do you usually walk outside with your baby on weekends (Saturday to Sunday)?

- ☐ (almost) never
- ☐ 1 to 3 times per weekend
- ☐ 4 to 6 times per weekend
- ☐ 7 to 9 times per weekend
- ☐ 10 times or more per weekend

2.10. In one week, how long do you usually walk outside with your baby (total in minutes over 7 days)?

2.10.1. How often do you use a baby carrier/sling to walk with your baby outside the home?

- ☐ (almost) never
- ☐ sometimes
- ☐ half the time
- ☐ usually
- ☐ always

2.11. For what reasons do you walk outside with your baby? (Multiple answers possible)

- ☐ as a leisure activity
- ☐ to reach a destination, such as the store or childcare

- o to walk the dog
- o to get the baby to sleep or soothe the baby
- o for my physical health
- o other, namely:

2.12. When you walk outside the house with your baby, how often do you walk with other people? (e.g. your partner, other children, friends)

- o never
- o sometimes
- o half the time
- o most of the time
- o always

2.13. Are there other people who regularly walk outside with your baby without you? (multiple options possible)

- o no
- o father of baby
- o baby's brother or sister
- o baby's grandmother or grandfather
- o babysitter or nursery employee
- o other, namely:

2.14. How much do you enjoy walking outside?

- o slider from not at all to very much

2.15. How much does your baby enjoy it when you walk him/her outside?

- o slider from not at all to very much

2.16. How satisfied are you with the amount of time you walk outside with your baby?

- o I am satisfied
- o I would like to walk more with my baby
- o I would like to walk less with my baby

2.17. What are reasons for you to decide not to walk outside with your baby?
(Multiple answers possible)

- ☐ it is easier to go by car
- ☐ there is too much traffic on the street
- ☐ there is no nice environment to walk in
- ☐ weather conditions
- ☐ my own health problems
- ☐ my baby's health problems
- ☐ no time
- ☐ not feeling like it
- ☐ other, namely:

2.18. Where do you usually walk outside with your baby? [Multiple options possible]

- ☐ city park
- ☐ square
- ☐ wooded or tree-rich environment
- ☐ green area with walking paths
- ☐ national park
- ☐ on the street, in the city/village
- ☐ other, namely

The following questions are about habits in the daily lives of you and your baby.

2.19. How does your baby fall asleep? [Multiple options possible]

- ☐ during feeding
- ☐ when he/she is being rocked
- ☐ when he/she is held on your lap
- ☐ while walking with the stroller
- ☐ when he/she is carried in the arms
- ☐ if he/she is carried in a baby carrier/sling
- ☐ in bed, with a parent nearby
- ☐ in bed, without a parent nearby
- ☐ otherwise, namely....

2.20. How does your baby behave at night?

- o The baby needs a lot of attention/has difficulty falling asleep/wakes up often during the night.
- o The baby needs regular attention/sometimes wakes up during the night.
- o The baby needs attention very occasionally/wakes up very occasionally during the night.
- o The baby almost never needs attention/falls asleep easily/almost never wakes up at night.

2.21. Do you ever use a baby carrier/sling for your baby (indoors or outdoors)?

- o no never
- o I have only used this once or twice
- o yes, regularly
- o yes, often or always

2.21.2. [If one of the last two options was chosen] How many hours per day do you use a baby carrier/sling on average?

- o less than one hour per day
- o (almost) never
- o less than 1 hour per day
- o 1 to 2 hours per day
- o 3 to 4 hours per day
- o 5 to 6 hours per day
- o 7 hours or more per day

The following questions are about bathing habits for your baby.

2.22. How often do you bathe your baby?

- o less than once a week
- o 1 to 2 times a week
- o up to 4 times a week
- o up to 6 times a week
- o 7 or more times a week

2.23. Do you use a washcloth to wash your baby during the bath?

- o (almost) never
- o yes

2.24. How long does it take you to give your baby a bath (from starting to undress to fully dressed again)?

- ☐ less than 5 minutes
- ☐ 5 to 10 minutes
- ☐ 11 to 15 minutes
- ☐ 16 to 20 minutes
- ☐ More than 20 minutes

2.25. What do you use to bathe your baby?

- ☐ bathtub for babies
- ☐ tummy tub
- ☐ sink or sink in the countertop
- ☐ other, namely:

2.26 Is your baby put outside in the garden or on the balcony/terrace to sleep during the day (for example in a stationary pram or cot, by you or other people, including the childcare center)?

- ☐ no
- ☐ yes

2.26.2. [If yes] How many times a week does your baby sleep outside in the garden or on the balcony/terrace?

- ☐ 1 to 2 times a week
- ☐ 3 to 4 times a week
- ☐ 5 to 6 times a week
- ☐ 7 or more times a week

2.26.3. In one week, how long does your baby usually sleep outside in the garden or on the balcony/terrace (total in hours over 7 days)?

2.27. Do you have any further comments regarding this survey?

Supplementary B: Benjamini-Hochberg corrections

Table S-B. Benjamini-Hochberg correction for aim 2

Predictor variable	Outcome	P-value	Rank	Critical value
Maternal enjoyment of walking	Walking weekly in minutes	8.32E-17	1	0.000649
Maternal enjoyment of walking	Frequency during weekends	3.77E-16	2	0.001299
Infant enjoyment of outdoor walks	Frequency during weekends	1.49E-14	3	0.001948
Infant enjoyment of outdoor walks	Walking weekly in minutes	1.97E-14	4	0.002597
Maternal enjoyment of walking	Frequency during weekdays	2.93E-12	5	0.003247
Infant behavior at night	Infant carrying (indoors+outdoors)	1.54E-11	6	0.003896
Infant enjoyment of outdoor walks	Frequency during weekdays	1.04E-10	7	0.004545
House (detached/semidetached/terraced/apartment)	Sleeping outdoors (Yes/No)	3.09E-08	8	0.005195
Infant behavior at night	Frequency carrying outdoors	4.64E-08	9	0.005844
Employment (working/maternity leave/unemployed)	Sleeping outdoors (Yes/No)	1.43E-06	10	0.006494
Infant age	Infant carrying (indoors+outdoors)	1.94E-06	11	0.007143
Education level (higher/lower)	Frequency during weekdays	4.30E-06	12	0.007792
Employment (working/maternity leave/unemployed)	Infant carrying (indoors+outdoors)	2.90E-05	13	0.008442
Employment (working/maternity leave/unemployed)	Frequency during weekdays	0.000156	14	0.009091
Education level (higher/lower)	Sleeping outdoors (Yes/No)	0.000199	15	0.009740
Infant age	Sleeping outdoors (Yes/No)	0.000263	16	0.010390
Types of different recreational areas nearby	Walking weekly in minutes	0.000301	17	0.011039
Season (spring/summer/fall/winter)	Sleeping outdoors (Yes/No)	0.001147	18	0.011688
House (detached/semidetached/terraced/apartment)	Frequency during weekdays	0.002468	19	0.012338
More than one child in household	Walking weekly in minutes	0.002618	20	0.012987

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Employment (working/ maternity leave/unemployed)	Walking weekly in minutes	0.003941	21	0.013636
City size	Weekly hours outdoor sleeping	0.004238	22	0.014286
Education level (higher/lower)	Frequency during weekends	0.004295	23	0.014935
Infant age	Frequency during weekdays	0.004416	24	0.015584
Maternal mental health issues (yes/no)	Frequency carrying outdoors	0.005125	25	0.016234
Types of different recreational areas nearby	Sleeping outdoors (Yes/No)	0.005643	26	0.016883
Season (spring/summer/ fall/winter)	Walking weekly in minutes	0.005726	27	0.017532
Season (spring/summer/ fall/winter)	Frequency during weekdays	0.006699	28	0.018182
Types of different recreational areas nearby	Frequency during weekends	0.007103	29	0.018831
Types of different recreational areas nearby	Infant carrying (indoors+outdoors)	0.008937	30	0.019481
More than one child in household	Frequency carrying outdoors	0.009161	31	0.020130
More than one adult in household	Frequency carrying outdoors	0.009612	32	0.020779
Infant age	Frequency outdoor sleeping	0.013188	33	0.021429
Infant age	Weekly hours outdoor sleeping	0.014533	34	0.022078
Education level (higher/lower)	Infant carrying (indoors+outdoors)	0.014809	35	0.022727
More than one child in household	Infant carrying (indoors+outdoors)	0.015670	36	0.023377
Season (spring/summer/ fall/winter)	Frequency during weekends	0.016142	37	0.024026
More than one child in household	Frequency during weekdays	0.017137	38	0.024675
Gestational age at birth	Frequency during weekdays	0.017597	39	0.025325
Types of different recreational areas nearby	Frequency during weekdays	0.019521	40	0.025974
City size	Sleeping outdoors (Yes/No)	0.019778	41	0.026623
Preterm (yes/no)	Walking weekly in minutes	0.021606	42	0.027273

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Education level (higher/lower)	Frequency carrying outdoors	0.022184	43	0.027922
House (detached/ semidetached/ terraced/apartment)	Walking weekly in minutes	0.023036	44	0.028571
Maternal mental health issues (yes/no)	Infant carrying (indoors+outdoors)	0.026970	45	0.029221
Types of different recreational areas nearby	Frequency carrying outdoors	0.027732	46	0.029870
Maternal age	Sleeping outdoors (Yes/No)	0.030790	47	0.030519
Maternal age	Frequency during weekdays	0.033012	48	0.031169
City size	Walking weekly in minutes	0.036775	49	0.031818
House (detached/ semidetached/ terraced/apartment)	Infant carrying (indoors+outdoors)	0.040783	50	0.032468
House (detached/ semidetached/ terraced/apartment)	Weekly hours outdoor sleeping	0.041122	51	0.033117
Season (spring/summer/ fall/winter)	Weekly hours outdoor sleeping	0.044046	52	0.033766
More than one adult in household	Weekly hours outdoor sleeping	0.045760	53	0.034416
Employment (working/ maternity leave/unemployed)	Frequency outdoor sleeping	0.051561	54	0.035065
Preterm (yes/no)	Frequency during weekdays	0.051862	55	0.035714
Gestational age at birth	Frequency carrying outdoors	0.061123	56	0.036364
Working hours weekly	Weekly hours outdoor sleeping	0.061163	57	0.037013
Gestational age at birth	Weekly hours outdoor sleeping	0.061248	58	0.037662
More than one child in household	Sleeping outdoors (Yes/No)	0.062647	59	0.038312
Employment (working/ maternity leave/unemployed)	Frequency carrying outdoors	0.066534	60	0.038961
Infant behavior at night	Frequency during weekdays	0.067303	61	0.039610
More than one adult in household	Frequency outdoor sleeping	0.075047	62	0.040260

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Working hours weekly	Frequency during weekdays	0.076284	63	0.040909
More than one child in household	Frequency during weekends	0.089743	64	0.041558
Infant sex	Frequency during weekends	0.108739	65	0.042208
Maternal physiological health issues (yes/no)	Frequency during weekends	0.111950	66	0.042857
House (detached/ semidetached/ terraced/apartment)	Frequency during weekends	0.113118	67	0.043506
Maternal mental health issues (yes/no)	Frequency during weekdays	0.115972	68	0.044156
City size	Frequency outdoor sleeping	0.117820	69	0.044805
Types of different recreational areas nearby	Frequency outdoor sleeping	0.131656	70	0.045455
House (detached/ semidetached/ terraced/apartment)	Frequency outdoor sleeping	0.133440	71	0.046104
Gestational age at birth	Walking weekly in minutes	0.134755	72	0.046753
Employment (working/ maternity leave/unemployed)	Weekly hours outdoor sleeping	0.141557	73	0.047403
Education level (higher/lower)	Weekly hours outdoor sleeping	0.145874	74	0.048052
More than one child in household	Frequency outdoor sleeping	0.151057	75	0.048701
Infant health issues (yes/no)	Walking weekly in minutes	0.151775	76	0.049351
Maternal physiological health issues (yes/no)	Frequency carrying outdoors	0.155933	77	0.050000
More than one adult in household	Sleeping outdoors (Yes/No)	0.159985	78	0.050649
Infant age	Walking weekly in minutes	0.168341	79	0.051299
City size	Infant carrying (indoors+outdoors)	0.169832	80	0.051948
Working hours weekly	Frequency outdoor sleeping	0.169937	81	0.052597
House (detached/ semidetached/ terraced/apartment)	Frequency carrying outdoors	0.176059	82	0.053247
Maternal age	Walking weekly in minutes	0.178507	83	0.053896
Infant sex	Weekly hours outdoor sleeping	0.181046	84	0.054545

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Infant behavior at night	Walking weekly in minutes	0.182443	85	0.055195
Maternal physiological health issues (yes/no)	Infant carrying (indoors+outdoors)	0.186183	86	0.055844
Infant health issues (yes/no)	Infant carrying (indoors+outdoors)	0.207275	87	0.056494
Infant age	Frequency carrying outdoors	0.234625	88	0.057143
Maternal physiological health issues (yes/no)	Walking weekly in minutes	0.236348	89	0.057792
Maternal age	Frequency during weekends	0.236854	90	0.058442
Gestational age at birth	Frequency outdoor sleeping	0.245822	91	0.059091
Types of different recreational areas nearby	Weekly hours outdoor sleeping	0.253751	92	0.059740
Infant enjoyment of outdoor walks	Infant carrying (indoors+outdoors)	0.254177	93	0.060390
Maternal enjoyment of outdoor walks	Frequency carrying outdoors	0.258624	94	0.061039
Infant health issues (yes/no)	Frequency during weekends	0.274817	95	0.061688
Infant health issues (yes/no)	Sleeping outdoors (Yes/No)	0.295835	96	0.062338
Gestational age at birth	Sleeping outdoors (Yes/No)	0.297608	97	0.062987
Infant age	Frequency during weekends	0.308034	98	0.063636
Infant behavior at night	Frequency outdoor sleeping	0.319681	99	0.064286
Infant behavior at night	Frequency during weekends	0.336017	100	0.064935
Infant enjoyment of outdoor walks	Frequency carrying outdoors	0.337374	101	0.065584
Maternal age	Frequency carrying outdoors	0.350415	102	0.066234
Preterm (yes/no)	Weekly hours outdoor sleeping	0.354915	103	0.066883
Infant sex	Infant carrying (indoors+outdoors)	0.357841	104	0.067532
Maternal enjoyment of outdoor walks	Infant carrying (indoors+outdoors)	0.358651	105	0.068182
Working hours weekly	Infant carrying (indoors+outdoors)	0.362114	106	0.068831

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Season (spring/summer/fall/winter)	Frequency outdoor sleeping	0.372870	107	0.069481
Infant behavior at night	Weekly hours outdoor sleeping	0.382411	108	0.070130
Health issues (yes/no)	Frequency during weekdays	0.383044	109	0.070779
Maternal age	Frequency outdoor sleeping	0.407550	110	0.071429
Season (spring/summer/fall/winter)	Frequency carrying outdoors	0.431373	111	0.072078
Preterm (yes/no)	Sleeping outdoors (Yes/No)	0.437216	112	0.072727
Infant sex	Walking weekly in minutes	0.447117	113	0.073377
City size	Frequency carrying outdoors	0.451154	114	0.074026
Infant behavior at night	Sleeping outdoors (Yes/No)	0.452820	115	0.074675
Maternal age	Weekly hours outdoor sleeping	0.478592	116	0.075325
Education level (higher/lower)	Frequency outdoor sleeping	0.482907	117	0.075974
Infant sex	Frequency during weekdays	0.485194	118	0.076623
More than one adult in household	Infant carrying (indoors+outdoors)	0.493723	119	0.077273
Health issues (yes/no)	Weekly hours outdoor sleeping	0.505543	120	0.077922
Employment (working/maternity leave/unemployed)	Frequency during weekends	0.546157	121	0.078571
Gestational age at birth	Infant carrying (indoors+outdoors)	0.548223	122	0.079221
Working hours weekly	Frequency carrying outdoors	0.557721	123	0.079870
Working hours weekly	Frequency during weekends	0.571810	124	0.080519
Working hours weekly	Sleeping outdoors (Yes/No)	0.596097	125	0.081169
Infant sex	Frequency outdoor sleeping	0.604391	126	0.081818
City size	Frequency during weekends	0.615183	127	0.082468

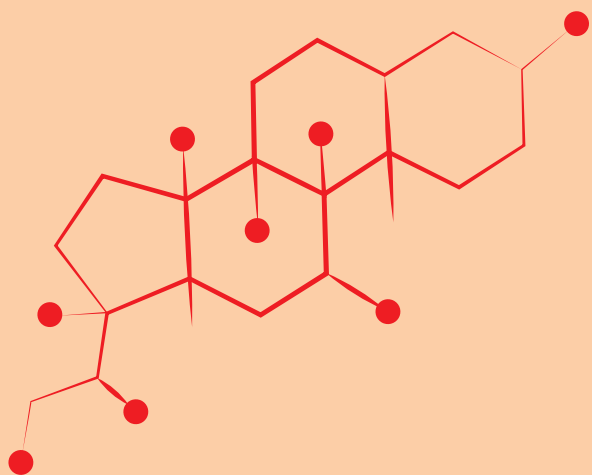
Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Maternal physiological health issues (yes/no)	Weekly hours outdoor sleeping	0.633605	128	0.083117
Gestational age at birth	Frequency during weekends	0.647112	129	0.083766
Health issues (yes/no)	Frequency carrying outdoors	0.651964	130	0.084416
More than one adult in household	Frequency during weekdays	0.662234	131	0.085065
Maternal age	Infant carrying (indoors+outdoors)	0.667253	132	0.085714
Infant sex	Sleeping outdoors (Yes/No)	0.683042	133	0.086364
Preterm (yes/no)	Frequency carrying outdoors	0.697365	134	0.087013
Education level (higher/lower)	Walking weekly in minutes	0.706569	135	0.087662
Preterm (yes/no)	Frequency during weekends	0.706649	136	0.088312
Maternal mental health issues (yes/no)	Frequency outdoor sleeping	0.709640	137	0.088961
More than one adult in household	Walking weekly in minutes	0.724912	138	0.089610
More than one child in household	Weekly hours outdoor sleeping	0.737770	139	0.090260
Maternal mental health issues (yes/no)	Weekly hours outdoor sleeping	0.746191	140	0.090909
Health issues (yes/no)	Frequency outdoor sleeping	0.794312	141	0.091558
Season (spring/summer/fall/winter)	Infant carrying (indoors+outdoors)	0.826307	142	0.092208
Preterm (yes/no)	Frequency outdoor sleeping	0.829618	143	0.092857
City size	Frequency during weekdays	0.850924	144	0.093506
Maternal physiological health issues (yes/no)	Sleeping outdoors (Yes/No)	0.863361	145	0.094156
More than one adult in household	Frequency during weekends	0.865196	146	0.094805
Infant sex	Frequency carrying outdoors	0.915924	147	0.095455
Maternal mental health issues (yes/no)	Walking weekly in minutes	0.921238	148	0.096104
Preterm (yes/no)	Infant carrying (indoors+outdoors)	0.942215	149	0.096753

Table S-B. Continued

Predictor variable	Outcome	P-value	Rank	Critical value
Maternal physiological health issues (yes/no)	Frequency outdoor sleeping	0.948564	150	0.097403
Maternal physiological health issues (yes/no)	Frequency during weekdays	0.952441	151	0.098052
Working hours weekly	Walking weekly in minutes	0.989466	152	0.098701
Maternal mental health issues (yes/no)	Frequency during weekends	0.996998	153	0.099351
Maternal mental health issues (yes/no)	Sleeping outdoors (Yes/No)	1.000000	154	0.100000

Note. Critical value = $(i/m)Q$; i = p-value's rank. m = total number of tests ($N = 154$). Q = false discovery rate. * The tests highlighted in grey were significant after the Benjamini-Hochberg correction.



Chapter 3

Effects of outdoor walking and infant carrying on behavioral and adrenocortical outcomes in mothers and infants

Based on: Rheinheimer, N., Vacaru, S. V., Kühn, S. & de Weerth, C.

Under review

Abstract

This study assessed the effects of a 30-minute walk in an outdoor green environment (vs. staying indoors) and proximity through infant carrying (vs. using a pram) on infants and their mothers. Effects on infant cortisol and sleep, maternal cortisol and mood, and mother-infant adrenocortical synchrony were examined. Infants ($N=101$, 0-5 months old) were exposed to a mild naturalistic stressor. Mother-infant dyads were subsequently randomized to one of four conditions: walking in an outdoor green environment with the infant in a pram or a chest carrier, or staying indoors with the infant in a pram or a chest carrier. Mothers reported infant's sleep in minutes after the conditions, and maternal mood through visual analogue vigor and affect scales both immediately before and after the conditions. Cortisol concentrations of mother and infant were determined through five saliva samples throughout the experiment. After the stressor, carried infants showed a greater decrease in cortisol values compared to infants in the pram, regardless of whether they were walked outdoors or stayed indoors. Infants who were walked outdoors in a carrier or pram slept longer than infants who stayed indoors in a pram. In contrast, mothers staying indoors showed a greater decrease in cortisol concentrations as compared to mothers walking outdoors. Compared to mothers having their infant in a pram, mothers who carried their infant showed a greater decrease in cortisol concentrations. Indoors, maternal vigor decreased from the pre- to post-condition, while mothers going outdoors showed no decrease. There was no difference in maternal affect or mother-infant adrenocortical synchrony between conditions. Our findings have implications for caregiving advice, as well as for future research on the stress-reducing potential of the outdoors in combination with infant carrying.

Introduction

Infants are born with an immature ability to regulate behavioral and physiological states, and hence highly depend on external regulation through their caregivers to regulate stress (Gunnar & Quevedo, 2007; Kopp & Neufeld, 2003; Loman & Gunnar, 2010). Mothers, who are typically primary caregivers, aid regulation through responding contingently and promptly to their infants' cues (Ainsworth et al., 1974; Bell & Ainsworth, 1972). Close proximity between mother and infant, for instance through infant carrying, can positively affect a mother's ability to detect and respond appropriately to her infant's needs (Esposito et al., 2013; Hofer, 1987; Hostinar et al., 2014; Kiel et al., 2024). The physical environment may also play a role, as documented in studies with older children and adults reporting positive associations between exposure to outdoor green environments and behavioral and physiological stress recovery (Corazon et al., 2019; Jones et al., 2021; Moll et al., 2022). To date, there is a lack of research on the effects of infant carrying, as well as the effects of the outdoors, on infant stress regulation. Moreover, they have not been studied in combination. The goal of the current quasi-randomized controlled trial was to investigate how these two factors independently and in conjunction affect infants' stress (measured through salivary cortisol) and sleep, maternal cortisol and mood, and mother-infant adrenocortical synchrony.

When infants are separated from their mothers' biological system at birth, they are required to develop self-regulation (Gunnar & Quevedo, 2007; Kopp & Neufeld, 2003). The hypothalamic-pituitary-adrenal axis (HPA axis) responds to internal and external stressors by producing the hormone cortisol (Gunnar & Quevedo, 2007; Jansen et al., 2010). Although this elevation is a natural reaction to stressors, repeated and prolonged cortisol elevations during infancy have been associated with negative outcomes for stress regulation, and physical and mental health later in life (Brandes-Aitken et al., 2023; Finegood et al., 2017; Mustonen et al., 2024; Nelemans et al., 2017; Radley et al., 2015; Ruttle et al., 2011). When infants are stressed, parents regulate them through prompt sensory cues (e.g., touch, vocalizations), physical closeness, and rocking motions (Hofer, 1987; Hostinar et al., 2014; Kiel et al., 2024). In a laboratory setting, short bouts of carrying in the mothers' arms have been shown to decrease infants' crying and heart rate (Esposito et al., 2013), and were more effective in facilitating sleep onset than infant holding while mothers were seated (Ohmura et al., 2022). The authors concluded that infants show an immediate Transport Response, comparable to reactions in mice when carried (Esposito et al., 2015; Ohmura et al., 2022).

The literature also indicates that increased proximity through infant carrying facilitates the exchange of sensory cues and improves maternal responsiveness to infant vocalizations, which, in turn, is suggested to aid stress recovery (Bigelow & Williams, 2020; Little et al., 2019; Norholt, 2020). Accordingly, an intervention using an infant carrier regularly was shown to facilitate bonding between adolescent mothers and infants (Williams & Turner, 2020). Yet, to our knowledge, no studies have assessed the effects of using an infant chest carrier on behavioral and physiological indicators of stress recovery. Maternal proximity in the form of skin-to-skin contact, however, has been shown to enhance infant sleep duration (Cooijmans, Beijers, & de Weerth, 2022) and reduce mother and infant cortisol - a physiological marker of stress (Beijers et al., 2016; Cong et al., 2015; Hardin et al., 2020; Mörelius et al., 2015). Studies in preterm infants furthermore found that regular skin-to-skin contact increases the attunement between mothers' and infants' cortisol concentrations (Mörelius et al., 2012; Mörelius et al., 2015). The attunement of biological processes is also called biological synchrony - a process suggested to further aid infant regulation (di Lorenzo et al., 2022; Reyna & Pickler, 2009).

Furthermore, the Stress Recovery Theory (SRT) hypothesizes that being outdoors, especially in green environments, facilitates recovery from daily stress (Ulrich et al., 1991). Accordingly, a large number of studies found beneficial effects of outdoor exposure on children's mood, mental health and perceived stress (McCormick, 2017; Moll et al., 2022). For instance, an experimental study in 4-to-5-year-olds found positive effects of time spent in a green schoolyard, as compared to staying indoors, on children's behavioral regulation (Taylor & Butts-Wilmsmeyer, 2020). Another study found positive associations between greener views at home and self-discipline in girls (Taylor et al., 2002), and one study reported positive associations between the amount of greenery around the school or home and socio-emotional regulation (Scott et al., 2018). The mechanisms underlying these potential effects of the outdoors on stress regulation remain largely unknown. The SRT proposes that humans have an innate preference for environments composed of more natural visual elements and fewer human-made stressors (e.g., noise and air pollution), called biophilia. These natural environments would have a lower demand on the human system, decreasing physiological measures of stress and elevating psychological mood (Ulrich et al., 1991).

Notably, previous studies have focused on the benefits of outdoor exposure from toddlerhood to adolescence. At these ages, spending time outdoors may

be linked to active play and sports, which may explain the beneficial effects of outdoor exposure (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011). Outdoor time is likely more passive for infants, as they rely on their caregivers to take them outdoors, for instance for a walk. Nevertheless, the SRT (Ulrich et al., 1991) might still apply to infants, as they may also benefit from more natural visual, auditory and olfactory elements. Moreover, one study has found increased sleep durations when infants were placed outdoors to sleep in a stationary cot as compared to sleeping indoors (Tourula et al., 2010). Furthermore, being walked outdoors, and especially in green environments, is anecdotally reported as calming for infants. To date, however, no studies have assessed the effects of being walked in a pram or carried outdoors in a green environment on behavioral and physiological restoration in infants. Studies in adults have reported the effects of walking in outdoor (green) environments on behavioral measures indicative of restoration from stress, including improved mental well-being, more positive affect, and decreased tiredness (Corazon et al., 2019; Gidlow et al., 2016; Komori et al., 2017; Legrand et al., 2022; Trammell et al., 2023). Furthermore, spending time outdoors, and especially in green environments, has been linked to a reduction of salivary cortisol in a large number of studies (Antonelli et al., 2019; Gidlow et al., 2016; Jones et al., 2021; Kobayashi et al., 2019; Komori et al., 2017; Olafsdottir et al., 2020). However, results on the effects of walking outdoors compared to staying indoors are conflicting. One study on college students found larger decreases in cortisol after going for a walk in a green environment compared to viewing natural landscapes on a screen indoors (Olafsdottir et al., 2020). In contrast, another study in adult males found a decrease of salivary cortisol in a sedentary indoor condition but no change in a forest-walking condition (Toda et al., 2013). Conflicting findings of previous studies might result from differences in study population and design, in terms of experimental conditions, walking duration and speed, and type of environment (Corazon et al., 2019). To date, only one study has assessed effects of outdoor walking on mothers in the postnatal period, reporting decreased postpartum depression after a pram-walking intervention (Armstrong & Edwards, 2004).

To our knowledge, there are no studies on the effects of an outdoor walk, nor the effects of infant carrying, on infants and mothers in one setting. In the current pre-registered study in the Netherlands, we assessed whether going for a 30-minute walk outdoors, as compared to staying indoors, would facilitate regulation after a mild laboratory stressor for the infant, in terms of decreased infant salivary cortisol concentrations and longer durations of sleep.

We furthermore expected that carrying, as compared to using a pram, would benefit infants' regulation. We hypothesized that being carried outdoors would benefit infant regulation the most, and staying in a pram indoors would benefit infant regulation the least. In mothers, we expected to find improved maternal vigor and affect after walking outdoors compared to staying indoors, as well as after infant carrying compared to having the infant in a pram. We hypothesized that mothers walking outdoors with their infant in a carrier would show the highest vigor and affect, while mothers staying indoors with their infant in a pram would show the lowest. We also assessed differences in maternal salivary cortisol between the four groups. However, we did not have a hypothesis on the directionality, as several factors might affect maternal cortisol, such as exercise intensity or infant weight. Furthermore, considering the scarcity of research on the role of proximity and environment on mother-infant adrenocortical synchrony, this effect was also explored without formulating any directional hypotheses.

Methods

Trial design

This quasi-randomized controlled trial, pre-registered at the Open Science Framework (osf.io/9b3eq) and reported in accordance with the CONSORT guidelines, assessed the effect of four parallel conditions in a two-by-two design (indoor vs. outdoor and carrying vs. pram) on infant sleep and cortisol, as well as maternal mood and cortisol. The Research Ethics Committee of the Radboud University Medical Centre declared that the study was in accordance with the applicable legislation (METC Oost-Nederland: 2022-13765). Informed consent was required prior to participation from mothers, as well as other legal guardians of the participating infants.

Participants and sample size

Recruitment took place in the vicinity of Nijmegen (the Netherlands) between August 2022 and March 2023. Mothers were recruited via social media and flyers (e.g., in waiting rooms of practitioners), as well as via the participant database of the Baby and Child Research Center Nijmegen, and via a pool of mothers who indicated willingness to be invited for other research at the end of a larger nationwide online survey (Rheinheimer et al., 2024). Mothers were screened beforehand via the phone on the following inclusion criteria: >18 years old, Dutch fluency, singleton infants between one and five months

old, and no severe maternal or infant health issues or medication that affects adrenocortical regulation (e.g., corticosteroids). Mothers were compensated with a 25 Euro voucher and a book for their infant.

The required sample size was calculated for the outcome of infant and maternal salivary cortisol using G*Power 3 (Faul et al., 2007). A sample of 80 dyads was required for a power of 80% in F-tests, assuming a 0.5 within-subject correlation of cortisol samples, to detect a small effect size (e.g., $f = .15$), based on studies on outdoor walking in adults (Kobayashi et al., 2019; Tyrväinen et al., 2014). Based on a previous study collecting infant salivary cortisol using eye sponges, we expected a 10-15% drop-out due to insufficient saliva (Rheinheimer et al., 2022). To account for that, and to maintain equal group sizes, we recruited 100 mother-infant dyads. Due to unexpected medication report by mother and infant within the same dyad after participation, one dyad was excluded from the study, and an additional dyad was recruited. Two additional mothers were excluded due to unexpected report of medication after participation. Their infants were not excluded, as one of the mothers exclusively formula fed her infant, and the other used medication that is unlikely to affect breastfeeding (LactMed®, 2006). Since the infants of these mothers were not excluded, no additional dyads were enrolled. An additional mother-infant dyad showed extreme values after cortisol determination in all samples ($nmol/L > 60$), suggesting potential contamination of the samples by unreported medication of either infant or mother (e.g., corticosteroid creme), and the dyad was hence excluded from all analyses. The participant flowchart is presented in Figure 1.

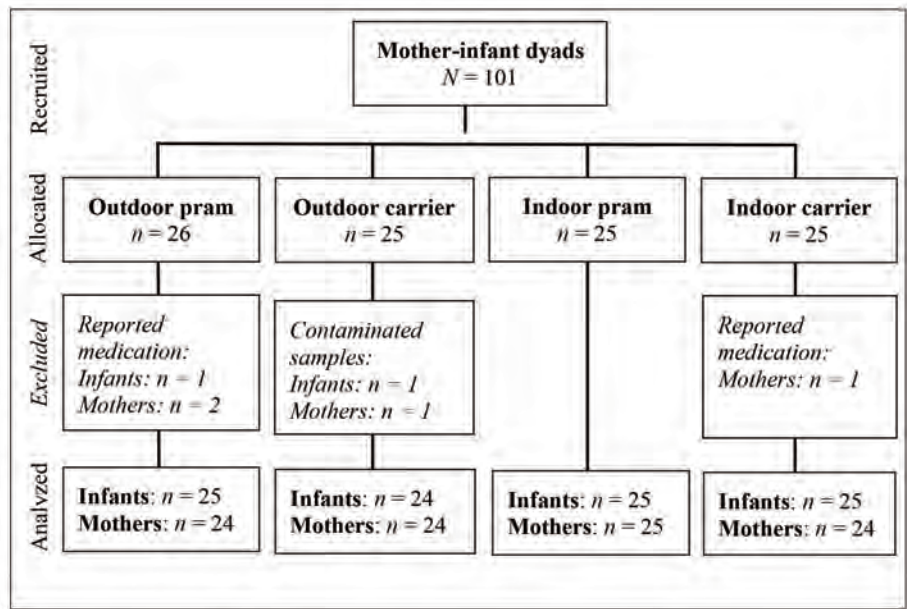


Figure 1. Participant flowchart.

Procedure

The mother-infant dyads were invited to the lab between 12:00 and 18:00 hours. Upon arrival, mothers filled in questionnaires on demographic information. Then, mothers were asked to give their infant a ‘mock bath’ for 12 minutes. Instructions were to undress the infant, change the diaper, ‘wash’ the infant with a dry cloth (chest and back), and then weigh and dress the infant. Previous research indicates that diaper changes and handling induce elevations of infants’ salivary cortisol (Jansen et al., 2010). The researcher left the room, and the task was videotaped.

After the task, dyads were randomly allocated by drawing a sealed envelope to one of the following conditions for a duration of 30 minutes: Walking outdoors with the infant in a pram (OP), or in a chest carrier (OC), or staying indoors, with the infant in a pram (IP), or in a chest carrier (IC). The condition began 20 minutes post-stressor in all dyads in order to allow for preparation (e.g., receiving instructions, bathroom visits, and putting on outdoor garments). Mothers in both outdoor conditions were provided with a map showing a simple route through a green, wooded environment, and were instructed to walk on this route at a pace that suited them and to take a break on a bench

if they felt like it. Mothers in the outdoor conditions were instructed to return to the research building after 30 minutes, regardless of whether they had completed the route or not. Mothers in the two indoor conditions could move around within the research facility and sit in the playroom, which was equipped with toys, children's books, and magazines. For both pram conditions, mothers used the model 'Capri' of the brand 'Bergsteiger', where the infant lay flat and faced upwards. Mothers were instructed to keep the infant in the pram for the entire duration unless the infant was crying and they wished to soothe the infant in their arms or if the infant needed a diaper change. In the carrier conditions, a chest carrier ('Bondolino' from 'Hoppediz') was used. Mothers in the indoor carrier condition could choose to hold the infant in their arms, as sitting in a chair with the chest carrier might feel uncomfortable. Mothers in all conditions were asked not to use their phones or feed the infant during the condition. During all conditions, the researchers waited in a separate room.

Before the start of the condition, mothers were informed that they would later be asked to give an estimate of the total time their infant slept during the condition. Mothers wore one Fitbit around their wrist, in order to keep track of time, and one around their ankle, in order to record steps (Klassen et al., 2016). During the visit, the researcher collected infant saliva by gently swabbing the mouth with an absorbent eye sponge (de Weerth et al., 2007). Mothers provided saliva through passive drool. At the end of the visit, mothers were debriefed and compensated for participation. Both after the stressor and after the conditions, mothers filled in a questionnaire on their mood. Immediately after the condition, mothers also reported the infants' estimated sleep duration in minutes, and the duration of time the infant spent in the pram, the chest carrier, their arm, or on other surfaces.

Randomization and masking

Recruitment included a cover story, stating that the study examined associations between caregiving tasks and hormones, keeping mothers blind to the different conditions. Proximity (pram vs. carrier) was randomized with a likelihood of 1:1 throughout the study. Environment (outdoor vs. indoor) was randomized with a likelihood of 3:1 in spring, summer, and fall and a likelihood of 1:1 in the winter to compensate for weather restrictions on the walk. An independent researcher performed a computer-generated randomization using random blocks of four and eight. Randomization was stored individually in sealed envelopes. All researchers present during the lab visit were unaware of the experimental condition until opening the envelope immediately before

the start of the condition. Due to bad weather (e.g., heat waves or heavy precipitation), 14 dyads had to be reallocated from the outdoor to the indoor condition before the start of the condition.

Measures

Demographic and lab visit information

We tested for group differences in the following variables, in which case the variable would be considered as a covariate: infant sex (boy or girl), infant and maternal age, maternal ethnicity (European or non-European), highest completed maternal education (lower = up to secondary (vocational) education - Dutch VWO/MBO; higher = college or university), time of day at the start of the condition measured in minutes after noon (12:00), temperature at the start of the conditions, and season. Mothers' steps during the condition were measured in order to confirm that mothers walked more steps during the outdoor conditions.

Salivary cortisol

Salivary samples reflect cortisol concentrations of 25 minutes prior to sampling (Dickerson & Kemeny, 2004; Jansen et al., 2010). Saliva was sampled from mothers and infants at arrival to the lab (T0, reflects 25 minutes before arrival), and after the stressor at: 0 minutes (T1, reflects baseline), at 20 minutes (T2, just before starting the condition; reflects expected stress-peak), at 55 minutes (T3, reflects minute 10 of the condition) and at 70 minutes (T4, reflects minute 25 of the condition). Due to great variation in timing between samples T0 and T1, T0 was not used for the analyses. Samples T1 and T2 were used to assess whether infants showed a stress-reaction, and samples T2-T4 were used for the main analyses on cortisol reduction. During the visit, infant and maternal saliva was stored in a portable refrigerator at 4°C. Afterwards, infant saliva was extracted from the eye sponges through centrifuging, and both infant and maternal samples were stored at -20°C. After completion of data collection, all frozen samples were transported on dry ice to the Laboratory of Endocrinology at UMC Utrecht, where cortisol levels were determined with an in-house competitive radioimmunoassay, employing a polyclonal anticortisol antibody (K7348), with the tracer [1,2-3H(N)]-hydrocortisone (PerkinElmer NET396250UC). The lowest detection limit was at 1.0 nmol/L, and inter-assay variation was <6% at 2.5-28 nmol/L, and intra-assay variation was <4%.

Infant sleep duration

The duration of infant sleep during the conditions was reported by the mothers in minutes, ranging from 0 to 30 minutes.

Maternal mood

Maternal mood was assessed through the 'Global Vigor and Affect Scale' (Monk, 1989) after the stressor and after the conditions. The scale consisted of the following eight items: Alertness, Sadness, Tenseness, Effort, Happiness, Weariness, Calmness and Sleepiness. The items were assessed using visual analogue scales ranging from 0 to 100. The items were summed to one score of Global Vigor (GV) and one score of Global Affect (GA), according to the formula below, resulting in scores between 0 and 100, with higher scores indicating better Global Vigor and Affect. Internal consistency was adequate for GV before ($\omega t = .79$) and after ($\omega t = .85$), as well as for GA before ($\omega t = .78$) and after ($\omega t = .76$) the conditions (Revelle & Condon, 2019).

$$GV = [(alert) + 300 - (sleepy) - (effort) - (weary)] / 4$$

$$GA = [(happy) + (calm) + 200 - (sad) - (tense)] / 4$$

Preliminary analyses

Cortisol values higher than the cut-off for biologically realistic values for mothers (> 60 nmol/L, Miller et al., 2013) and infants (> 100 nmol/L, Tollenaar et al., 2010) were considered missing values. Outliers greater than three times the standard deviation plus or minus the mean for all outcome variables were winsorized (Tukey, 1977). All cortisol variables were log-transformed, in accordance with the common practice for salivary cortisol (Simons et al., 2019).

Preliminary group comparisons were performed between all four groups on demographic information, as well as time of day, temperature at the start of the condition, and season, as these variables might differ due to the quasi-randomized design. In case a variable differed significantly across conditions, the variable was added as a covariate in the main analyses. Additionally, preliminary group comparisons for the outcome variables were performed. We performed analyses of variance (ANOVAs) for normally, and Mann-Whitney U tests and Kruskal-Wallis tests for non-normally distributed continuous data, as well as chi-square tests for categorical variables. An additional within-subjects repeated measures ANOVA was performed testing whether infant and maternal cortisol changed from baseline (T1) to the expected stress-peak (T2). Furthermore, a between-subjects ANOVA was performed to confirm whether

mothers in the outdoor condition walked more steps than mothers indoors. Lastly, we computed correlations among all study variables.

Main analyses

Statistical approaches

All analyses were performed using two approaches for each dependent variable (i.e., infant cortisol and sleep, maternal cortisol and mood, adrenocortical synchrony). The first approach had the aim of assessing the combined effects of the environment and proximity by determining differences between all four conditions (OP, OC, IP, IC) in one analysis. In the second approach, two separate analyses were performed, one assessing the main effect of the environment by collapsing the two outdoor and the two indoor conditions (OC + OP vs. IP + IC) and one assessing the main effect of proximity by collapsing the two carrying and the two pram conditions (OC + IC vs. OP + IP). The second approach enabled us to assess the main effects of the environment and proximity independently, with enhanced statistical power through merging the groups. Analyses were performed in R (R Core Team, 2021) using the packages lme4 (Bates et al., 2015), rstatix (Kassambara, 2023), ggstatsplot (Patil, 2021), ggplot2 (Wickham, 2016), FSA (Ogle et al., 2023), DescTools (Signorell, 2017) and stats (R Core Team, 2021).

Infant cortisol

Multilevel growth curve models (MLM) were performed using infants' cortisol of T2 (expected stress-peak), T3 (minute 10 of condition) and T4 (minute 25 of condition) as the outcome. The intercept was added as a random effect. Contrary to the pre-registration, the random slope was not added, as it did not explain sufficient variance ($Var = -0.0001$) and hereby prevented model convergence. The Intraclass Correlation Coefficient (*ICC*) for the raw model was appropriate for infant cortisol (*ICC* = .53). Linear and quadratic time were added as fixed effects. Quadratic time was only kept if it improved the model. Improvement of the model was defined as a significant decrease in the Watanabe-Akaike Information Criterion (WAIC, Hamaker et al., 2011). Preliminarily identified covariates were added in a build-up fashion if they led to a decrease in the WAIC. For the first approach, condition (OP, OC, IC, IP), and the interaction of condition with time were entered as fixed effects. In the second approach, the main effects of the environment (outdoor vs. indoor) or the main effects of proximity (pram vs. carrying), as well as their interaction with time were entered as fixed effects in two separate MLMs. The residuals of all models on infant cortisol were normally distributed.

Infant sleep duration

The distribution of the residuals of the pre-registered between-subjects ANOVAs on infant sleep was left skewed, and normality could not be achieved through transformation (e.g., square root, log transform, cube root). Therefore, non-parametric tests were performed instead. For the first approach, we performed a Kruskal-Wallis test, with sleep as the dependent variable and condition (OP, OC, IP, IC) as the predictor. In this approach, significant differences between the four conditions were further assessed using Dunn's post-hoc test. For the second approach, we performed two separate Mann-Whitney U tests with sleep duration as the dependent variable and, in one analysis, adding environment (outdoor vs. indoor), and in the other analysis, adding proximity (pram vs. carrying) as the predictors.

Maternal cortisol

Maternal cortisol was assessed using the T2, T3, and T4 samples as an outcome using MLM, as described above. The ICC for the raw model on the outcome of maternal cortisol was appropriate ($ICC = .82$), and the residuals were normally distributed.

Maternal mood

Contrary to the pre-registered multivariate repeated measures analysis of variance (rm-ANOVA), because the correlation between maternal Vigor and maternal Affect was low ($r = .30 - .41$; Table 2), we chose to carry out separate rm-ANOVAs for the two maternal mood variables. In the first approach, we performed rm-ANOVAs with all four conditions (OP, OC, IP, IC) as the predictor. For the second approach, we performed rm-ANOVAs with environment (outdoor vs. indoor) or proximity (pram vs. carrying) as the predictors. The residuals of the rm-ANOVAs were left-skewed, and hence Global Vigor and Global Affect were square root transformed, through which multivariate normality was achieved.

Mother-infant adrenocortical synchrony

Mother-infant synchrony was assessed using MLMs with infant cortisol of T2, T3 and T4 as the outcome, and linear as well as quadratic time, potential covariates, maternal cortisol, as well as the interaction of maternal cortisol with condition as predictors. To prevent overfitting, the three-way interaction between maternal cortisol, condition and time was only added if this led to a significant decrease of the WAIC. The residuals were normally distributed.

Sensitivity analyses

We performed additional sensitivity analyses applying per-protocol rules, including only dyads who fulfilled the criteria of the assigned experimental condition. In accordance with a previous RCT on mother-infant contact, a cut-off of 80% was chosen (Cooijmans et al., 2017), meaning that infants in the pram condition were excluded if they spent less than 24 minutes in the pram ($N = 8$), and infants in the carrying condition were excluded if they spent less than 24 minutes on the mothers' chest ($N = 0$). Results of the per-protocol analyses are only reported if they were not in accordance with the intention-to-treat analyses.

Results

Preliminary results

There was no missing data for infant sleep and maternal mood. In total, 495 infant saliva samples and 485 maternal saliva samples were collected. Due to insufficient saliva, infant cortisol concentrations could not be determined for one sample at T0 (1.01%), two samples at T1 (2.02%), three samples at T2 (3.03%), four samples at T3 (4.04%), and five samples at T4 (5.05%). One maternal cortisol concentration could not be determined at T2 (1.03%). One maternal cortisol sample at T4 was replaced with a missing value due to being higher than the cut-off for realistic values ($\text{nmol/L} = 98$). For infant cortisol, we winsorized two outliers at T1, at T2, and at T3, and one outlier at T4. There were no outliers for the duration of infant sleep. For maternal cortisol, we winsorized one outlier at T1, two outliers at T2, and one outlier at T3 and at T4. For maternal Global Vigor at pre-condition, one outlier was winsorized, and for maternal Global Affect at post-condition, two outliers were winsorized.

Group comparisons of demographic information, lab visit information, as well as the outcome variables are shown in Table 1. There were no significant group differences in demographics, time of day, temperature, or season in the intention-to-treat analyses or per-protocol analyses. There was no significant change in infant cortisol ($F[93,1] = 1.72$, $p = .193$, $\eta^2 = .003$) between the samples reflecting baseline (T1, $M = 11.92$, $SD = 5.52$) and the expected stress-peak (T2, $M = 11.53$, $SD = 5.35$). Maternal cortisol reduced significantly ($F[95,1] = 57.168$, $p = .000$, $\eta^2 = .044$) from T1 ($M = 8.47$, $SD = 2.77$) to T2 ($M = 7.42$, $SD = 2.05$). Figure 2 shows infants' and mothers' raw cortisol from T0 to T4. We found that mothers walked significantly more steps outdoors

($M = 2707$, $SD = 575$) as compared to indoors ($M = 680$, $SD = 710$) ($U = 88.5$, $r = .799$, $p = .000$, $95\%CI[-2415, -2006]$). Correlations among study variables are displayed in Table 2.

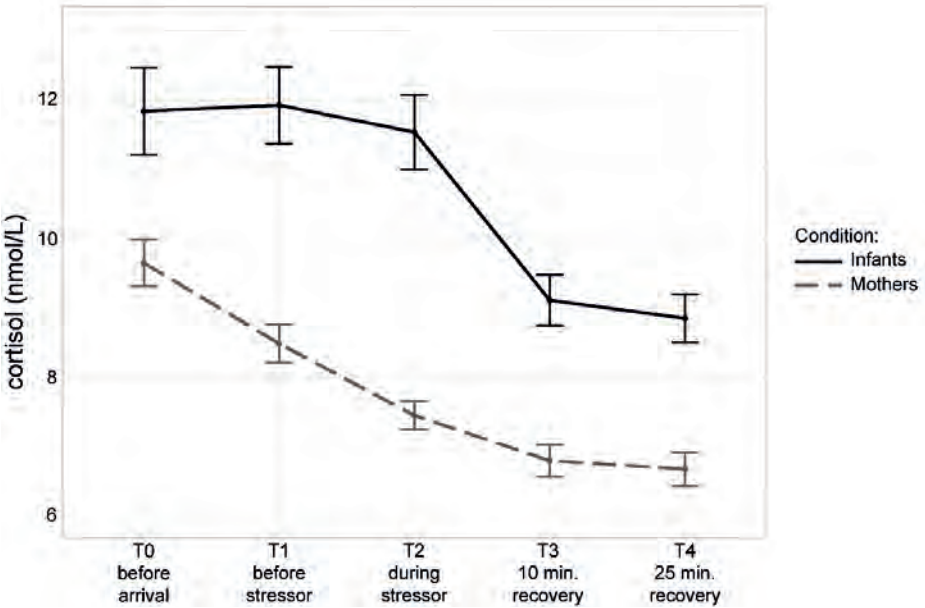


Figure 2. Average cortisol concentrations of infants and mothers. Means and standard errors are plotted for winsorized, non-transformed data.

Table 1. Descriptive statistics and group comparisons

	Approach 1 ^a				Approach 2 ^b			
	Outdoor		Indoor		Environment		Proximity	
	Pram (N=25)	Carrier (N=24)	Pram (N=25)	Carrier (N=25)	Outdoor (N=49)	Indoor (N=50)	Pram (N=50)	Carrier (N=49)
Demographics	M (SD) ^c or %				M (SD) ^e or %		M (SD) ^e or %	
					Stat.	Stat.	Stat.	Stat.
Maternal age (years)	32.32 (4.09)	31.46 (3.31)	31.64 (3.91)	31.76 (4.21)	0.22 ^a	31.90 (3.72)	31.70 (4.02)	31.61 (3.76)
Education (% high)	68%	79%	76%	56%	3.74 ^b	73%	66%	67%
Mother European (% yes)	92%	92%	96%	88%	12.11 ^b	92%	92%	90%
Infant sex (% girls)	48%	42%	48%	28%	2.75 ^b	45%	38%	35%
Infant age (days)	89.44 (35.26)	84.54 (37.96)	94.12 (40.00)	90.36 (39.83)	0.26 ^a	87.04 (36.31)	92.24 (39.55)	87.51 (38.63)
Lab visit								
Visit time in minutes after noon ^g	107.16 (76.94)	136.71 (86.58)	108.64 (68.36)	140.36 (88.76)	2.92 ^d	121.63 (83.31)	124.50 (80.02)	138.57 (86.80) ^c
Outdoor temperature ^h	14.08 (6.63)	14.33 (7.94)	10.84 (9.10)	12.52 (6.42)	1.12 ^a	14.20 (7.23)	11.68 (7.84)	13.41 (7.18)
Season								
Spring	8%	4%	8%	0%	7.28 ^b	6%	4%	2%
Summer	12%	21%	12%	8%		16%	10%	14%
Fall	52%	46%	36%	40%		49%	38%	42%
Winter	28%	29%	44%	52%		29%	48%	40%
Number of steps walked	2728 (516)	2685 (641)	704 (548)	657 (853)	63.54 ^{d***}	2707 (575)	680 (710)	1650 (1269)

Table 1. Continued

	Approach 1 ^a					Approach 2 ^b				
	Outdoor		Indoor			Environment		Proximity		
	Pram	Carrier	Carrier	Pram	Carrier	Outdoor	Indoor	Pram	Carrier	Stat.
	M (SD) ^c or %					M (SD) ^c or %				
Infant cortisol (nmol/L) ^{e,f}	N=25	N=24	N=25	N=25	N=25	N=49	N=50	N=50	N=49	
Baseline (T1)	11.84 (5.99)	12.42 (4.34)	10.74 (3.89)	12.77 (7.41)	0.60 ^a	12.12 (5.20)	11.71 (5.87)	11.29 (5.03)	12.59 (5.98)	1.39 ^a
Stress-peak (T2)	10.78 (5.22)	11.33 (4.34)	11.40 (6.03)	12.57 (5.68)	0.64 ^a	11.03 (4.79)	11.99 (5.83)	11.09 (5.59)	12.01 (5.10)	1.36 ^a
Condition minute 10 (T3)	8.19 (3.21)	8.93 (2.72)	9.46 (3.93)	9.86 (4.45)	0.93 ^a	8.54 (2.98)	9.65 (4.15)	8.81 (3.60)	9.39 (3.68)	0.83 ^a
Condition minute 25 (T4)	9.50 (4.56)	8.00 (2.37)	9.13 (3.93)	8.73 (2.60)	0.42 ^a	8.75 (3.67)	8.92 (3.27)	9.32 (4.23)	8.36 (2.49)	0.59 ^a
Infant sleep duration ^e	N=25	N=24	N=25	N=25	N=25	N=49	N=50	N=50	N=49	
Sleep in minutes	19.40 (11.39)	20.67 (9.46)	10.88 (10.42)	19.12 (9.94)	12.12 ^{d**}	20.02 (10.40)	15.00 (10.90)	15.14 (11.63)	19.88 (9.64)	964.5 ^c
Maternal cortisol (nmol/L) ^{e,f}	N=24	N=24	N=25	N=24	N=24	N=48	N=49	N=49	N=48	
Before stressor (T1)	8.93 (2.67)	7.87 (1.73)	8.69 (2.42)	8.36 (3.88)	0.83 ^a	8.40 (2.29)	8.53 (3.19)	8.81 (2.52)	8.12 (2.98)	2.45 ^a
During stressor (T2)	7.80 (2.29)	6.97 (1.36)	7.84 (2.03)	7.08 (2.34)	0.94 ^a	7.38 (1.90)	7.47 (2.20)	7.82 (2.13)	7.02 (1.89)	2.86 ^a
10 minute recovery (T3)	7.49 (2.76)	6.38 (1.92)	7.13 (2.27)	6.06 (2.08)	1.49 ^a	6.93 (2.42)	6.61 (2.22)	7.31 (2.50)	6.22 (1.99)	3.78 ^a
25 minute recovery (T4)	7.64 (3.31)	6.38 (2.03)	6.91 (1.93)	5.60 (1.72)	3.01 ^{a*}	7.01 (2.79)	6.28 (1.93)	7.27 (2.69)	6.00 (1.91)	6.63 ^{a*}

Table 1. Continued

	Approach 1 ^a				Approach 2 ^b			
	Outdoor		Indoor		Environment		Proximity	
	Pram	Carrier	Pram	Carrier	Outdoor	Indoor	Pram	Carrier
	M (SD) ^e or %				M (SD) ^e or %		M (SD) ^e or %	
	Stat.				Stat.		Stat.	
Maternal mood^f	N=24	N=24	N=25	N=24	N=48	N=49	N=49	N=48
<i>Affect pre-condition</i>	82.39 (10.92)	85.92 (12.20)	84.86 (11.90)	86.71 (10.10)	84.15 (11.59)	85.77 (10.98)	83.65 (11.38)	86.31 (11.08)
<i>Affect post-condition</i>	81.17 (14.50)	86.99 (10.02)	84.43 (11.49)	87.43 (9.88)	84.08 (12.68)	85.90 (10.73)	82.84 (13.02)	87.21 (9.85)
<i>Vigor pre-condition</i>	71.17 (13.93)	73.80 (16.68)	74.39 (16.16)	73.22 (15.52)	72.48 (15.26)	73.82 (15.70)	72.81 (15.04)	73.51 (15.94)
<i>Vigor post-condition</i>	68.67 (17.53)	72.53 (17.44)	62.76 (23.58)	63.72 (19.98)	70.60 (17.41)	63.23 (21.67)	65.65 (20.84)	68.13 (19.08)

Note. M, Mean; SD, Standard Deviation; Stat., Test statistic. ^a Cohen's F for analyses of variance comparing group means. ^b χ^2 for chi-square tests on categorical data. ^c U for Mann-Whitney U tests for non-normally distributed data. ^d χ^2 for Kruskal-Wallis tests comparing more than two group means with non-normally distributed data. ^e M and SD are presented for non-transformed data. ^f Winsorized data. ^g Approach 1 comparing the four experimental conditions. ^h Approach 2 separately assessing the effects of Outdoor versus Indoor and Pram versus Carrier by merging the conditions. * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 2. Correlations among study variables across the entire study group (N=99)

Variables	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.
1. Infant age	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2. Maternal age	.16 ^a	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3. Time of day ^c	.10 ^b	-.10 ^b	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
4. Outdoor temperature ^d	.34^{a***}	.07 ^a	.09 ^b	.	.	.	.	.	.	.	.	.	.	.	.	.	.
5. Steps walked	-.04 ^b	.00 ^b	-.05 ^b	.12 ^b	.	.	.	.	.	.	.	.	.	.	.	.	.
6. Infant cortisol T1	-.13 ^a	.05 ^a	-.06 ^b	.06 ^a	.11 ^b	.	.	.	.	.	.	.	.	.	.	.	.
7. Infant cortisol T2	-.35^{a***}	-.03 ^a	-.16 ^b	-.22^{a*}	.06 ^b	.63^{a***}	.	.	.	.	.	.	.	.	.	.	.
8. Infant cortisol T3	-.29^{a**}	.11 ^a	-.25^{b*}	-.17 ^a	-.05 ^b	.45^{a***}	.81^{a***}	.	.	.	.	.	.	.	.	.	.
9. Infant cortisol T4	-.04 ^a	.18 ^a	-.17 ^b	-.05 ^a	-.09 ^b	.17 ^a	.41^{a***}	.61^{a***}	.	.	.	.	.	.	.	.	.
10. Infant sleep	-.36^{b***}	.03 ^b	-.09 ^b	-.10 ^b	.05 ^b	.10 ^b	.18 ^b	.05 ^b	-.09 ^b	.	.	.	.	.	.	.	.
11. Maternal cortisol T1	-.07 ^a	-.09 ^a	-.28^{b**}	.06 ^a	.04 ^b	.03 ^a	.17 ^a	.24^{a*}	.21^{a*}	.03 ^b	.	.	.	.	.	.	.
12. Maternal cortisol T2	-.03 ^a	-.12 ^a	-.31^{b***}	.04 ^a	.02 ^b	.06 ^a	.21^{a*}	.32^{a**}	.23^{a*}	-.03 ^b	.85^{a***}	.	.	.	.	.	.
13. Maternal cortisol T3	-.02 ^a	-.11 ^a	-.37^{b***}	.02 ^a	.06 ^b	.10 ^a	.16 ^a	.27^{a**}	.21^{a*}	-.12 ^b	.71^{a***}	.86^{a***}	.	.	.	.	.
14. Maternal cortisol T4	.01 ^a	.06 ^a	-.39^{b***}	.03 ^a	.07 ^b	.11 ^a	.14 ^a	.26^{a*}	.19 ^a	-.10 ^b	.61^{a***}	.79^{a***}	.93^{a***}	.	.	.	.
15. Maternal Vigor pre	.08 ^b	-.10 ^b	-.13 ^b	.07 ^b	-.04 ^b	-.09 ^b	-.10 ^b	-.12 ^b	-.29^{b**}	-.03 ^b	.09 ^b	.15 ^b	.12 ^b	.15 ^b	.	.	.
16. Maternal Vigor post	.04 ^b	-.10 ^b	-.14 ^b	.12 ^b	.17 ^b	-.01 ^b	-.10 ^b	-.18 ^b	-.29^{b**}	.17 ^b	.15 ^b	.16 ^b	.14 ^b	.14 ^b	.77^{b***}	.	.
17. Maternal Affect pre	.16 ^b	.02 ^b	.01 ^b	.04 ^b	-.00 ^b	-.05 ^b	-.06 ^b	-.07 ^b	-.20 ^b	.04 ^b	.08 ^b	.01 ^b	-.07 ^b	-.01 ^b	.41^{b***}	.41^{b***}	.
18. Maternal Affect post	-.01 ^b	.05 ^b	-.04 ^b	-.05 ^b	-.07 ^b	-.08 ^b	-.04 ^b	-.09 ^b	-.19 ^b	.27^{a**}	.06 ^b	-.00 ^b	.06 ^b	-.00 ^b	.30^{b**}	.40^{b*}	.64^{b***}

Note. ^a Pearson correlation. ^b Spearman correlation. ^c Start of the condition in minutes after noon (12:00). ^d Outdoor temperature in degrees Celsius.

*p<.05, **p<.01, ***p<.001.

Main results

Infant cortisol

The final MLMs for infant cortisol are displayed in Table 3. There were significant main effects of linear time for all models, indicating a decrease of infant cortisol over time. In approach 1, there was no significant interaction of condition with time. In the per-protocol analyses, however, infants in the indoor carrier condition showed a larger decrease in cortisol over time compared to infants in the indoor pram condition ($B = 0.002$, $SE = 0.001$, $t = 2.053$, $p = .042$, $95\%CI[0.0001,0.0034]$). In approach 2, infants in the carrier condition showed a larger decrease in cortisol over time than infants in the pram condition ($B = -0.001$, $SE = 0.001$, $t = -2.288$, $p = .023$, $95\%CI[-0.0025,-0.0002]$). Infant cortisol by condition is illustrated in Figure 3.

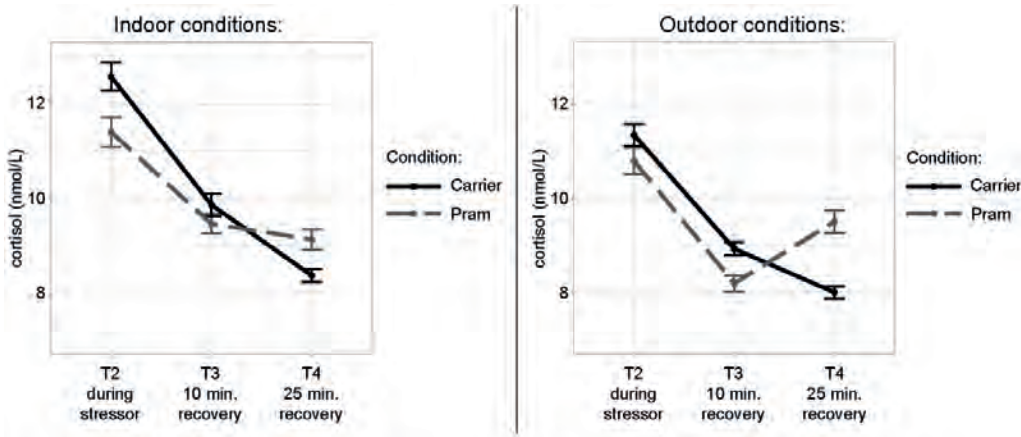


Figure 3. Average infant cortisol concentrations per condition. Means and standard errors are plotted for winsorized, non-transformed data.

Table 3. Multilevel growth curve models for infant cortisol

Approach 1 ^{a,b}					
<i>Condition = Outdoor pram - outdoor carrier - indoor pram - indoor carrier</i>					
Intercept		<i>B(SE)</i>	<i>t</i>	<i>p</i>	
		0.977 (0.029)	33.941		.000
Time					
		-0.003 (0.001)	-5.021		.000
Condition					
	Indoor Carrier - Indoor Pram	-0.012 (0.041)	-0.299		.766
	Indoor Carrier - Outdoor Carrier	-0.031 (0.041)	-0.757		.451
	Indoor Carrier - Outdoor Pram	-0.040 (0.041)	-0.989		.325
	Indoor Pram - Outdoor Carrier	-0.019 (0.041)	-0.459		.647
	Outdoor Pram - Indoor Pram	0.028 (0.041)	0.687		.494
	Outdoor Pram - Outdoor Carrier	0.009 (0.041)	0.220		.827
	Time x Indoor Carrier - Indoor Pram	0.001 (0.001)	1.558		.121
	Time x Indoor Carrier - Outdoor Carrier	0.000 (0.001)	0.085		.933
	Time x Indoor Carrier - Outdoor Pram	0.001 (0.001)	1.795		.074
	Time x Indoor Pram - Outdoor Carrier	-0.001 (0.001)	-1.427		.155
	Time x Outdoor Pram - Indoor Pram	-0.000 (0.001)	-0.203		.839
	Time x Outdoor Pram - Outdoor Carrier	-0.001 (0.001)	-1.654		.100
Approach 2 ^{a,c}					
<i>Environment(Condition=Outdoor-Indoor)</i>					
<i>Proximity(Condition=Pram-Carrier)</i>					
<i>B(SE)</i>					
Intercept		<i>t</i>	<i>p</i>	<i>B(SE)</i>	<i>t</i>
	0.971 (0.020)	47.648	.000	0.951 (0.020)	46.45
Time					
	-0.002 (0.000)	-5.413	.000	-0.002 (0.000)	-3.737
Condition					
	-0.030 (0.029)	-1.034	.304	0.011 (0.029)	0.378
Condition x Time					
	0.000 (0.001)	0.314	.754	-0.001 (0.001)	-2.288

Note. *Time*, Linear Time; *SE*, Standard Error. ^a Log-transformed and winsorized outcome variables. ^b Approach 1 comparing the four experimental conditions. ^c Approach 2 separately assessing the effects of Outdoor versus Indoor and Pram versus Carrier by merging the conditions. P-values highlighted in bold were significant.

Infant sleep duration

Since there were no significant group differences in demographic characteristics, and as such no need to control for covariates, we refer to the group differences for infant sleep duration as reported in Table 1. For approach 1, there was a significant difference comparing all four conditions ($\chi^2 = 12.12$, $p = .007$, $\eta^2 = .10$). Dunn's post-hoc tests indicated significant group differences for infant's sleep duration between the indoor pram ($Mdn = 10$, $M = 10.88$, $SD = 10.42$) and the outdoor pram ($Mdn = 25$, $M = 19.40$, $SD = 11.39$) condition ($Z = -2.90$, $p_{\text{adjusted}} = .019$), and between the indoor pram and the outdoor carrier ($Mdn = 24.5$, $M = 20.67$, $SD = 9.46$) condition ($Z = -3.03$, $p_{\text{adjusted}} = .015$). In approach 2, infants in the outdoor condition ($Mdn = 25$, $M = 20.02$, $SD = 10.40$) slept for a significantly longer duration ($U = 874.50$, $r = .248$, $p = .014$, $95\%CI[-10.00, -0.00]$) than infants in the indoor condition ($Mdn = 15$, $M = 15.00$, $SD = 10.90$). The average infant sleep duration per condition is shown in Figure 4.

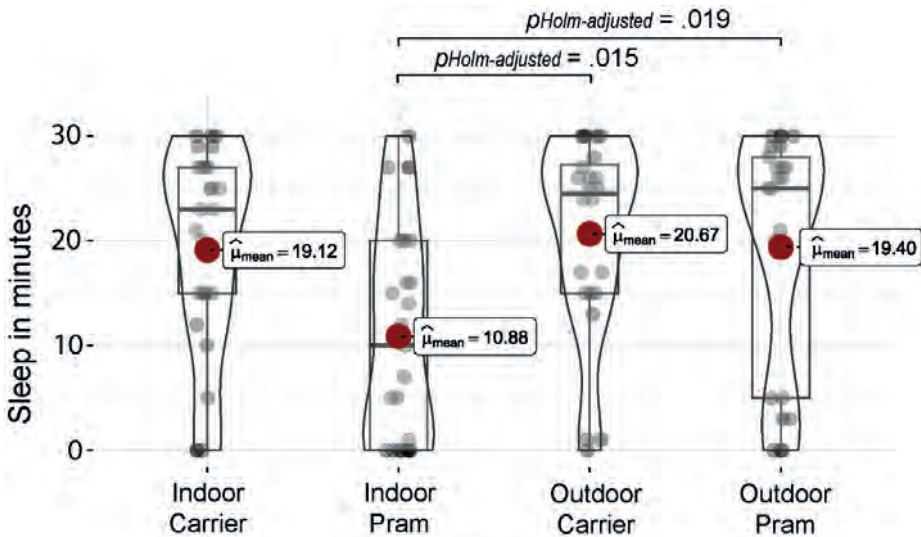


Figure 4. Average infant sleep duration in minutes per condition. Data distribution is shown through the width of the violin shape, where a larger width indicates a higher frequency of scores. Red dots show the group mean.

Maternal cortisol

Table 4 shows the final models for maternal cortisol. There was a significant effect of linear time, indicating a decrease in maternal cortisol. In approach 1, mothers in the indoor carrier condition showed a larger decrease of cortisol over time than mothers in the outdoor pram condition ($B = 0.001$, $SE = 0.000$, $t = 2.563$, $p = .011$, $95\%CI[0.0002,0.0019]$). In approach 2, mothers in the indoor condition showed a larger decrease of cortisol over time compared to mothers outdoors ($B = 0.001$, $SE = 0.000$, $t = 2.031$, $p = .044$, $95\%CI[0.00002,0.00119]$). The main effect of proximity (pram vs. carrier) was significant in the intention-to-treat analyses. Mothers in the carrier condition showed lower overall cortisol values than mothers in the pram condition ($B = -0.059$, $SE = 0.027$, $t = -2.163$, $p = .033$, $95\%CI[-0.1132,-0.0050]$). However, this main effect of proximity (pram vs. carrying) was not significant in the per-protocol analyses ($B = -0.041$, $SE = 0.028$, $t = -1.458$, $p = .148$, $95\%CI[-0.0966,0.0147]$). The change of maternal cortisol over time is illustrated in Figure 5.

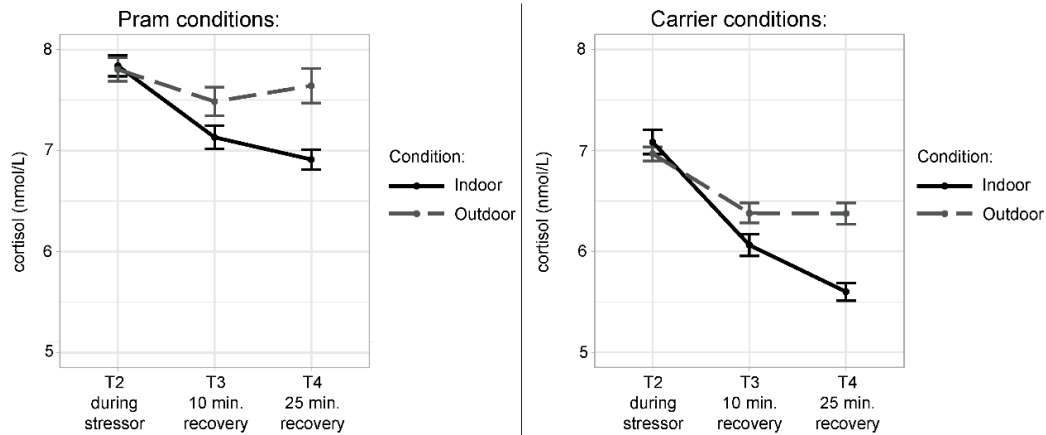


Figure 5. Average maternal cortisol concentrations per condition. Means and standard errors are plotted for winsorized, non-transformed data.

Table 4. Multilevel growth curve models for maternal cortisol

Approach 1 ^{a,b}				
<i>Condition= Outdoor pram - outdoor carrier - indoor pram - indoor carrier</i>				
Intercept		<i>B(SE)</i>	<i>t</i>	<i>p</i>
		0.777 (0.027)	28.433	.000
Time				
		-0.002 (0.000)	-6.121	.000
Condition				
	Indoor Carrier - Indoor Pram	0.061 (0.038)	1.594	.114
	Indoor Carrier - Outdoor Carrier	0.026 (0.039)	0.661	.510
	Indoor Carrier - Outdoor Pram	0.083 (0.039)	2.152	.034
	Indoor Pram - Outdoor Carrier	-0.035 (0.038)	-0.927	.356
	Outdoor Pram - Indoor Pram	-0.022 (0.038)	-0.580	.563
	Outdoor Pram - Outdoor Carrier	-0.058 (0.039)	-1.492	.139
	Time x Indoor Carrier - Indoor Pram	0.001 (0.000)	1.602	.111
	Time x Indoor Carrier - Outdoor Carrier	0.001 (0.000)	1.953	.052
	Time x Indoor Carrier - Outdoor Pram	0.001 (0.000)	2563	.011
	Time x Indoor Pram - Outdoor Carrier	0.000 (0.000)	0.361	.718
	Time x Outdoor Pram - Indoor Pram	-0.000 (0.000)	-0.993	.322
	Time x Outdoor Pram - Outdoor Carrier	-0.000 (0.000)	-0.633	.528
Approach 2 ^{a,c}				
<i>Environment(Condition=Outdoor-Indoor)</i>				
<i>Proximity(Condition=Pram-Carrier)</i>				
	<i>B(SE)</i>	<i>t</i>	<i>p</i>	
Intercept	0.809 (0.020)	41.183	.000	
Time	-0.001 (0.000)	-7.106	.000	
Condition	0.023 (0.028)	0.834	.407	
Condition x Time	0.001 (0.000)	2.031	.044	

Note. Time, Linear Time; SE, Standard Error. ^a Log transformed and winsorized outcome variables. ^b Approach 1 comparing the four experimental conditions. ^c Approach 2 separately assessing the effects of Outdoor versus Indoor and Pram versus Carrier by merging the conditions. P-values highlighted in bold were significant.

Maternal mood

Table 5 shows the results for maternal mood. In approach 1, there was a significant difference in the change of global vigor over time between the four conditions ($F[3,93] = 3.294, \eta^2 = .096, p = .024$). Post-hoc analyses for approach 1 showed that Global Vigor decreased significantly from pre- to post-condition in the indoor pram ($F[1,23] = 19.50, \eta^2 = .054, p_{\text{adjusted}} = .001$) and the indoor carrier ($F[1,23] = 7.380, \eta^2 = .061, p_{\text{adjusted}} = .048$) conditions, but not in the outdoor pram ($F[1,23] = 0.475, \eta^2 = .003, p > .999$) and the outdoor carrier ($F[1,23] = 0.361, \eta^2 = .001, p > .999$) conditions. Accordingly, in approach 2, mothers in the indoor condition showed a significantly larger decrease in vigor compared to mothers in the outdoor condition ($F[1,95] = 9.985, \eta^2 = .095, p = .002$). The change of Global Vigor from pre- to post-condition is illustrated in Figure 6. There were no differences between conditions for Global Affect. Most per-protocol results were in accordance with the intention-to-treat analyses, however, for approach 1, the interaction of condition with time became marginally significant for Global Vigor ($F[3,85] = 2.334, \eta^2 = .009, p = .080$).

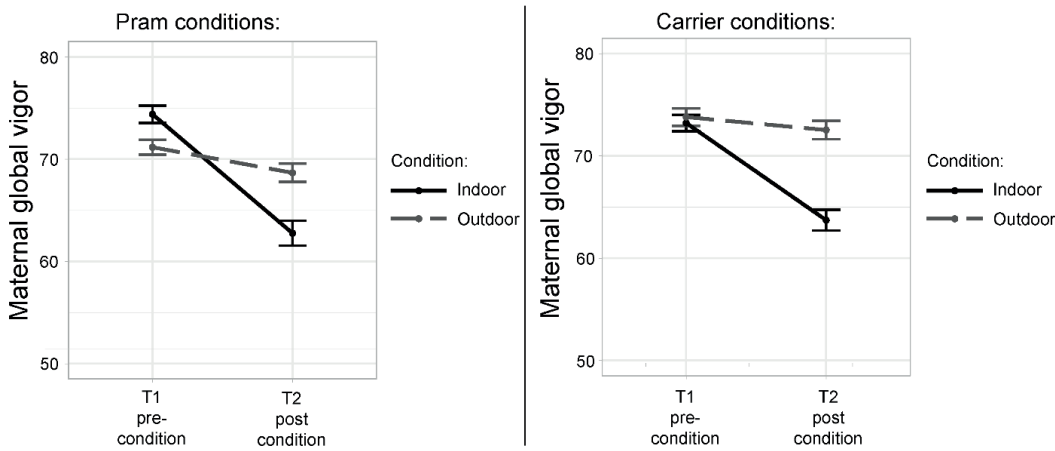


Figure 6. Change of maternal Global Vigor from pre- to post-condition for winsorized, non-transformed data.

Table 5. Repeated measures analyses of variance for maternal mood

Approach 1^b				Approach 2^c					
<i>Cond. = Outdoor pram - outdoor carrier - indoor pram - indoor carrier</i>				<i>Environment Cond. = Outdoor - Indoor</i>		<i>Proximity Cond. = Pram - Carrier</i>			
Global Vigor^a	η^2	<i>F(df)</i>	<i>p</i>	η^2	<i>F(1,95)</i>	<i>p</i>	η^2	<i>F(1,95)</i>	<i>p</i>
Time	.164	18.215(1,93)	.000	.164	18.624	.000	.020	17.099	.000
Cond.	.015	0.458(3,93)	.713	.006	0.571	.452	.002	0.209	.649
Time*Cond.	.096	3.294(3,93)	.024	.095	9.985	.002	.000	0.105	.747
Global Affect^a	η^2	<i>F(df)</i>	<i>p</i>	η^2	<i>F(1,95)</i>	<i>p</i>	η^2	<i>F(1,95)</i>	<i>p</i>
Time	.001	0.113(1,93)	.738	.001	0.110	.741	.001	0.115	.735
Cond.	.037	1.205(3,93)	.312	.005	0.509	.477	.029	2.796	.098
Time*Cond.	.004	0.130(3,93)	.942	.000	0.023	.880	.004	0.342	.560

Note. *Cond.*, Condition; η^2 , partial eta². ^a Square root transformed dependent variables.

^b Approach 1 comparing the four experimental conditions. ^c Approach 2 separately assessing the effects of Outdoor versus Indoor and Pram versus Carrier by merging the conditions.

P-values highlighted in bold were significant.

Mother-infant adrenocortical synchrony

The final models for mother-infant adrenocortical synchrony are displayed in Table 6. While maternal cortisol positively predicted infant cortisol, none of the analyses showed significant interactions between maternal cortisol and condition in predicting infant cortisol.

Table 6. Exploratory multilevel growth curve models for mother-infant adrenocortical synchrony

Approach 1 ^{a,b}				
<i>Condition= Outdoor pram - outdoor carrier - indoor pram - indoor carrier</i>				
Intercept	<i>B(SE)</i>	<i>t</i>	<i>p</i>	
	0.845 (0.134)	6.315	.000	
Time	-0.002 (0.000)	-5.949	.000	
Maternal cortisol	0.321 (0.160)	2.004	.046	
Condition				
Indoor Carrier - Indoor Pram	0.138 (0.183)	0.755	.451	
Indoor Carrier - Outdoor Carrier	0.037 (0.202)	0.182	.856	
Indoor Carrier - Outdoor Pram	0.027 (0.183)	0.124	.902	
Indoor Pram - Outdoor Carrier	-0.101 (0.208)	-0.486	.627	
Outdoor Pram - Indoor Pram	0.115 (0.189)	0.612	.541	
Outdoor Pram - Outdoor Carrier	0.014 (0.208)	0.068	.946	
Maternal Cortisol x Indoor Carrier - Indoor Pram	-0.207 (0.220)	-0.940	.348	
Maternal Cortisol x Indoor Carrier - Outdoor Carrier	-0.099 (0.250)	-0.396	.693	
Maternal Cortisol x Indoor Carrier - Outdoor Pram	-0.106 (0.218)	-0.485	.628	
Maternal Cortisol x Indoor Pram - Outdoor Carrier	0.108 (0.250)	0.432	.666	
Maternal Cortisol x Outdoor Pram - Indoor Pram	-0.101 (0.217)	-0.466	.642	
Maternal Cortisol x Outdoor Pram - Outdoor Carrier	0.007 (0.248)	0.028	.978	
Approach 2 ^{a,c}				
<i>Environment(Condition=Outdoor-Indoor)</i>				
<i>Proximity(Condition=Pram-Carrier)</i>				
	<i>B(SE)</i>	<i>t</i>	<i>p</i>	<i>p</i>
Intercept	0.930 (0.100)	9.279	0.932 (0.101)	9.240
Time	-0.002 (0.000)	-6.116	-0.002 (0.000)	-6.021
Condition	-0.041 (0.136)	-0.301	-0.066 (0.138)	-0.483
Maternal Cortisol	0.196 (0.113)	1.743	0.159 (0.110)	1.442
Maternal Cortisol x Condition	0.007 (0.161)	0.046	0.111 (0.165)	0.672

Note. SE, Standard Error. ^a Log transformed and winsorized outcome variables. ^b Approach 1 comparing the four experimental conditions. ^c Approach 2 separately assessing the effects of Outdoor versus Indoor and Pram versus Carrier by merging the conditions. P-values highlighted in bold were significant.

Discussion

This study experimentally assessed effects of outdoor walking in a green environment, compared to staying indoors, combined with two types of proximity, namely infant in pram and infant carrying, on infant cortisol and sleep, maternal cortisol and mood, and mother-infant adrenocortical synchrony.

Infant cortisol

Unexpectedly, our first hypothesis, stating that the outdoor environment has a greater effect on infants' physiological stress recovery, was not confirmed. Results showed no differences in cortisol between the indoor and outdoor conditions. However, our stressor did not elicit significant increases in infant cortisol, indicating that infants may not have been stressed sufficiently to note a meaningful recovery. On the other hand, while cortisol typically follows a circadian rhythm, with a linear decrease in the afternoon (Gröschl et al., 2003), the infants in our study showed rather stable cortisol concentrations between the sample reflecting the time before their arrival (T0) and during the stressor approximately one hour later (T2, Figure 2). This absence of a circadian decline suggests that being in the laboratory and undergoing a mock bath might have been slightly stressful for the infants, possibly due to the unfamiliar facilities and researchers. Nevertheless, future studies assessing whether being walked outdoors has stress-reducing effects should consider using more challenging stressors, such as a doctor's examination or a heel prick (Jansen et al., 2010). Notably, studies in adults found decreasing effects of the outdoors on cortisol even without employing a stressor beforehand (Antonelli et al., 2019; Gidlow et al., 2016; Jones et al., 2021; Kobayashi et al., 2019; Komori et al., 2017; Olafsdottir et al., 2020). Potentially, young infants' immature sensory processing (e.g. vision and color perception) may have led to less sensory input, and to less down-regulation by the outdoors (Clark-Gambelunghé & Clark, 2015).

In line with our expectations, we found an effect of proximity following the laboratory procedure on infant cortisol, regardless of whether the infants were walked outdoors or stayed indoors. Infants who were carried and/or held showed a greater decrease of cortisol over time, as compared to infants in the pram. These findings are in accordance with studies reporting stress-reducing effects of carrying in the mothers' arms in the laboratory (Esposito et al., 2013) and skin-to-skin contact on infant cortisol (Beijers et al., 2016; Hardin et al., 2020; Mörelius et al., 2015), and support the hypothesis that

maternal closeness and carrying facilitate infant (stress) regulation (Bigelow & Williams, 2020; Feldman, 2007; Li et al., 2018; Norholt, 2020). As the effects of carrying and/or holding indoors on infant cortisol were equal to being carried outdoors, these findings suggest that maternal proximity may facilitate infant regulation beyond a Transport Response (Esposito et al., 2015), possibly through the exchange of physical (e.g., thermal and olfactory) and socio-emotional (e.g. vocalizations, smiling) cues (Kiel et al., 2024; Norholt, 2020).

Infant sleep

According to our hypotheses, infants who were walked outdoors slept longer than infants staying indoors. Interestingly, as 0-to-6-month-olds typically nap for more than 30-minutes (Galland et al., 2012; Trujillo-Priego et al., 2020), most infants, once asleep, did not awaken during the 30-minute condition, and hence the current measure possibly reflects a faster sleep onset in the outdoor conditions. Also, as expected, mothers outdoors walked significantly more steps as compared to mothers indoors, thereby possibly causing more rocking motions. Interestingly, however, the number of steps walked was not correlated to infant sleep durations, suggesting that outdoor exposure might benefit infant sleep beyond increased rocking motion. Accordingly, a study using stationary cots found longer sleep durations when infants were sleeping outdoors as compared to indoors (Tourula et al., 2010). In line with the Stress Recovery Theory (Ulrich et al., 1991), our findings suggest that effects of outdoor green environments may already manifest early in life. While our study provides evidence on the positive effects of the outdoors on infant sleep, both replication studies as well as studies aiming to unveil underlying mechanisms are dearly needed.

Additionally, infants who were carried or held slept equally long in the current study, regardless of whether they were walked outdoors or stayed indoors. This suggests that maternal proximity also facilitated infant sleep, similarly to the effects of proximity on infant cortisol. Accordingly, mother-infant skin-to-skin contact has been shown to facilitate infant sleep (Cooijmans, Beijers, & de Weerth, 2022).

We also hypothesized that being carried outdoors would benefit infant regulation the most, and staying in a pram indoors would benefit regulation the least. We did not find differences between the indoor pram and the outdoor carrier condition in terms of infant cortisol. However, in support of our hypothesis, infants in the outdoor carrier condition slept significantly longer than infants in the indoor pram condition.

Maternal cortisol

For mothers who stayed indoors, we found a greater decrease of cortisol as compared to mothers walking outdoors. These findings are in contrast with the reported cortisol decreases after outdoor walking in a study on college students (Olafsdottir et al., 2020). Current findings are more in line with a study reporting a decrease of salivary cortisol in adults after a sedentary indoor condition but not after a forest-walking condition (Toda et al., 2013). Notably, moderate to high exercise intensities have been shown to increase cortisol in adults (Hill et al., 2008). One could conclude that in the current study, higher cortisol concentrations after walking outdoors as compared to staying indoors may reflect added physical strain, as mothers outdoors had to transport their infant (either in pram or chest carrier) and walked more steps. Nevertheless, the number of steps walked did not correlate with maternal cortisol across the entire sample, indicating that other factors contributed to the greater cortisol decreases indoors. Possibly, the unfamiliar outdoor environment and imposed experimental instructions (e.g., following a route, tracking time) posed a greater challenge to mothers outdoors, whereas mothers staying indoors had already familiarized themselves with the environment in the hour before the conditions. It remains of interest to assess whether walking in a familiar outdoor environment has stress-reducing effects on mothers' physiology. Furthermore, future research should assess whether the outdoors has stress-reducing effects after mothers experience an acute stressor.

We found that carrying and/or holding the infant, as compared to having the infant in a pram, reduced maternal cortisol. This is in line with previous research demonstrating that skin-to-skin contact decreases salivary cortisol and increases oxytocin in mothers of preterm infants (Cong et al., 2015). The physical contact between mothers and their infants may be stress-reducing for mothers, potentially due to oxytocin increases, and because the infant is in a safe place and can be closely monitored (Norholt, 2020; Winberg, 2005). Our results suggest that close physical contact, even without direct skin-to-skin contact, can reduce distress in mothers and infants, delivering insights for future research on the potential of interventions manipulating caregiver-infant physical contact.

Maternal mood

In line with our hypothesis, mothers indoors showed a decrease in vigor, while mothers who walked outdoors did not. Accordingly, previous experimental studies found higher reports of vigor after walking in green as compared

to urban environments (Komori et al., 2017; Song et al., 2019). We did not find differences between the conditions for maternal affect. While vigor entailed items on alertness or tiredness, our affect scale assessed mood and happiness. Previous studies reported a decrease in tension, depression and anger after walking in green environments (Komori et al., 2017; Song et al., 2019). Notably, previous studies compared walking in green to walking in urban environments, whereas the current study used an indoor condition. Possibly, walking in urban environments is less pleasant than staying indoors. Future studies should compare effects of different outdoor environments to the indoors.

We also hypothesized that mothers walking outdoors with their infant in a carrier would show the highest vigor and affect, while mothers staying indoors with their infant in a pram would show the lowest. Accordingly, we found that mothers in the outdoor carrier condition showed no decrease in vigor, whereas mothers in the indoor pram condition showed a significant decrease from the pre- to post-condition.

Mother-infant adrenocortical synchrony

Lastly, we did not find the expected effect of carrying on mother-infant adrenocortical synchrony. Notably, previous studies reporting associations of skin-to-skin contact with mother-infant synchrony employed an intervention over a longer period of time (Mörelus et al., 2012, 2015). The prolonged and repeated contact might have allowed for familiarization with each other's cues and hence improved co-regulation (Feldman, 2007). Repeated skin-to-skin contact has been shown to facilitate breast-feeding (Cooijmans et al., 2022), which may, in turn, benefit adrenocortical synchrony (Hollanders et al., 2017). Furthermore, skin-to-skin contact might allow for more direct exchange of physical processes, such as heart-beat and thermo-regulation, which may, in turn, help to synchronize adrenocortical functioning (Gupta et al., 2021). Future studies are required to assess whether repeated infant carrying might facilitate mother-infant adrenocortical synchrony.

Strengths and limitations

To our knowledge, this is the first study to assess restorative effects of outdoor walking and carrying in infants. The current two-by-two design allowed us to assess the effects of the environment and proximity in combination, and hereby delivered novel insights on the combined role of both factors on infant regulation. Additionally, the quasi-randomized controlled design

enabled us to assess the directionality of the effects. A limitation is that the infants did not show a cortisol increase after the stressor, preventing us from assessing stress recovery. In addition, although dyads were assigned to the conditions based on blinded randomization, we adapted the ratio of outdoor versus indoor conditions depending on the season, and some dyads needed to be re-allocated due to heat waves or precipitation. Notably, we did not find differences between the conditions in terms of season or outdoor temperature. Furthermore, fathers were not included, and most mothers participating in the current study were highly educated (70%) and European (92%), restricting generalizability. Lastly, sleep was measured using maternal observation instead of wearables on the infant. Since mothers were asked to pay attention to their infants' sleep, we assume that the large difference found was indeed due to the effect of the outdoor walk, but we recommend the use of polysomnography in future studies.

Conclusion

Our quasi-experimental study showed positive effects of outdoor walking on infant sleep and maternal mood. Furthermore, we found cortisol-reducing effects of carrying on both mothers and infants. Strikingly, children nowadays spend as little as 15% of their waketime outdoors (Downing et al., 2022; Gao et al., 2022; Matz et al., 2014), and mothers in the Netherlands walk outdoors with their infants for less than 20 minutes daily (Rheinheimer et al., 2024). Given the positive effects found for mothers and infants, we hope the current findings promote increased research on outdoor time and carrying in infancy.

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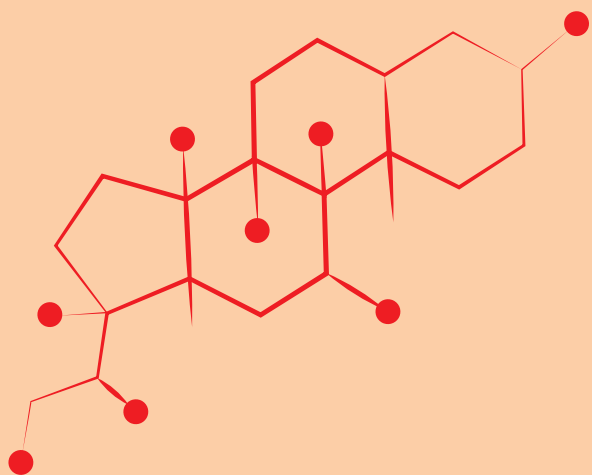
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Chapter 4

Effects of skin-to-skin contact on full-term infants' stress reactivity and quality of mother-infant interactions

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Abstract

Skin-to-skin contact (SSC) between mothers and their infants has beneficial effects in both preterm and full-term infants. Underlying mechanisms are largely unknown. This randomized controlled trial assessed whether daily SSC in full-term mother–infant dyads: (1) decreases infants' cortisol and behavioral reactivity to a mild naturalistic stressor, and (2) facilitates interaction quality between infants and mothers (i.e., improved maternal caregiving behavior and mother–infant adrenocortical synchrony). Pregnant Dutch women ($N = 116$) were recruited and randomly allocated to an SSC or care-as-usual condition. The SSC condition performed 1 h of SSC daily, from birth until postnatal week 5. In week 5, mothers bathed the infant (known mild stressor). Infant and maternal cortisol was sampled at baseline, 25 and 40 min after bathing, and infant and maternal behavior was rated. Results did not indicate effects of SSC on infant behavioral and cortisol reactivity to the bathing session. Similarly, no effect of SSC was found on maternal caregiving behavior and mother–infant adrenocortical synchrony. In conclusion, the findings provide no evidence that daily mother–infant SSC is associated with full-term infants' behavioral and adrenocortical stress reactivity or mother–infant interaction quality. Future studies should replicate these findings and unveil other potential mechanisms underlying beneficial effects of SSC.

Introduction

Skin-to-skin contact (SSC) is very beneficial for young infants. In both preterm and full-term infants, SSC has, for instance, been shown to improve health outcomes, facilitate sleep, and decrease crying behavior (Campbell-Yeo et al., 2015; Moore et al., 2016; Norholt, 2020). Nevertheless, there is a lack of randomized controlled trials (RCT) on the effects of SSC, and it is unclear whether SSC in the hours immediately after birth is more beneficial than delayed SSC procedures (Moore et al., 2016). Moreover, underlying working mechanisms of SSC are widely unknown. Researchers hypothesize that the close contact enables mothers to provide sensory cues (e.g. touch, odor, vocalizations), which facilitate the development of self-regulation of the infant (Feldman et al., 2002; Feldman, 2012b; Norholt, 2020). Accordingly, studies on preterm infants found positive effects of daily SSC on infants' biological and behavioral reaction to stress (Feldman et al., 2014; Ionio et al., 2021; Mörelius et al., 2015). Furthermore, research in preterm infants also indicates that daily SSC improves the mother-infant interaction quality, in terms of maternal caregiving behavior toward the infant, and mother-infant synchronization of biological processes (Feldman et al., 2014; Mörelius et al., 2015). In this RCT, we assess whether daily SSC affects full-term infants' stress reactivity, as well as the quality of the mother-infant interaction.

When exposed to stressful situations, the hypothalamic-pituitary-adrenal (HPA) axis produces the hormone cortisol. Although this HPA axis reaction enables infants to cope with stressful situations, repeated elevations of the hormone cortisol can have a negative impact on physiological and mental health (Nelson et al., 2011; Radley et al., 2015). Human infants are born with an immature ability to regulate their biological and behavioral stress reactions (Schore, 2001). Hence, infants highly depend on external regulation, provided through interactive cues during close proximity with their caregiver (Hofer, 1987; Hostinar et al., 2014; Loman & Gunnar, 2010; McKenna & Mosko, 1994). During SSC, the infant, wearing only a diaper, is placed on the mother's bare chest (World Health Organization, 2003). This full-body contact allows mothers to provide infants with essential regulatory cues, such as touch, warmth, and vocalizations (Feldman et al., 2014; Ionio et al., 2021). Accordingly, research indicates that a single episode of SSC significantly decreases baseline cortisol levels in full-term infants (Beijers et al., 2016), and when performed prior to an injection stressor, SSC decreases infants' crying response (Gray et al., 2000; Johnston et al., 2014).

The ability to regulate distress, including the functioning of the HPA axis, matures throughout infancy and is sensitive to environmental circumstances, such as continuous maternal proximity (Gunnar et al., 2009; Herman et al., 2016; Jansen et al., 2010b). According to Feldman's biobehavioral theory on parent–infant interactions, repeated mother–infant contact and the resulting exchange of biobehavioral cues in the first postnatal months, facilitate infants' maturation of their ability to regulate autonomous stress reactions (Feldman, 2012a). In line with this, an RCT on preterm infants demonstrated that performing SSC daily in the first postnatal weeks, as compared with care-as-usual (CAU), decreased infants' cortisol reactions to a stressor at one month of age (Mörelus et al., 2015). A study on full-term infants also reported that infants who had received daily SSC for the first six postnatal weeks showed decreased cortisol reactivity to a stressor (Hardin et al., 2020). However, previous findings were not based on a randomized sample, and carried out statistical analyses on a small number of dyads who had adhered with the SSC intervention protocol, excluding infants of noncompliant mothers.

Apart from affecting physiological reactivity, daily SSC might also affect infants' behavior during distress. Through repeated face-to-face interactions during SSC, infants are suggested to become familiarized with maternal cues, and hence learn to rely more on their mother when confronted by a challenging situation (Feldman et al., 2014; Tessier et al., 1998). Accordingly, studies on preterm infants report that infants who received repeated SSC in the first postnatal weeks, compared with CAU, showed increased responsivity to maternal cues, less gaze aversions, and decreased negative emotionality when exposed to a stressor (Chiu & Anderson, 2009; Feldman et al., 2002). Furthermore, Neu and Robinson (2010) observed that preterm infants receiving SSC regularly initiated more positive interactions (e.g., smiling) when reunited with their mothers after a period of separation – a behavior reflecting infants' involvement with their caregiver. The only study on longitudinal effects of daily SSC on full-term infants' behavior to date reported that infants in the intervention condition were more socially bidding toward their mothers at three months of age (Bigelow & Power, 2012). However, this study was not an RCT.

Next to affecting the infant, SSC might also affect the quality of maternal caregiving. Feldman et al. (2014) suggest that close physical contact allows mothers to familiarize with their infants' cues, enabling them to react more promptly and appropriately. This ability to pick up and interpret infants' cues is

characterized as sensitive caregiving (Ainsworth et al., 1978; Leerkes, 2010). In preterm infants, more sensitive, as well as more affectionate caregiving, has been reported when mothers performed daily SSC (Bigelow et al., 2010; Feldman et al., 2002; Tessier et al., 1998). Additionally, one study in preterm infants reported that mothers performing daily SSC were more cooperative, as they adapted their own actions in order to avoid interference with their infant's autonomous behavior (Feldman et al., 2002). To date, there is a lack of RCTs on the effects of daily SSC on maternal caregiving behavior in infants born full term.

A novel way of assessing dyadic interaction quality is the alignment of mothers' and infants' physiological processes - a construct called bio-behavioral synchrony (di Lorenzo et al., 2022; Feldman, 2012b; Reyna & Pickler, 2009). Synchronization of physiological rhythms emerges in late pregnancy and is suggested to be a critical component of human attachment, shaping later coordination of social behavior (Feldman, 2007, 2017). Synchronization of biological processes can aid mother-infant dyads in the regulation of distress (di Lorenzo et al., 2022; Reyna & Pickler, 2009). In the first month after delivery, proximity between mother and infant is suggested to enhance physiological synchrony of the HPA axis. Synchrony of cortisol levels between mothers and preterm infants has, for instance, been found after a period of room sharing at the neonatal intensive care unit (Mörelus et al., 2012). Daily SSC might foster biological mother-infant synchronization in a similar fashion. A study on preterm infants found a correlation of baseline cortisol levels between mothers and infants who had provided SSC, while this correlation was not present in dyads providing CAU (Mörelus et al., 2015). However, no study to date has assessed synchronization of cortisol levels in the presence of a stressor. Additionally, effects of SSC on mother-infant adrenocortical synchrony have not yet been assessed in full-term infants.

Altogether, the existing body of literature suggests that daily SSC facilitates infants' stress regulation and improves the interaction quality with their mother. However, there is a lack of RCTs on the potential effects of an SSC intervention for full-term infants. In the current RCT, we investigated whether daily SSC between mothers and their full-term infants during the first five postnatal weeks improved infants' stress regulation, by assessing (1a) infants' cortisol reactions, and (1b) infants' behavioral reactions, to a mild natural stressor that consisted of the mother bathing the infant and hence included mother-infant interaction throughout the caregiving session. Additionally, we

assessed effects of daily SSC on the quality of the mother–infant interaction in terms of (2a) maternal caregiving behavior, and (2b) mother–infant adrenocortical synchrony. We hypothesized that we would find decreased cortisol reactivity, less emotional distress, and increased responsiveness as well as involvement in infants of the SSC condition. We also hypothesized that mothers in the SSC condition would provide more sensitive, cooperative, and affectionate care, and that SSC would facilitate mother–infant adrenocortical synchrony. In order to achieve a comprehensive overview of the data, we additionally explored effects of the intervention on mothers' cortisol reactivity.

This study is based on secondary outcomes of an RCT (Cooijmans et al., 2017). Previous assessments of this RCT demonstrated positive effects of SSC on the duration of breastfeeding (Cooijmans, Beijers, Brett, & de Weerth, 2022), as well as on infant crying and sleep (Cooijmans, Beijers, & de Weerth, 2022).

Methods

Trial design

This RCT assessed two parallel conditions (SSC intervention vs. CAU). The current study focuses on secondary outcomes of this RCT. Primary outcome of this RCT was the effect of SSC on maternal postpartum depression (not addressed in this study). The RCT was reported in accordance with CONSORT guidelines, was registered at the Dutch Trial Register (Trial ID: NL5591), and the study protocol was additionally published (Cooijmans et al., 2017). The ethics committee of the faculty of Social Sciences (Radboud University) approved the trial in 2016 (ECSW2015-2311-358).

Participants

Recruitment of 116 pregnant women took place in the region of Nijmegen (the Netherlands) between April 2016 and September 2017. Recruitment took place via social media, flyers, as well as a database of pregnant women interested in participation in scientific studies. Inclusion criteria were: fluency in Dutch, older than 18, no twin pregnancy, no medication or drug use, no serious mental or physical health issues, and no participation in other intervention studies. Inclusion criteria for infants were: born at ≥ 37 weeks, with a birthweight of at least 2500 g, no congenital anomalies, and a 5-min APGAR score of seven or higher. The participant flow is presented in Figure 1.

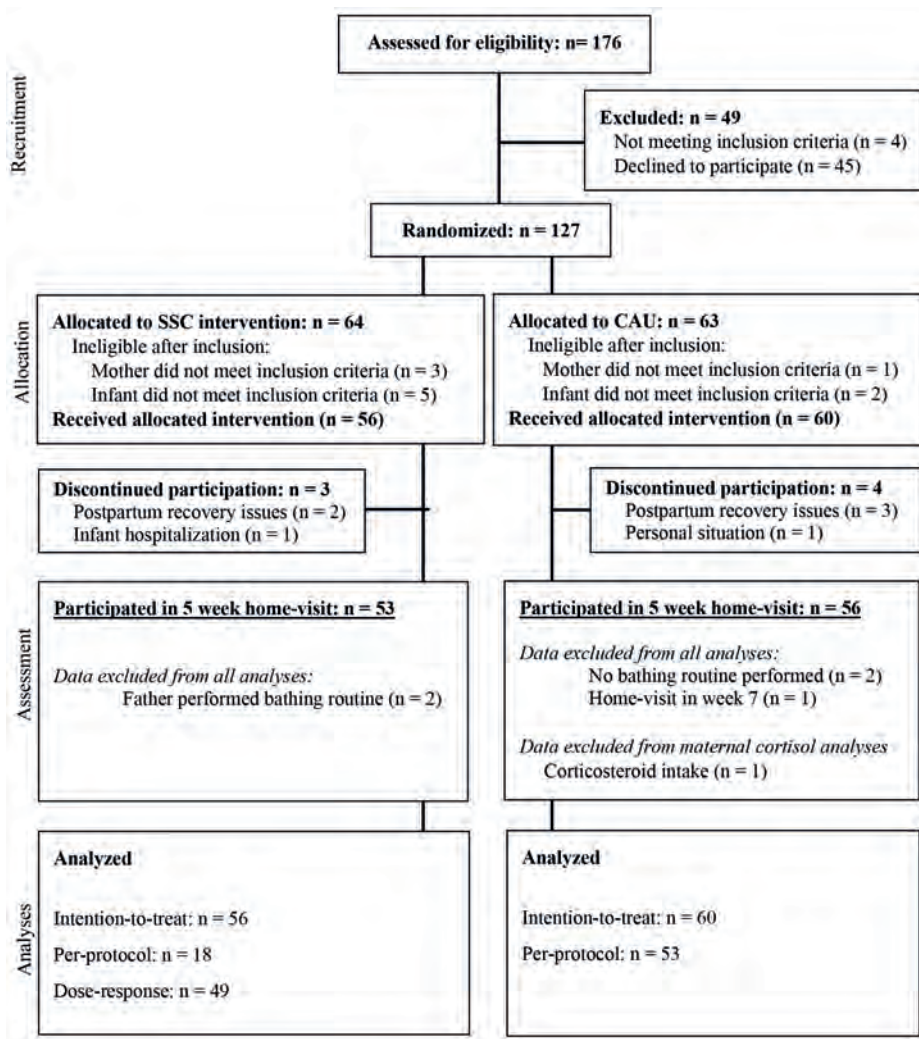


Figure 1. Participant flowchart. SSC = skin-to-skin contact; CAU = care-as-usual.

Randomization and masking

Recruitment included a cover story about the study examining associations between infant feeding behavior, sleep, mother–infant contact, as well as maternal and infant health. Pregnant women were also informed that participation entailed a simple mother–infant contact period after delivery for a subgroup of the sample. With a computer-generated allocation sequence, mothers were randomly assigned to the SSC or CAU conditions (1:1), with a

stratification by parity (primiparae vs. multiparae), using random blocks of four and six. Randomization was performed, and sealed in envelopes, by an independent researcher.

Procedure

Prenatal period

Women were visited by a researcher (K. C.) between weeks 34 and 36 of gestation, received information in line with the cover story, signed informed consent forms, and were allocated to a condition. The SSC condition received detailed verbal and written instructions on the intervention by the researcher, while the CAU condition did not receive further information. Mothers in the SSC condition were instructed to undress the infant, and then position the diapered infant in an upright position on the mother's bare chest (see also Cooijmans et al., 2017). The researcher also provided information regarding optimal positioning and safety during SSC. Then, all women filled in questionnaires on demographics.

Postnatal period

Women in the SSC condition were encouraged to perform one daily uninterrupted hour of SSC from birth until postnatal week five (see also Cooijmans et al., 2017). Providing one hour of SSC uninterrupted was requested for two reasons. First, a single sleep cycle of a newborn infant lasts approximately 47 min, and hence it would be less likely that infants are woken up during a cycle of sleep if a full hour of SSC is provided (Stern et al., 1969). Second, undressing and dressing an infant has been shown to elicit mild distress, and providing SSC spread over several sessions a day would require infants to be undressed and dressed more often, provoking unnecessary stress in the infant (Jansen et al., 2010a). In both conditions, all mothers were contacted weekly (via telephone, e-mail, or text message), and reminded to fill in a daily contact logbook. Mothers in the SSC condition were also asked how SSC went and potential obstacles were discussed. None of the mothers reported adverse events or intervention-related issues.

When the infant was five weeks old, a home visit took place during a weekday. As is customary in the Netherlands, all mothers were on maternity leave at this time. In order to take the fluctuation in diurnal cortisol levels in mothers and infants into account, home visits took place between 12 pm and 5 pm. During the visit, mothers bathed their infant according to their usual routine, while

being unobtrusively videotaped by the researcher. Bathing produces cortisol increases in infants and has been used as a mild stressor in previous research (Albers et al., 2008; Jansen et al., 2010a; Tollenaar et al., 2011). Saliva was sampled from mother and infant before undressing (baseline, T1), as well as 25 min (poststressor, T2) and 40 min (recovery, T3) after the routine. Infants' saliva was sampled by gently swabbing the infant's mouth with absorbent eye sponges that were thereafter placed in tubes (de Weerth et al., 2007). Mothers provided saliva in tubes by passive drooling. We investigated cortisol reactivity (T2) as well recovery (T3) from the stressor, to which we refer to as "stress reactivity" throughout the manuscript.

Videotapes were used to score infant behavioral reactions and the quality of maternal caregiving behavior afterward. Mothers also filled in questionnaires on postnatal mental health for the primary aim of this RCT, including questionnaires on postpartum depression (Edinburgh Postnatal Depression Scale; EPDS; Cox et al., 1987) and anxiety (State-Trait Anxiety Inventory; STAI; Spielberger et al., 1983). During debriefing at infant age one, none of the mothers in the CAU condition reported knowing, nor having heard from others, about the aim of the intervention.

Measures

Skin-to-skin contact

Mothers noted periods of contact, including SSC, holding (including breastfeeding), as well as periods of no contact, in a contact logbook for 15-min time intervals. Mothers kept track of the logbook approximately every 2–3 h, during moments suiting them best throughout the day (i.e., after diaper changes or breastfeeding). Daily durations of SSC were calculated for logbooks when at least 80% of a day was filled in for at least 21 of the 35 days. Additionally, it was assessed on how many days SSC was performed uninterruptedly. Missing days were replaced with the mean amount of SSC of two days prior and two days after that day for valid logbooks (Beijers et al., 2012). Total SSC during the intervention was calculated in minutes, only for logbooks that contained sufficient data.

Infant stress reactivity

Infant cortisol reactions. The eye sponges containing infant saliva were centrifuged and the extracted saliva was stored at -20°C . Cortisol levels were determined at the Laboratory of Endocrinology at UMC Utrecht, with an in-house competitive radioimmunoassay, by employing a polyclonal anticortisol antibody (K7348), with the tracer [1,2- ^3H (N)]-hydrocortisone (PerkinElmer NET396250UC). The lower detection limit was 1.0 nmol/l, interassay variation was $<6\%$ at 2.5–28 nmol/l, and intraassay variation was $<4\%$. Of the available 312 infant samples, 228 samples (CAU: $N = 116$; SSC: $N = 112$) contained sufficient saliva for cortisol determination. Missing samples due to a lack of saliva were evenly distributed over the two groups (CAU: $N = 43$; SSC: $N = 41$).

Infant behavioral reactions. Videotapes of the bathing routine were rated by five trained researchers. Infant behavior was rated on responsivity (paying attention and reacting to maternal cues) and involvement (autonomously initiating interactions) on 9-point scales, and negative mood (showing distress or crying) on a 7-point scale (Ainsworth et al., 1978). Pearson's correlations (r) between scores on the scales Responsivity and Involvement were high ($r = .90$), and the two scales were therefore averaged to a composite score. This strategy of combining variables that assess similar constructs is a common practice, as it reduces the number of outcome variables, and hereby the risk of Type I errors (Song et al., 2013).

Raters double scored 52% of the videos. For double scored videos, the final score was determined by combining the scores of the two raters. If they differed by one point, the score deviating more from the scale mean was chosen, in order to overcome regression toward the mean. If the two scores differed by more than one point, an independent third observer scored the video, and the scores of the two raters agreeing the most on all constructs were chosen for determination of the final scores. Interrater agreement (Weighted Cohen's kappa, k) was strong for the ratings of responsivity ($k = .90$), involvement ($k = .92$), and negative mood ($k = .96$).

Interaction quality

Quality of maternal caregiving. The videotapes were also rated on maternal caregiving behavior. Mothers were rated on the constructs: sensitivity ($k = .95$; responding appropriately and immediately to infant's cues) and cooperation ($k = .92$; adapting behavior to the needs, and avoiding interference with infant's autonomous behavior) on 9-point scales, and positive regard ($k = .82$;

acting warmly and appreciatively), as well as negative regard ($k = .81$; showing disregard or harshness) on 7-point scales (Ainsworth et al., 1978). Since the constructs sensitivity and cooperation correlated highly ($r = .93$), an average score was created across the two scales (Song et al., 2013).

Mother–infant adrenocortical synchrony. Cortisol levels of mothers' samples were also determined at the Laboratory of Endocrinology at UMC Utrecht, following the same procedure as infants' samples. If mothers' and infants' cortisol levels had been taken more than 10 min apart, the two samples of that time point were excluded from the synchrony analyses (two out of the 222 complete mother–infant samples). For synchrony analyses, both mothers' and infants' cortisol levels were log transformed in order to achieve a normal distribution.

Statistical approaches

Analyses were performed using R version 3.6.1. (R Core Team, 2021). As in previous studies on this RCT (Cooijmans, Beijers, Brett, et al., 2022), the current study was assessed with three different approaches. All mother–infant dyads were included in the intention-to-treat approach (ITT), regardless of protocol adherence or withdrawal from the study. In the ITT approach, missing outcome data in the (multivariate) analyses of variance (ANOVAs) were imputed with the expectation-maximization method (Liu & Brown, 2013). For multilevel model analyses (MLM), no imputation was performed, as MLM is robust for missing data (Snijders & Bosker, 1999). In the per-protocol approach (PP), dyads of the SSC condition were only included if they had sufficiently filled in the SSC diary (at least 21 of the 35 days), and performed at least one hour of uninterrupted SSC on ≥ 28 of the 35 days. Also, in this PP approach, dyads were only included if they had outcome data for the five-week assessment, and no data were imputed. In previous studies on this RCT, dyads of both conditions were excluded in the PP approach if they had provided incomplete outcome data (Cooijmans, Beijers, Brett, et al., 2022). In this study, dyads with missing cortisol values were not excluded in the PP approach, as missingness was caused by a lack of sufficient saliva for analysis in several infant samples. The exploratory dose–response approach (DR) was performed within the SSC condition, on dyads who had sufficiently filled in the logbook. In the DR analyses, the total duration of SSC in minutes was used as a continuous predictor, and for ANOVAs, imputed data were used. All analyses were repeated excluding dyads with mothers scoring above the clinical cut-off

on the EPDS (score ≥ 10 ; Cox et al., 1987) and/or STAI (score ≥ 40 ; Spielberger et al., 1983).

Preliminary analyses

Power calculations on the primary outcome (maternal depressive symptoms) retrieved that, taking attrition into account, 116 dyads were required with a power of 80% to detect a medium effect size ($f = .24$) (Cooijmans et al., 2017). For all outcome variables, outliers were identified and winsorized, replacing the score with the mean plus/minus three times the standard deviation (Tukey, 1977). Demographic information and study variables are reported for the ITT and PP samples (Table 1). Group comparisons for continuous variables were assessed with independent sample t-tests if they were normally distributed, and Mann-Whitney U tests if they were nonnormally distributed ("stats"; R Core Team, 2021). Group differences on categorical variables were assessed with χ^2 tests.

Main analyses

Infant stress reactivity

Infant cortisol reactions. To examine whether SSC had an effect on infants' adrenocortical stress reactivity, multilevel growth curve models (MLM) were performed on infants' log transformed cortisol levels ("lme4"; Bates et al., 2015). Linear time (exact sample timing in minutes) and intercept were added as random effects, and linear, as well as quadratic time were added as fixed effects. Covariates were added in a build-up fashion if they led to a decrease of the Watanabe-Akaike Information Criterion (WAIC; Hamaker et al., 2011). Potential covariates were bathing duration, and position during the bathing routine (horizontal: bathtub vs. vertical: tummy tub), since these variables differed based on maternal choice. Condition (total amount of SSC in DR approach) was entered as a fixed effect. Interactions of condition with time were only added if the WAIC decreased (Hamaker et al., 2011).

Table 1. Descriptive statistics and group comparisons for mother-infant dyads in the skin-to-skin contact (SSC) and care-as-usual (CAU) condition

	Intention-to-treat		Per-protocol	
	CAU (N=60)	SSC (N=56)	SSC (N=18)	Statistic
Baseline characteristics				
	M (SD) ^a	M (SD) ^a	M (SD) ^a	Statistic
Maternal age (years)	32.48(3.05)	32.36(3.85)	32.90(3.80)	524.00 ^b
Maternal educational level	6.87(1.79)	6.82(1.55)	6.78(1.48)	463.50 ^b
Smoking (% no)	100.00	96.43	96.43	3.38 ^c
Alcohol (% no)	100.00	98.21	98.21	3.38 ^c
C-section (% no)	32.48(3.05)	32.36(3.85)	32.90(3.80)	524.00 ^b
APGAR score	9.70(0.62)	9.84(0.42)	9.72(0.58)	534.50 ^b
Infant sex (% girls)	43.33	58.93	58.93	1.76 ^c
Weight at birth (grams)	3567.47(385.77)	3650.05(414.93)	3760.56(4.56)	-1.79 ^d
Gest. age at birth (weeks)	40.02(1.10)	40.08(1.01)	40.16(1.03)	501.50 ^b
Age at home visit (days)	39.98(2.66)	40.56(3.79)	40.61(2.55)	404.50 ^b
Birth order (%)				
First	46.70	48.22	48.21	1.83 ^c
Second	38.30	32.14	32.12	
Third	15.00	19.64	19.64	
Total duration SSC (min.)	308.17(442.41)	2067.68(850.65)	2905.90(497.52)	-19.99 ^{***c}
Covariates ^{e,f}				
Total duration bath (sec.)	820.38(180.25)	826.96(197.01)	840.41(247.06)	438.50 ^b
Bath position (% sitting up)	24.53	17.65	11.11	0.82 ^c

Table 1. Continued

	Intention-to-treat		Per-protocol	
	CAU (N=60)	SSC (N=56)	SSC (N=18)	
	M (SD) ^a	M (SD) ^a	M (SD) ^a	Statistic
Infant stress reactivity^e				
Infant cortisol (nmol/L)				
Baseline	10.53(6.35)	9.90(3.59)	9.39(3.15)	0.17 ^d
Poststressor	14.55(8.49)	12.82(5.63)	14.19(6.47)	-0.34 ^d
Recovery	11.74(5.04)	11.59(4.29)	13.64(4.50)	-1.17 ^d
Infant behavior				
Responsivity-Involvement	4.53(1.48)	4.41(1.43)	4.11(1.42)	550.00 ^b
Negative mood	3.85(1.88)	3.40(1.94)	3.56(2.03)	509.50 ^b
Interaction quality^e				
Mat. caregiving quality				
Sensitivity-Cooperation	5.95(2.07)	6.19(1.84)	5.86(1.64)	501.50 ^b
Positive regard	4.92(1.51)	5.24(1.30)	4.89(0.90)	485.00 ^b
Negative regard	1.25(0.51)	1.24(0.55)	1.44(0.78)	422.00 ^b
Cort. difference scores ^g				
Baseline	4.99 (5.56)	3.56 (3.27)	3.19(2.74)	0.75 ^d
Poststressor	8.16 (8.57)	6.68 (5.16)	8.02(5.99)	-0.12 ^d
Recovery	6.08 (5.37)	5.52 (3.79)	7.83(3.73)	-1.15 ^d

Table 1. Continued

	Intention-to-treat		Per-protocol	
	CAU (N=60)	SSC (N=56)	SSC (N=18)	
	M (SD) ^a	M (SD) ^a	M (SD) ^a	Statistic
Maternal cortisol (nmol/L)				
Baseline	7.24(2.08)	6.98(2.48)	7.08(2.97)	0.61 ^d
Poststressor	7.07(1.78)	7.36(2.44)	7.07(1.92)	0.02 ^d
Recovery	6.65(1.74)	6.95(2.15)	6.57(1.74)	0.20 ^d

Notes. *M*, mean; *SD*, standard deviation; *Gest.*, gestational; *Mat.*, maternal. ^a *M* and *SD* are presented as nonimputed and nontransformed data. ^b Mann-Whitney U tests for nonnormally distributed data. ^c χ^2 tests for categorical data. ^d Independent samples t-tests for data normally distributed after square root transform. ^e Winsorized data are presented for all moderator and outcome variables with outliers. ^f Standardized data is presented for all moderators. ^g Absolute values of maternal minus infant cortisol. * $p < .05$, ** $p < .01$, *** $p < .001$.

Infant behavioral reactions. Effects of condition (total amount of SSC in DR approach) on infant behavior during the stressor were assessed with multivariate analyses of variance (MANOVA; R Core Team, 2021). Dependent variables were infant negative mood, and the composite score of responsivity and involvement. Since the assumption of a multivariate normal distribution was not met, the dependent variables were square root transformed.

Interaction quality

Quality of maternal caregiving. Condition effects on the quality of maternal caregiving behavior were assessed with a MANOVA including the composite of maternal Sensitivity and Cooperation, as well as positive and negative regard ("stats"; R Core Team, 2021). Dependent variables were square root transformed.

Mother-infant adrenocortical synchrony. Two MLM models were used in order to assess group differences in mother-infant synchrony in terms of (1) maternal cortisol predicting infant cortisol, and (2) mother-infant synchrony across baseline, poststressor, and recovery (Ludmer Nofech-Mozes et al., 2020). In the first MLM, infant cortisol was predicted with the interaction between condition and maternal cortisol. Linear time was added as a random effect, and linear as well as quadratic time, potential moderators, maternal cortisol, condition, and the interaction of condition with maternal cortisol were added as fixed effects. The three-way interaction between maternal cortisol, condition and time could not be assessed in this analysis due to a lack of power. A second MLM was performed in order to assess mother-infant adrenocortical synchrony over time. In this MLM, absolute values of difference scores (maternal minus infant cortisol) were predicted by condition. The interaction of condition with time was added based on the WAIC (Hamaker et al., 2011).

An additional MLM was performed on the effect of condition on mothers' cortisol reactivity, including linear sampling time and intercept as random effects, and linear, as well as quadratic time, potential covariates, and condition as fixed effects.

Results

Missing data and outliers

Cortisol concentrations for infant analyses were missing for 28 samples at baseline, 23 samples at poststressor, and 23 samples at recovery due to a lack of saliva. Overall, 27% of the infant cortisol concentrations were missing in the SSC condition, and 21% were missing in the CAU condition. Maternal cortisol levels were missing for one sample of the SSC condition at baseline, and no maternal samples were missing at poststressor and recovery. One mother of the CAU condition was excluded due to corticosteroid intake. Five outliers on infant cortisol, and two outliers on maternal cortisol were winsorized. There were no outliers on other outcome variables. Two videotapes were missing for analyses on infant behavior and maternal caregiving quality due to technical problems (e.g., recording inadvertently stopped after a few minutes).

Preliminary analyses

Group comparisons of demographic information and outcome variables are displayed in Table 1. Mothers in the CAU condition provided 308 min ($SD = 442$), and mothers in the SSC condition provided 2068 min ($SD = 851$) of SSC throughout the intervention phase. In the SSC condition, 18 mothers provided sufficient SSC for the PP approach (>60 consecutive minutes on at least 80% of the days); these mothers provided 2906 min ($SD = 498$) of SSC. Mann-Whitney U tests showed that the mean daily duration of SSC performed was significantly higher in the SSC condition than in the CAU condition for the ITT and the PP approach (Table 1). The clinical cut-off on the EPDS was reached by five mothers in the CAU and five mothers in the SSC condition. On the STAI, seven mothers in the CAU condition and five mothers in the SSC condition scored above the clinical cut-off. Sensitivity analyses excluding these mothers from the analyses indicated no change in the results.

Main analyses

Infant stress reactivity

Infant cortisol reactions. Table 2 displays outcomes of the MLM on infant cortisol reactivity. There were no significant differences between conditions in infant cortisol. The effect of quadratic time was significant in the ITT, PP, and DR approaches. Infants' cortisol levels increased at poststressor and decreased again at recovery.

Infant behavioral reactions. Results of the MANOVAs on ratings of infants' behavior during the bathing routine did not reveal significant differences between conditions in the ITT, PP, or DR approaches (Table 3).

Interaction quality

Quality of maternal caregiving. MANOVAs on maternal caregiving behavior during the bathing routine did not show an effect of condition in the ITT, PP, or DR approaches (Table 3).

Mother–infant adrenocortical synchrony. Outcomes of both analyses regarding mother–infant synchrony are displayed in Table 2. In the first MLM, the interaction of maternal cortisol levels with condition on infant cortisol was marginally significant in the ITT ($b = .435$, $SE = .229$, $t = 1.91$, $p = .057$) and PP ($b = -.601$, $SE = .311$, $t = 1.93$, $p = .055$) approaches. Compared with the CAU condition, cortisol of mothers in the SSC condition were overall more similar to infants' cortisol levels (Figure 2). MLM on mother–infant cortisol difference scores did not show significant effects of condition.

There were no significant differences of maternal cortisol reactivity between conditions (Table 2).

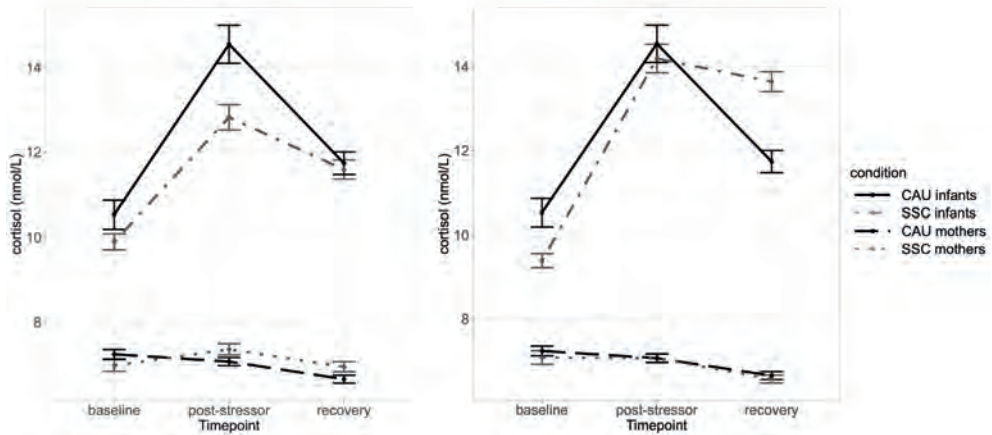


Figure 2. Cortisol levels of infants and mothers at baseline, post-stressor (25 minutes) and recovery (40 minutes) for the skin-to-skin contact (SSC) and care-as-usual (CAU) condition in the intention-to-treat (left) and the per-protocol (right) approaches.

Table 2. Multilevel growth curve models for intention-to-treat, per-protocol, and dose-response approaches

Infant cortisol ^{a,b}	Intention-to-treat		Per-protocol		Dose-response	
	B(SE)	t	B(SE)	t	B(SE)	t
Intercept	2.462(.062)	39.78***	2.485(.073)	33.87***	2.464(.059)	41.88***
Linear Time	.001(.002)	0.47	.002(.003)	0.62	.022(.044)	0.49
Quadratic time	-.001(.000)	-4.30***	-.001(.000)	-3.92***	-.120(.040)	-2.98**
Duration	-.088(.039)	-2.24*	/	/	/	/
Condition	-.008(.077)	-0.11	-.015(.118)	-0.12	-.003(.042)	-0.06
Mother-infant adrenocortical synchrony^{a,b}						
Outcome: infant cort.	B(SE)	t	B(SE)	t	B(SE)	t
Intercept	2.879(.350)	8.22***	3.019(.390)	7.73***	2.173(.233)	9.31***
Linear Time	.001(.002)	0.36	.001(.003)	0.50	.018(.044)	0.40
Quadratic time	-.001(.000)	-4.20***	-.001(.000)	-3.96***	-.116(.040)	-2.90**
Duration	-.100(.040)	-2.50*	/	/	/	/
Condition	-.829(.441)	-1.88†	-1.144(.601)	-1.90†	.078(.242)	0.32
Mat. cortisol	-.222(.179)	-1.24	-.283(.199)	-1.42	.151(.117)	1.29
Condition x Mat. cort.	.435(.229)	1.91†	.596(.311)	1.92†	-.042(.122)	-0.35
Outcome: diff. score ^c	B(SE)	t	B(SE)	t	B(SE)	t
Intercept	.725(.055)	13.23***	.722(.064)	11.28***	.654(.055)	11.83***
Linear Time	.003(.002)	1.68	.005(.002)	2.13*	.041(.039)	1.05
Quadratic time	-.000(.000)	-2.67**	-.000(.000)	-1.79	-.106(.038)	-2.78**
Duration	-.059(.033)	-1.76	/	/	-.103(.043)	-2.38*
Condition	-.081(.064)	-1.27	-.044(.094)	-0.46	.034(.042)	0.80

Table 2. Continued

Maternal cortisol ^{a,b}	Intention-to-treat		Per-protocol		Dose-response	
	B(SE)	t	B(SE)	t	B(SE)	t
Intercept	1.917(.040)	48.19***	1.914(.038)	49.74***	1.946(.048)	40.28***
Linear Time	-.002(.001)	-1.98*	-.002(.001)	-2.48*	-.002(.020)	-0.12
Quadratic time	-.000(.000)	-3.10**	-.000(.000)	-2.24*	-.042(.016)	-2.68**
Duration	.070(.028)	2.54*	.089(.031)	2.87**	-.071(.047)	1.52
Condition	-.005(.055)	-0.09	-.010(.070)	-0.14	-.003(.046)	-0.07

Notes. SE, standard error; Mat., maternal ; Cort, cortisol. ^a Cortisol values were log transformed. ^b Duration of skin-to-skin contact as a continuous predictor for dose-response analyses ^c Absolute value of maternal – infant cortisol. ^t $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 3. Multivariate analysis of variance on effects of condition on square-root transformed infant behavioral reactions and quality of maternal caregiving for intention-to-treat, per-protocol, and dose-response approaches

	Intention-to-treat			Per-protocol			Dose-response					
	Λ	η^2	p	Λ	η^2	p	Λ	η^2	p			
Infant behavior												
Condition ^a	.962	.040	2.225	.113	.935	.066	2.300	.103	.980	.020	.461	.634
Maternal caregiving	Λ	η^2	$F(1,114)$	p	Λ	η^2	$F(1,68)$	p	Λ	η^2	$F(1,47)$	p
Condition ^a	.983	.017	.642	.590	.976	.024	.540	.655	.917	.083	1.357	.268

Note. Λ , Wilks' Lambda; η^2 , eta squared. ^a Duration of skin-to-skin contact as a continuous predictor for dose-response analyses.

Discussion

The aims of this study were to assess whether full-term infants receiving a daily SSC intervention, compared with CAU, in the first five postnatal weeks showed (1) lower stress reactivity, in terms of cortisol and behavioral reactivity, and (2) improved mother–infant interaction quality, in terms of maternal caregiving quality and mother–infant adrenocortical synchrony, during a bathing routine provided by the mother. Contrary to our hypotheses, we did not find significant effects of daily SSC on infants' stress reactivity and mother–infant interaction quality in the ITT, PP, and DR analyses. Interestingly, we did find marginally significant effects in ITT and PP analyses indicating that maternal cortisol concentrations tended to be more alike to infants' cortisol concentrations in the SSC group as compared with the CAU group.

Potentially, the SSC intervention revealed no significant effects on our outcomes due to the low compliance with the protocol of mothers in the SSC condition. Despite elaborate instructions and regular contact with participating mothers, not all mothers provided one uninterrupted hour daily. Summing up all SSC performed a day, about one third of the SSC mothers regularly performed one hour of SSC. Similarly, a previous study on full-term infants also reported relatively low protocol compliance (Hardin et al., 2020). This study only found facilitating effects of SSC on infant cortisol reactivity in their PP analyses, including a small sample of infants who had actually received the recommended hour of SSC (Hardin et al., 2020). In the current assessment, we performed similar PP analyses. However, since only 18 mothers were included in these analyses, the PP analyses were underpowered. The other study on the effects of SSC on full-term infants reported higher intervention compliance, and found beneficial effects of SSC on infants' behavioral stress regulation (Bigelow & Power, 2012). Mothers in this previous study, however, were informed about the aims of the intervention beforehand which may have induced a sampling bias, as mothers might have only signed up if they were interested in SSC. Contrary to the previous study, we used a cover story and randomly allocated mothers to the conditions irrespective of their interest in SSC, which presumably led to lower intervention compliance.

It is also possible that SSC effects did not become apparent due to the timing and nature of the assessment. For instance, SSC effects on infants' stress regulation and the mother–infant interaction quality might emerge at a later age. A study in full-term infants showed that mothers' quality of caregiving

behavior was not associated with infants' cortisol reactivity to a bathing session at five weeks of age (Jansen et al., 2010b), while another study revealed that higher quality of maternal caregiving behavior was related to decreased cortisol reactivity to a bathing situation at three months of age (Albers et al., 2008). In addition, the current assessment focused on direct effects of daily SSC on the infant HPA axis reactivity, which is part of the sympathetic nervous system. A review of family interventions including SSC in neonatal intensive care units, however, indicated that repeated mother-infant contact sessions facilitate infants' development of the ability to regulate parasympathetic states (Porges et al., 2019; Welch et al., 2017). Finally, while the current study assessed infant and maternal behavior separately, future studies might explore potential effects of daily SSC on the autonomous emotional connection between the dyad, as a facilitator of infants' biobehavioral stress regulation (Hane et al., 2019; Porges et al., 2019; Welch et al., 2017).

The absence of effects might also be explained due to the nature of the stressor. SSC may not have an effect on reactions to mild physical stressors, such as a bathing session, but it might have an effect on infant stress reactions to other types of stressors (e.g., socioemotional and novel stressors; Puhakka & Peltola, 2020), or infants' stress levels throughout the day. A previous experimental study on full-term infants found that one SSC episode decreased infants' stress levels immediately, but that subsequent cortisol reactions to a bathing session were increased (Beijers et al., 2016). In addition, while the current study found no evidence that SSC was associated with infant behavioral stress reactivity to a bathing session, the same RCT revealed in another study that SSC was associated with decreased daily crying and fussing during the first 12 postnatal weeks (Cooijmans, Beijers, & de Weerth, 2022). Future studies should investigate whether daily SSC also decreases infants' cortisol concentrations throughout the day, ideally after the circadian rhythm has matured in the second half of the first year of life (de Weerth et al., 2003).

The last explanation for the absence of significant SSC effects might be that SSC does not affect full-term infants as much as it affects infants born preterm or with low birth weight. To our knowledge, all RCTs demonstrating benefits of SSC for infants' stress reactivity and mother-infant interaction quality were performed with infants born preterm or with a very low weight (Mörelus et al., 2015; Tessier et al., 1998). While full-term infants are usually cared for in proximity immediately after birth (e.g., carried, held, breastfed), preterm infants are more vulnerable as their neurodevelopment is strained

(Fleiss & Gressens, 2019; Norholt, 2020) and they additionally experience less physical contact (i.e., due to incubator care). Potentially, a subgroup of full-term infants and/or mothers might have benefitted from the SSC intervention, such as dyads exposed to adversity and risks. For instance, full-term infants who are exposed to maternal stress during pregnancy showed altered stress reactivity (Tollenaar et al., 2011), and these infants and their mothers might have benefitted from SSC, but this hypothesis remains for future research.

The current study has substantial strengths. We used a RCT with blind recruitment, and the drop-out rate was low throughout the intervention phase. However, the current study also suffered limitations: many infant samples lacked sufficient saliva for analysis, producing missing data. Even though MLM is robust for missing data (Snijders & Bosker, 1999), the lack of power did not allow us to look at more complex three-way interactions, or more elaborate time-lagged synchrony effects. Finally, our study did not include a diverse sample in terms of ethnicity, socio-economic status, or maternal age, making it less representative of the population.

Conclusion

The current RCT did not find evidence of effects of daily SSC on infant stress reactivity or the quality of the mother–infant interaction. Further research should assess whether daily SSC affects full-term infants' daily levels of distress. Additionally, future studies are required to explore possibilities to enhance adherence to the intervention and unveil other potential underlying mechanisms of SSC effects in full-term infants.

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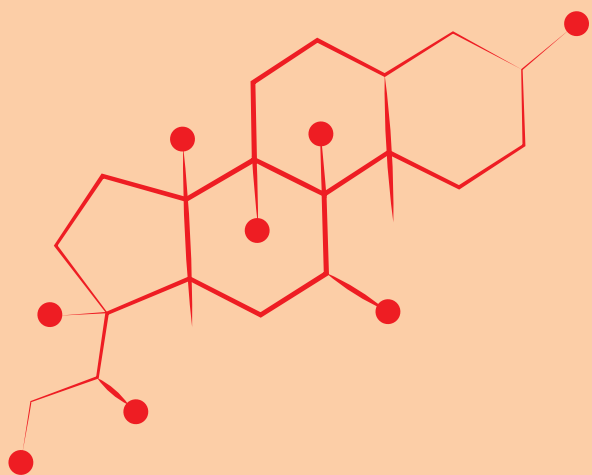
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Chapter 5

Effects of daily full-term infant skin-to-skin contact on behavior and cognition at age three – secondary outcomes of a randomized controlled trial

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Abstract

Background: Daily skin-to-skin contact (SSC) during early infancy fosters the long-term development of children born preterm. This is the first randomized controlled trial assessing the potential beneficial effects of daily SSC on executive functioning and socio-emotional behavior of children born full-term. Whether children of mothers who experienced prenatal stress and anxiety benefitted more from SSC was also explored.

Methods: Pregnant women ($N = 116$) were randomly assigned to a SSC or care-as-usual (CAU) condition. Women in the SSC condition were instructed to perform one hour of SSC daily from birth until postnatal week five. Prenatal stress was measured with questionnaires on general and pregnancy-specific stress and anxiety completed by the mothers in gestational week 37. At child age three, mothers filled in questionnaires on children's executive functioning, and externalizing and internalizing behavior. Analyses were performed in an intention-to-treat (ITT), per-protocol, and dose-response approach. Netherlands Trial Register: NL5591.

Results: In the ITT approach, fewer internalizing (95% CI = 0.11–1.00, $U = 2148.50$, $r = .24$, $p = .001$) and externalizing (95% CI = 0.04–2.62, $t = 2.04$, $d = 0.38$, $p = .04$) problems were reported in the SSC condition compared to the CAU condition. Multivariate analyses of variance did not show group differences on executive functioning. Additional analyses of covariance showed no moderations by maternal prenatal stress.

Conclusions: Current findings indicate that early daily SSC in full-term infants may foster children's behavioral development. Future replications, including behavioral observations of child behavior to complement maternal reports, are warranted.

Introduction

For preterm infants, skin-to-skin contact (SSC) during hospitalization results in positive outcomes, such as increased cardiorespiratory and thermal regulation, fewer infections, faster weight gain, enhanced sleep, and decreased crying behavior (Feldman et al., 2014; Kostandy & Ludington-Hoe, 2019). Several studies have shown that benefits of SSC extend to full-term infants. For instance, in full-term infants, the practice of SSC immediately after delivery is related to improved cardiovascular stability, weight gain, sleep, as well as decreased crying behavior (Ionio et al., 2021; Moore et al., 2016). While assessments of SSC in full-term infants have largely been restricted to the hours after delivery, research on preterm infants indicates that SSC is beneficial beyond the first postnatal hours. When performed daily throughout preterm infants' first postnatal weeks or month, SSC has been related to improved long-term cognitive and behavioral development (Feldman et al., 2014). The current paper reports results of the first randomized controlled trial (RCT) to investigate effects of daily SSC in full-term children on cognitive and behavioral outcomes in early childhood.

During SSC, the naked infant is placed on the mother's bare chest (World Health Organization, 2003). The precise mechanisms underlying the effects of SSC on infants are mainly unknown (Ionio et al., 2021). However, it is suggested that the exchange of sensory cues during SSC (i.e., touch, warmth, odor, vocalizations) has regulating effects on the infant's physiology. For instance, SSC immediately decreases infants' levels of the stress hormone cortisol, and increases the release of the hormone oxytocin (Beijers et al., 2016; Vittner et al., 2018). Additionally, repeated SSC facilitates face-to-face interactions, and allows mother and infant to familiarize with each other's interactive cues, hereby fostering the development of reciprocal interaction patterns (Moore et al., 2016). These positive reciprocal mother–infant interactions can, in turn, benefit infant regulation of the neuro-endocrine system (Nagasawa et al., 2012; Vittner et al., 2018). In general, it is thought that repeated SSC might facilitate the development of neuro-biobehavioral systems early in life, which, in turn, foster development throughout childhood (Moberg et al., 2020).

As mentioned before, longitudinal studies show beneficial effects of SSC in the first postnatal month on child outcomes later in life (Moore et al., 2016). Studies on preterm infants linked the practice of daily SSC to improved cognitive functioning, including executive functioning, across childhood

and beyond (Charpak et al., 2017; Feldman et al., 2014; Ropars et al., 2018). Additionally, studies on preterm infants also showed that SSC can benefit children's behavioral development. Charpak et al. (2017) reported that preterm infants receiving daily SSC displayed fewer externalizing problems (e.g., hyperactivity, aggressiveness, socio-deviant conduct) at age 20. No effects were found on internalizing problems (e.g., social problems, withdrawal, and anxiety). However, another study on preterm infants reported that SSC facilitated children's reciprocity during conversations with their mother at age ten (Feldman et al., 2014). Likewise, the only longitudinal study to date on daily SSC with full-term infants reported enhanced engagement and reciprocity during a mother-child conversation on emotional memories at age nine (Bigelow & Power, 2020).

However, these previous findings on full-term infants were restricted to the assessment of a mother-child conversation, and additionally, this study was not an RCT (Bigelow & Power, 2020). Moreover, mothers in this study were requested to perform up to six hours of SSC a day. This long period of SSC requires a large time investment, and may hamper implementation of SSC into daily routines for some mothers. The current RCT is the first to study long-term effects of SSC on the development of children born full-term. We report secondary outcomes of an intervention consisting of a five-week period in which mothers of full-term infants were asked to perform one daily hour of SSC. Specifically, we assessed whether SSC benefits three-year-olds' executive functioning, as well as externalizing and internalizing behavior. Previous assessments of this RCT found beneficial effects of SSC on breastfeeding duration (Cooijmans et al., 2022).

Studies often report relations between maternal stress and anxiety during pregnancy and compromised offspring behavioral and cognitive development (Gragnic-Philippe et al., 2014; van den Bergh et al., 2020). However, prenatal psychosocial stress may not only increase offspring's vulnerability for poorer outcomes later in life, but also offspring's plasticity, making them more susceptible to early postnatal circumstances, for better and for worse (Beijers et al., 2020). This enhanced plasticity would increase offspring's vulnerability to negative experiences, but also increase their susceptibility to positive experiences in the postnatal period (Gragnic-Philippe et al., 2014). Therefore, we additionally explored whether children of mothers with increased prenatal psychosocial stress benefitted more from the SSC intervention in terms of

cognitive and behavioral development than children of mothers with lower prenatal psychosocial stress.

Methods

Trial design

This RCT consisted of two groups (SSC intervention vs. care-as-usual). The primary aim was to test the effectiveness of SSC in decreasing maternal postpartum depressive symptoms (not reported here). This study examines secondary outcomes of a follow-up assessment at age three. The baseline assessment of this RCT was registered at the Netherlands Trial Register (Trial-ID: [NL5591](#)), according to CONSORT guidelines. The trial protocol was also published (Cooijmans et al., 2017). All assessments of this RCT were approved by the ethics committee of the Faculty of Social Sciences at Radboud University (Baseline: ECSW2015-2311-358; Follow-up: SW2017-1303-497).

Participants

Pregnant women ($N=116$) were recruited in Nijmegen, the Netherlands, through flyers, social media, and a participant database. Inclusion criteria were: singleton pregnancy, no use of drugs, fluent in Dutch, ≥ 18 years old, no severe physical/mental health issues, and no ongoing participation in other studies. Infants' inclusion criteria at birth were: born full-term (≥ 37 weeks), birthweight $\geq 2,500$ g, no congenital anomalies, and an Apgar score of ≥ 7 at five minutes post-birth.

Randomization and masking

During recruitment, a cover story was used. Pregnant women were informed that the study investigated associations between infant sleep and feeding, the role of mother-infant contact, as well as physical and mental health of mother and infant. They were also told that a subgroup would perform a daily contact-period throughout the first five weeks after delivery. An independent researcher performed computer-generated randomization to the care-as-usual (CAU) or SSC condition (1:1), with random blocks of four and six, stratified by parity (multiparae or primiparae). Randomization was stored individually in sealed envelopes.

Procedure

Interested women were visited at home between gestational week 34 and 36. They received further information in accordance with the cover story, gave written informed consent, filled in questionnaires on demographics, as well as prenatal stress and anxiety, and were assigned to a group. Women in the SSC condition were additionally instructed to practice SSC for one hour a day for five weeks, starting immediately after birth. From birth, mothers of both conditions filled in daily physical contact-logbooks, including information on the amount of SSC, holding, and breastfeeding performed. Debriefing took place at a follow-up visit after one year. Another follow-up assessment took place around the children's third birthday, including online questionnaires on their children's cognition and behavior.

Measures

For all outcome variables, internal consistency was assessed using Revelle's omega total (ω_t , Revelle & Condon, 2019). Internal consistency estimates $>.70$ are considered adequate for questionnaire-based group comparisons (Nunnally & Bernstein, 1994).

Maternal prenatal stress and anxiety

During the prenatal home-visit, women filled in four questionnaires on pregnancy-specific, as well as general stress and anxiety. The State Anxiety Scale of the State-Trait Anxiety Inventory ($\omega_t = .91$; STAI; Van der Ploeg et al., 1981) measures general state anxiety with 20 questions on a four-point scale, for which a sum score is computed. Pregnancy-specific anxiety was measured with a sum score of the Pregnancy-Related Anxiety Questionnaire ($\omega_t = .90$; PRAQ; van den Bergh et al., 2020), which contains 34 questions on anxiety experienced during pregnancy on five-point scales. Daily hassles were measured with the Alledaagse Problemen Lijst ($\omega_t = .79$; APL; Vingerhoets et al., 1989), containing 49 questions addressing general stressful events. Participants indicated whether an event had occurred in the past two months, and how affected they had been by it on four-point scales. Scores of how much the hassles affected mothers were summed up. The Pregnancy Experience Scale ($\omega_t = .90$; PES; DiPietro et al., 2004) measured pregnancy-specific stress. On 43 items, participants indicated whether a situation was an uplift and/or hassle, on two four-point scales. Ratio scores were computed per participant, dividing the sum score of uplifts ($\omega_t = .92$) by that of hassles ($\omega_t = .85$).

A single grand composite 'Maternal prenatal stress' ($\omega t = .90$) was created by standardizing and averaging the four questionnaires (Beijers et al., 2020). If one questionnaire was missing, an average was computed across the other three. If more than one questionnaire was missing, no composite was computed for that participant and their score on maternal stress was considered missing.

Skin-to-skin contact (SSC)

The mother-infant physical contact-logbook was used to track periods of holding, breastfeeding, or SSC, in five-minute intervals during the first five postnatal weeks. Maternal holding and breastfeeding were not counted as SSC. Moreover, SSC and holding by other people were reported in the logbook, but were not counted toward mother-infant SSC. Mothers in both conditions filled in the logbook every two to three hours throughout the day, on a moment that suited them well during their daily routine (e.g., after feeding or diaper changes). The amount of SSC performed a day was only computed if at least 80% of that day was filled, and if logbooks were filled in sufficiently (≥ 21 of 35 days). In total, 90 mothers (CAU = 41; SSC = 49) had filled in the logbook sufficiently. For valid logbooks, missing days were replaced with the dyad's mean amount of SSC of two days before and after. The total amount of SSC performed throughout the intervention period was only computed for logbooks with sufficient data.

Children's executive functioning at age three

The Behavior Rating Inventory of Executive Function-Preschool (BRIEF-P) examined everyday executive functioning with 63 items on three-point scales (Sherman & Brooks, 2010). The questionnaire contained five subscales: Flexibility ($\omega t = .92$), Inhibition ($\omega t = .91$), Emotion Regulation ($\omega t = .86$), Planning and Organizing ($\omega t = .73$), and Working Memory ($\omega t = .87$). Higher scores on the BRIEF-P indicated more difficulties. While an overall score of executive functioning is commonly computed for the BRIEF-P in older children, Skogan et al. (2016) have demonstrated that this unidimensional conceptualization is not adequate at age three. In young children, different components of executive functioning develop at differing paces (Anderson, 2002). We therefore included the five BRIEF-P subscales in the analyses.

Children's problem behavior at age three

Mothers reported on their children's internalizing and externalizing behavior in two questionnaires. The first questionnaire, the Dutch version of the Child Behavior Checklist/1.5-5, contained 99 items on five-point Likert

scales (CBCL; Achenbach & Rescorla, 2000). The CBCL factor Internalizing ($\omega t = .76$) included the subscales emotionally reactive, anxious/depressed, somatic complaints, and withdrawal. The CBCL factor Externalizing ($\omega t = .92$) contained the subscales attention problems, and aggressive behavior. Higher scores on the CBCL indicated more problem behavior. Mothers also filled in the Strengths and Difficulties questionnaire (SDQ; Goodman, 1997). The SDQ contained 25 items (10 reversed) on three-point scales. The SDQ factor Internalizing ($\omega t = .65$) consisted of the subscales emotional symptoms, and peer problems. The factor Externalizing ($\omega t = .71$) consisted of prosocial behavior, and hyperactivity. Due to relatively low internal consistency, the SDQ was not included in further analyses.

Missing data

Of all 116 mothers (CAU = 60; SSC = 56), four mothers in the CAU and three mothers in the SSC condition discontinued the intervention (see Figure 1). Of the 104 mothers (CAU = 53; SSC = 49) participating in the three-year follow-up, the BRIEF-P was incomplete for two mothers in the SSC and four mothers in the CAU condition. Five mothers in the SSC and five in the CAU condition did not complete the CBCL. Prenatal questionnaires STAI and PRAQ were missing for one mother in the SSC condition. The APL was missing for one mother in the CAU condition. The PES was missing for two mothers in the SSC and two mothers in the CAU condition. Composite scores on prenatal stress were missing for one mother in the SSC and one in the CAU condition.

Statistical analyses

Statistical approaches

All analyses were conducted in R version 4.1.1 (R Core Team, 2020). Similar to previous assessments of this RCT (Cooijmans et al., 2022), current analyses were performed with three approaches. In the intention-to-treat (ITT) approach, all dyads were included in the analyses, regardless of compliance (CAU = 60; SSC = 56). Missing values on moderators and outcome variables were imputed with the expectation-maximization method (Liu & Brown, 2013). In the per-protocol (PP) approach, dyads of both conditions were only included if they had no missing outcome data on the BRIEF-P (CAU = 49; SSC = 18) and the CBCL (CAU = 48; SSC = 17). Dyads of the SSC condition were included in the PP approach if they had complete logbooks (>60% filled in) and if they had performed at least one hour of SSC on at least 28 of the 35 days (i.e., 80% of the days). This 80% criterion is based on a prior study that asked

mothers to perform SSC for 4 weeks (Bigelow et al., 2012). The exploratory dose-response (DR) approach was performed within the SSC condition, including only mothers with valid logbooks (SSC = 49). In DR analyses, the total duration of SSC was used as a continuous predictor, and missing outcome values were imputed.

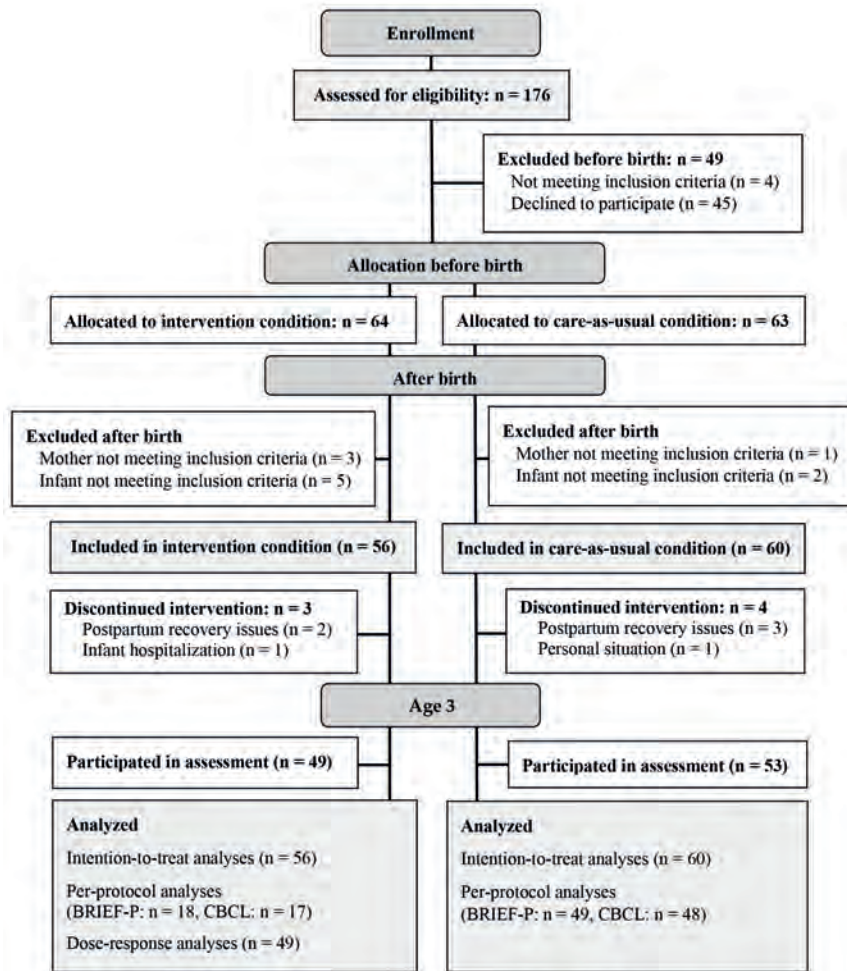


Figure 1. Participant flowchart.

Preliminary analyses

Sample size calculations for the primary study outcome (maternal depressive symptoms) indicated that, accounting for attrition, 116 dyads suffice to detect a medium effect size ($f = 0.24$) with a power of 80% (Cooijmans et al., 2017). Outliers of the BRIEF-P subscales and CBCL factors were winsorized (replaced with the mean plus/minus three times the standard deviation; Tukey, 1977). Differences in baseline characteristics and study variables were assessed for the ITT and PP approaches, using independent sample t-tests for normally, and Mann-Whitney U tests for non-normally distributed continuous data. For categorical data, χ^2 tests were used. For the DR approach, Pearson correlations were computed ('stats', R Core Team, 2020).

Main analyses

Children's executive functioning. Group differences on executive functioning were assessed with five subscales of the BRIEF-P, in a one-way multivariate analysis of variance (MANOVA). In case of group differences on baseline characteristics, the variable was corrected for, using a multivariate analysis of covariance (MANCOVA). The interaction of maternal prenatal stress with condition was assessed in an additional MANCOVA ('car', Fox & Weisberg, 2019).

Children's problem behavior. In case of group differences in baseline characteristics, two analyses of covariance (ANCOVA) were performed, one on internalizing and one on externalizing behavior. If no group differences were indicated, we referred to the outcomes of previously described t-tests, Mann-Whitney U tests, and Pearson correlations to answer our research question. The interaction of maternal prenatal stress with condition was assessed in two additional ANCOVAs.

Results

Participants were recruited from April 2016 until September 2017. The follow-up assessment took place between September 2019 and August 2020. The participant flow is presented in Figure 1. No study-related harms were reported.

Preliminary analyses

Outliers were identified on the following variables: BRIEF-P subscales Flexibility ($N = 1$), Inhibition ($N = 1$) and Regulation ($N = 1$); CBCL Internalizing ($N = 2$); prenatal questionnaires: PES ($N = 1$), STAI ($N = 1$), APL ($N = 1$), and the composite of prenatal stress ($N = 1$). Group comparisons of baseline characteristics and study variables are listed in Table 1. The intervention condition performed significantly more SSC than the CAU condition. On average, mothers in the SSC condition performed 58 min ($SD = 26$ min) and the CAU condition 12 min ($SD = 23$ min) of SSC a day throughout the intervention phase. Across the intervention period, mothers in the SSC condition provided approximately between 42 and 83 min of daily SSC whereas mothers in the CAU condition provided between zero and 60 min (for a day-by-day graph see Cooijmans et al., 2022). There was no significant difference between primiparae and multiparae women in the amount of SSC performed ($t = 0.37$, $d = 0.08$, $p = .72$). Of all mothers in the SSC condition, 18 performed sufficient daily SSC for PP analyses (>60 min on at least 28 of the 35 days). Correlations between outcome variables are reported in Table 2. Pearson correlations of the total amount of SSC with the outcome variables for the DR approach were insignificant.

Main analyses

Children's executive functioning

Assumptions of multivariate normality for the MANOVAs on the five BRIEF-P subscales were not met. The dependent variables were therefore square root transformed, and Pillai's Trace is reported as a robust statistic (Ateş et al., 2019). There were no significant differences between conditions on executive functioning (Table 3).

MANCOVAs testing the interaction of condition with prenatal stress on the BRIEF-P subscales were insignificant (Table 3).

Table 1. Descriptive statistics and group comparisons for mother-infants dyads of the three-year follow-up assessment in the skin-to-skin contact (SSC) and care-as-usual (CAU) conditions

	Intention-to-treat ^a			Per-Protocol	
	CAU (N=60)	SSC (N=56)		SSC (N=18)	
Baseline characteristics ^a	M(SD)	M(SD)		M(SD)	Statistic ^g
Maternal age (years)	32.48(3.05)	32.36(3.85)		32.90(3.80)	478.00 ^b
Maternal educational level	6.87(1.79)	6.82(1.55)		6.78(1.48)	564.00 ^b
Smoking (% No)	100.00	96.43		97.87	.33 ^c
Alcohol (% No)	100.00	98.21		97.87	.33 ^c
C-section (% No)	94.80	92.70		97.87	.00 ^c
Birth order (%)					
First	46.70	48.21		33.33	1.25 ^c
Second	38.33	19.64		38.89	
Third	15.00	19.64		27.78	
APGAR score	9.70(0.62)	9.84(0.42)		9.72(.58)	474.50 ^b
Child sex (% girls)	43.33	58.93		61.11	1.25 ^c
Birthweight (grams)	3567.47(358.77)	3650.05(414.93)		3760.56(454.59)	-1.59 ^d
Gestat. age at birth (weeks)	40.02(1.10)	40.08(1.01)		40.16(1.03)	-.51 ^d
Age at follow-up (years)	3.02(0.12)	3.03(0.12)		3.02(.10)	437.50 ^b
Total SSC (min.)^a	308.17(442.41)	2067.68(850.65)		2905.90(497.52)	18.00*** ^b
Moderators^f	M(SD)	M(SD)	Statistic	M(SD)	Statistic
Maternal Prenatal Stress ^e	-0.09(.85)	0.10(.1.14)	1569.00 ^b	-0.06(.92)	305.00 ^b
PRAQ ^a	-0.01(.96)	-0.02(1.05)	1257.50 ^b	-0.05(.89)	453.00 ^b
STAI State ^a	-0.16(.83)	0.15(1.14)	1037.00 ^b	-0.01(1.00)	456.50 ^b
PES ^a	-0.08(0.88)	0.07(1.11)	1160.00 ^b	-0.10(.92)	427.50 ^b
APL ^a	-0.08(0.93)	0.09(1.08)	1144.50 ^b	-0.06 (.62)	474.00 ^b
Outcome Variables^e	M (SD)	M (SD)	Statistic	M (SD)	Statistic
BRIEF-P					
Flexibility	3.91(2.63)	3.42(2.77)	1887.50 ^b	6.22(5.44)	514.50 ^b
Inhibition	8.40(5.59)	7.12(4.26)	1872.50 ^b	7.78(5.54)	483.00 ^b
Memory	6.94(4.62)	5.65(4.30)	1952.50 ^b	5.83(4.81)	477.00 ^b
Planning	4.77(2.79)	4.02(2.49)	1927.00 ^b	4.06(2.75)	488.50 ^b
Regulation	5.61(3.85)	4.05(3.00)	2104.50* ^b	3.94(2.69)	563.00 ^b
CBCL Internalizing	10.65(1.18)	10.10(1.05)	2148.50** ^b	10.09(0.90)	497.00 ^b
CBCL Externalizing	17.83(3.88)	16.51(3.10)	2.04* ^d	16.24(3.19)	1.79 ^d

Note. M, Mean; SD, Standard deviation; ^a M and SD are presented for non-imputed data. ^b Mann-Whitney U tests for non-normally distributed data. ^c χ^2 tests for categorical data. ^d Independent samples t-tests for normally distributed data. ^e M and SD for winsorized and imputed data. ^f Standardized data for all moderators. ^g Comparing baseline statistics of the per-protocol sample. * $p < .05$, ** $p < .01$ ***, $p < .001$.

Table 2. Pearson correlations among study variables across the entire sample

Variable	BRIEF-P ^a				CBCL ^a			Moderator ^b	
	Flexibility	Inhibition	Memory	Planning	Regulation	CBCL Int.	CBCL Ext.	Pre. Stress	
Flexibility	-	-	-	-	-	-	-	-	-
Inhibition	.20*	-	-	-	-	-	-	-	-
Memory	.20*	.72***	-	-	-	-	-	-	-
Planning	.14	.64***	.72***	-	-	-	-	-	-
Regulation	.40***	.43***	.35***	.36**	-	-	-	-	-
CBCL Int.	.57***	.44***	.40***	.40**	.56***	-	-	-	-
CBCL Ext.	.23*	.78***	.60***	.44***	.58***	.59***	-	-	-
Pre. Stress	.22*	.20*	.25**	.23*	.16	.13	.08	-	-
Total SSC ^b	.05	-.08	-.01	.08	-.04	.05	-.23	.17	

Note. *Pre. Stress*, Maternal prenatal stress; ^aWinsorized and imputed data. Higher scores indicate more difficulties. ^bCorrelations with total amount of SSC for the dose-response approach within the intervention condition (*N* = 49).

p* < .05, *p* < .01, ****p* < .001.

Table 3. Multivariate analyses of variance (MANOVA) on executive functioning and exploratory analyses of covariance on executive functioning and behavior

Intention-to-treat					Per-protocol				Dose-response ^a			
Main Analysis												
<i>BRIEF-P^b</i>	<i>V</i>	η^2	<i>F(5,110)</i>	<i>p</i>	<i>V</i>	η^2	<i>F(5,65)</i>	<i>p</i>	<i>V</i>	η^2	<i>F(5,45)</i>	<i>p</i>
Condition	.043	.043	0.95	.450	.057	.057	0.74	.594	.023	.023	0.19	.965
Exploratory Analyses												
<i>BRIEF-P^b</i>	<i>V</i>	η^2	<i>F(5,108)</i>	<i>p</i>	<i>V</i>	η^2	<i>F(5,62)</i>	<i>p</i>	<i>V</i>	η^2	<i>F(5,45)</i>	<i>p</i>
Condition	.048	.067	1.17	.329	.069	.068	0.85	.518	.024	.040	1.19	.965
Pren.	.125	.126	3.00	.014	.190	.190	2.73	.028	.181	.181	1.72	.153
Cond. x Pren.	.019	.022	0.47	.799	.036	.036	0.43	.825	.157	.157	1.45	.229
<i>Internalizing^b</i>		η^2	<i>F(1,112)</i>	<i>p</i>		η^2	<i>F(1,60)</i>	<i>p</i>		η^2	<i>F(1,45)</i>	<i>p</i>
Condition		.071	7.43	.007		.071	2.92	.093		.000	0.125	.725
Pren.		.042	4.93	.029		.076	0.28	.278		.132	6.835	.012
Cond. x Pren.		.016	1.76	.187		.002	0.09	.761		.014	0.630	.432
<i>Externalizing</i>		η^2	<i>F(1,112)</i>	<i>p</i>		η^2	<i>F(1,60)</i>	<i>p</i>		η^2	<i>F(1,45)</i>	<i>p</i>
Condition		.042	4.17	.043		.045	2.75	.102		.077	2.68	.109
Pren.		.030	3.50	.064		.008	0.47	.495		.078	3.82	.057
Cond. x Pren.		.003	0.33	.567		.007	0.44	.512		.010	0.47	.495

Note. *V*, Pillai's trace for MANOVAs; η^2 , partial eta²; *Cond.*, Condition; *Pren.*, Prenatal stress.

^aDose-response analyses within intervention condition with duration of skin-to-skin as continuous predictor. ^bDependent variables were square-root transformed.

Children's problem behavior

Since there were no significant group differences in baseline characteristics, and as such no need to control for variables, we could rely on the group differences as reported in Tables 1 and 2. Group differences in internalizing and externalizing problems for the ITT approach are visualized in Figures 2 and 3.

In the ITT approach, a Mann-Whitney U test on internalizing problems was significant (95% CI = 0.11–1.00, $U = 2148.50$, $r = .24$, $p = .01$). The SSC condition ($Mdn = 9.88$, $M = 10.10$, $SD = 1.05$) showed fewer internalizing problems compared to the CAU condition ($Mdn = 10.74$, $M = 10.65$, $SD = 1.18$). An independent samples t-test showed significantly fewer externalizing problems (95% CI = 0.04–2.62, $t = 2.04$, $d = 0.38$, $p = .04$) in the SSC condition ($M = 16.51$, $SD = 3.10$), compared to the CAU condition ($M = 17.83$, $SD = 3.88$) in the ITT approach. No significant group differences were found in the PP (Table 1) and DR approaches (Table 2).

ANCOVAs testing the interaction of condition with prenatal stress on internalizing and externalizing behavior were insignificant (Table 3).

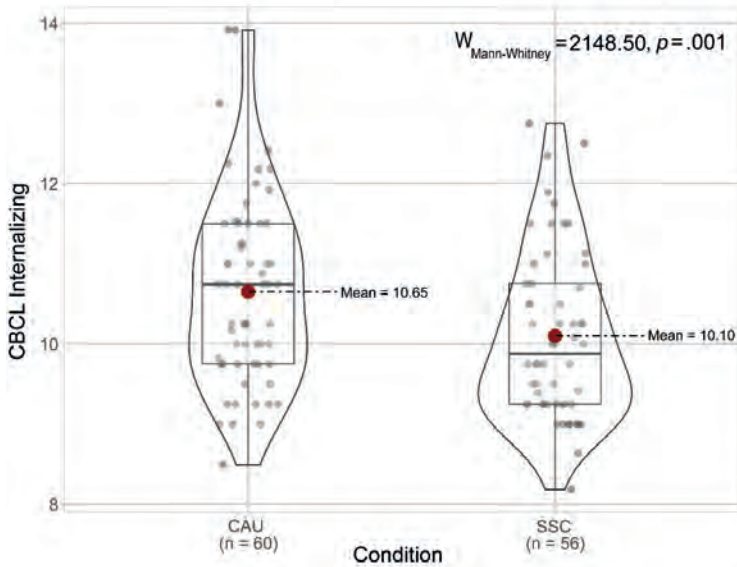


Figure 2. Means, standard deviations and distributions of scores on Internalizing behavior for the CAU and SSC condition for the intention-to-treat approach.

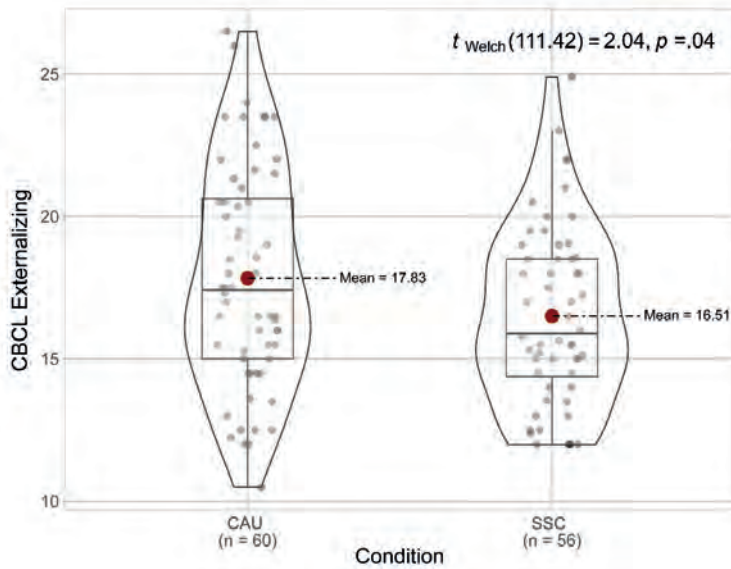


Figure 3. Means, standard deviations and distributions of scores on Externalizing behavior for the CAU and SSC condition for the intention-to-treat approach.

Discussion

This RCT investigated whether skin-to-skin contact (SSC) with full-term infants during the first five postnatal weeks affected executive functioning and child behavior problems three years later. Additionally, we explored whether the intervention was more beneficial for children of mothers who had experienced prenatal stress and anxiety, compared to those of mothers who had not. In the intention-to-treat analyses, children of the SSC condition showed fewer internalizing and externalizing behavior problems than children of the CAU condition. No group differences were found on executive functioning. Maternal prenatal symptoms did not moderate the effects of SSC on executive functioning and behavior problems. Lastly, no significant results were found in per-protocol and dose-response analyses.

Beneficial effects of SSC on children's behavior, as reported in the intention-to-treat analyses, are in line with findings in preterm infants (Charpak et al., 2017; Feldman et al., 2014). The only previous study to date on long-term outcomes of SSC for full-term infants reported beneficial effects of SSC on children's behavior during a mother-child conversation (Bigelow & Power, 2020). However, this study was not an RCT and mothers were not blind to the study goal during recruitment, potentially introducing a sampling bias to the study. The current RCT recruited mothers with a cover story, and significant effects on behavior were found in the fully randomized sample. Therefore, these findings constitute substantial evidence that in full-term infants, just as in preterm infants, early SSC may benefit their behavioral development.

We also performed per-protocol analyses (PP), including mothers of the SSC condition only if they had performed the requested hour of SSC regularly. However, only 18 mothers had performed sufficient SSC, and we did not find significant effects despite the PP means being virtually identical to the ITT means (see Table 1), potentially due to a lack of power. We also did not find dose-response effects of the amount of SSC performed within the SSC condition, which possibly indicates that shorter durations of SSC might suffice to achieve desired effects on child behavior. DR effects of SSC have, however, been found on breastfeeding duration, indicating that increased amounts of SSC might benefit other important outcomes for infant and mother (Cooijmans et al., 2022).

The current absence of an effect on EF is not in line with literature on preterm infants. For example, a previous study on preterm children reported facilitating effects of daily SSC on EF throughout childhood (Feldman et al., 2014). However, to our knowledge, no studies have assessed the effects of SSC on EF in full-term infants, and SSC possibly may not have large effects on EF in infants born full-term. Preterm infants' cognitive development may benefit more from SSC because they are generally more fragile, their neurodevelopment is strained, and they are deprived of physical contact because of their need of incubator care (Norholt, 2020).

Another reason for the current null-findings on EF might be the chosen assessment age. We assessed children at age three, while the previous study on preterm infants reported effects on EF at age five and 10 years (Feldman et al., 2014). It is suggested that EF undergoes crucial developmental shifts after age three, and therefore EF assessments are more reliable later in childhood (Anderson, 2002; Garon et al., 2016). Potentially, effects on EF in our study may not yet be visible. Additionally, the current assessment relied on parental report, while previous effects of SSC on preterm infants' EF were assessed through a cognitive task (Feldman et al., 2014). Parental report and experimental tasks on EF have been suggested to be incongruent (Garon et al., 2016), and future research should therefore combine parental reports with cognitive tasks. Combining these measures may additionally rule out the possibility of maternal response biases.

Finally, our low intervention compliance may have played a role, as higher SSC intervention compliance has been reported in preterm infants (Charpak et al., 2017; Feldman et al., 2014), where the intervention is usually integrated into hospital care (Blomqvist et al., 2012). Implementation of the intervention into daily home routines may be challenging for mothers of full-term infants. Also, mothers in the current study were blind to the intervention aims. In preterm infants, mothers are aware of the potential of SSC, and might therefore be more engaged.

The current study has substantial strengths. This is the first RCT assessing long-term benefits of SSC in full-term infants, and drop-out rate was considerably low throughout the study. However, limitations should be noted. First, the current cohort was largely homogeneous, including mainly families of high SES and education. Second, mothers were debriefed when their child turned one. This might have influenced maternal reports on child EF and

behavior at age three. Although this cannot entirely be ruled out, we consider it unlikely, since biased maternal assessments would have caused similar effects on EF reporting. Lastly, the restricted sample size in the current study did not allow for an assessment of potential variables that may mediate the effects of daily SSC on child outcomes, hence revealing the underlying working mechanisms. This is an important next step to pursue in future research in larger study populations.

Conclusion

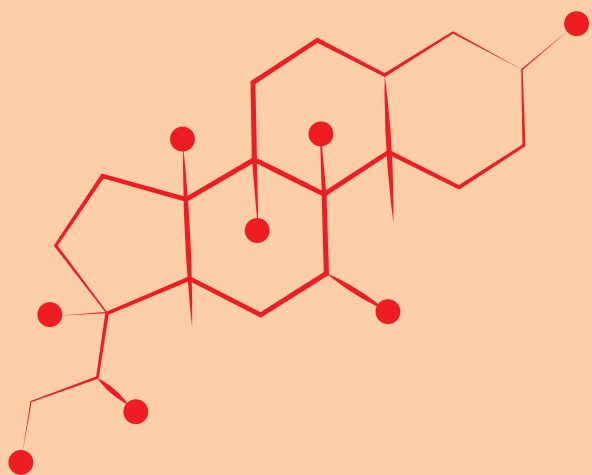
This study indicates that daily SSC in full-term infants' first postnatal month may help prevent behavioral problems three years later. Additionally, previous assessments of this RCT demonstrated beneficial effects on breastfeeding duration (Cooijmans et al., 2022). Taken together, the current RCT contributes substantially to the evidence of SSC effects on children born full-term. This RCT hopefully motivates further research on daily SSC interventions with healthy full-term children. Future studies should address ways of enhancing parental intervention compliance, and combine questionnaire-based assessments with behavioral observations.

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Chapter 6

Infant colic and sleeping problems from early childhood through adolescence

Based on: Rheinheimer, N. & de Weerth, C.

Under review

Abstract

Our aims are 1) to assess whether sleeping problems persist from early childhood until adolescence, and 2) to investigate whether infant colic is associated with more sleeping problems throughout childhood and adolescence. Furthermore, we explore a moderation by parent-infant room sharing of potential associations between infant colic and sleeping problems. Data originate from a prospective longitudinal study in a healthy community sample ($N=185$). Infant colic data were collected using cry diaries, filled in by the mothers for four days at age six weeks. The number of weeks of parent-infant room sharing from zero to six months of age were recorded using daily maternal diaries. Sleeping problems were assessed through maternal report at ages 2.5, 6 and 10 years, and child report at ages 12.5, 14 and 16.5 years. We used a score of Total Sleeping Problems, as well as subscales on Night Waking and Sleep Duration. Correlations were found between sleeping problems measured from 2.5 through 16.5 years for the Total Sleeping Problems, as well as for Night Waking and Sleep Duration. Compared to participants without infant colic, those with colic showed higher scores of Total Sleeping Problems between ages 12.5 and 16.5 years. We found no differences in sleeping problems between 2.5 and 10 years, nor evidence of a moderation by room sharing. Current findings suggest that sleeping problems developing in early and middle childhood persist throughout adolescence, and that children with infant colic may be prone to developing sleeping problems during adolescence.

Introduction

Sleep plays a fundamental role in children's psychological and physiological development, as it, for instance, allows the body to grow, recover, and consolidate memory (Mason et al., 2021; Schlieber & Han, 2021; Zhou et al., 2015). However, roughly one-third of children and adolescents are affected by sleeping problems, such as increased night waking, delayed sleep onset or low sleep duration (Cook et al., 2019; Tsao et al., 2021). Sleeping problems throughout childhood have, in turn, been related to poorer cognitive and behavioral functioning as well as physical and mental health (Matricciani et al., 2019; Shimizu et al., 2021; Tarokh et al., 2016; Tsao et al., 2021; Vriend et al., 2015; Zhou et al., 2015). Understanding whether sleeping problems persist from early childhood through adulthood is essential for the promotion of future sleep health (Reynolds et al., 2023). To date, research suggests that the emergence of sleeping problems is routed in early developmental stages and may persist into adulthood (Adair & Bauchner, 1993). One longitudinal study found that sleeping problems were largely consistent from age 10 to 12 (Cooper et al., 2023). Another study following children from age nine to 18 found that sleeping problems at age nine correlated with sleeping problems until age 18, and furthermore predicted poorer mental health at age 18 (Shimizu et al., 2021). In another study, shorter sleep durations at ages 11 to 13 were related to the development of delayed sleep phase disorder at ages 16 to 19 (Hysing et al., 2018). However, previous studies have focused on a restricted timeframe of a few years in late childhood, and although literature commonly assumes that the emergence of sleeping problems is routed in early childhood, there is currently a lack of longitudinal research documenting this development from toddlerhood onwards (Reynolds et al., 2023). The first aim of this study was to fill this gap by documenting the development of sleeping problems from toddlerhood through adolescence (*Aim 1*).

Studies suggest a particularly high prevalence of early sleeping problems in infants with colic (Helseth et al., 2022; Weissbluth et al., 1984). Infant colic is characterized by high levels of crying, often unsoothably and for more than three daily hours on at least three days per week, starting at around two weeks and peaking around six weeks postpartum (Savino, 2007; Wessel et al., 1954; Zeevenhooven et al., 2017). Underlying causes of colic cannot always be determined but may include inflammation, an immature central nervous system, allergies, and gastrointestinal problems (Cirgin Ellett, 2003; de Weerth et al., 2013; Pärtty et al., 2017; Zeevenhooven et al., 2018).

Although colic mostly resolves around the age of three months without further intervention, the condition has been suggested to be a precursor of difficulties with regulatory behavior later in life (Canivet et al., 2000; Galling et al., 2023; Indrio et al., 2023; Valla et al., 2021; Zeevenhooven et al., 2022). With respect to sleep, studies found an association of infant colic with parental reports of increased sleeping problems and sleep disorders, reduced sleep duration, and increased nightly awakenings in children up to 10 years of age (Helseth et al., 2022; Savino et al., 2005; Ståhlberg, 1984). In contrast, a study using sleep polysomnography (Kirjavainen et al., 2001), and three studies using parental report of sleeping problems (Bell et al., 2018; Canivet et al., 2000; Lehtonen et al., 1994), did not find associations of infant colic with sleep later in infancy or childhood. Interestingly, findings in the cohort of the current study furthermore indicated that infant colic was associated with steeper diurnal cortisol slopes and slightly higher cortisol concentrations throughout childhood, suggesting altered circadian functioning (Brett et al., 2024). In sum, previous findings on the associations of infant colic with sleep development are conflicting, and to date, no studies have assessed the association of infant colic with sleeping problems beyond the age of 10 years. The second aim of this study was to investigate the association of infant colic at age six weeks in a healthy community sample with sleeping problems between 2.5 and 16.5 years of age (*Aim 2*). Lastly, studies suggest that sleeping in the same room with the parents might facilitate external regulation by parents and benefit the development of an infant's own regulatory capacities (Barry, 2019; Beijers et al., 2019; Tollenaar et al., 2012). We therefore additionally explored whether more weeks of parent-infant room sharing in the first six months of life moderate the association between infant colic and sleeping problems throughout childhood.

Methods

Participants and recruitment

This preregistered study (<https://osf.io/ubgnf>) uses data of a prospective longitudinal cohort (Beijers et al., 2010), follows the declaration of Helsinki and was approved by the ethical committee of the Radboud University Nijmegen (ECG300107/SW2017-1303-497/SW 2017-1303-498/ECSW-2022-095). A community sample of 220 pregnant women was recruited through midwife practices from 2006 to 2007. Inclusion criteria were Dutch fluency, uncomplicated, singleton pregnancy, term birth, 5-minute Apgar score ≥ 7 ,

no drugs or alcohol during pregnancy, and no severe physical or mental health issues. Written informed consent was acquired from mothers until child age 14, and from children from ages 12.5 through 16.5. Of the recruited 220 women, eight were excluded after birth due to medical issues, and 19 dropped out due to personal circumstances, resulting in a final sample of 193 mother-infant dyads. Of these, 185 mother-child dyads participated in at least one assessment of the outcome variables for the current study. Participants with chronic illnesses or medication that affect sleeping behavior were excluded.

Measures

Colic

At age six weeks (41 ± 5 days), mothers filled in a validated four-day diary on infant crying every couple of hours (based on Barr et al., 1988, see Hechler et al., 2018). Infant 'fussing', 'crying', and 'crying unsoothably' was tracked with five-minute intervals. All three behaviors were summed up and averaged over the four days. Colic was determined using the modified Wessel's criteria of infant colic (≥ 180 minutes of daily crying (Wessel et al., 1954; Zeevenhooven et al., 2017)).

Room sharing

From infancy through age six months, mothers completed a daily diary on the infants' sleeping place divided in 30-minute intervals between 24:00 and 5:00 (Beijers et al., 2019). A week was considered a room sharing week if the infant spent 10%-100% of the night-time sleep in the parents' room (based on Tollenaar et al., 2012).

Sleeping problems

Children's Sleep Habits Questionnaire. At approximate child age of 2.5 ($M = 2.52$, $SD = 0.05$, Range = 2.41 – 2.76), 6 ($M = 6.11$, $SD = 0.18$, Range = 5.85 – 6.99) and 10 ($M = 10.06$, $SD = 0.21$, Range = 9.57 – 10.75) years, mothers filled in the Children's Sleep Habits Questionnaire (CSHQ) (Owens et al., 2000). The CSHQ contains 35 items measured on a three-point scale, which are summed into the subscales: Bedtime Resistance, Sleep Anxiety, Night Waking, Sleep Onset Delay, Atypical Sleep Duration, Parasomnias, Sleep Disordered Breathing, and Daytime Sleepiness. Combining 33 items (excluding two nominal items) results in a score of Total Sleeping Problems ranging from 33 to 99. Next to the Total Sleeping Problems, the subscales Night Waking and Atypical Sleep Duration were used as

outcome measures in this study, as these behaviors have been associated with colic in previous studies (Helseth et al., 2022; Ståhlberg, 1984; Weissbluth et al., 1984). Internal consistency (ωt) (Revelle & Condon, 2019) in the current sample was adequate at ages 2.5 ($\omega t = .73$), 6 ($\omega t = .72$) and 10 ($\omega t = .80$).

Pittsburgh Sleep Quality Index. At approximate child age 12.5 ($M = 12.67$, $SD = 0.29$, Range = 12.10 – 13.50), 14 ($M = 14.44$, $SD = 0.20$, Range = 14.07 – 15.05) and 16.5 ($M = 16.85$, $SD = 0.28$, Range = 16.18 – 17.49) years, children filled in the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989). The PSQI consists of 19 items on sleeping behavior over a typical month, which are divided into the subscales: Subjective Sleep Quality, Sleep Latency, Sleep Duration in hours per day, Habitual Sleep Efficiency, Sleep Disturbances, Use of Sleep Medication, and Daytime Drowsiness. A score of Total Sleeping Problems is computed by recoding the seven subscales into component scores ranging from zero to three, and subsequently summing up the component scores, resulting in a score that ranges from zero to 21. The Total Sleeping Problems, as well as the raw subscales Sleep Disturbances and Sleep Duration in hours per day were used in this study. Internal consistency in the current sample was adequate at ages 12.5 ($\omega t = .81$), 14 ($\omega t = .79$) and 16.5 ($\omega t = .72$).

Analytic plan

Descriptive statistics were computed for the whole sample, as well as for the colic and the non-colic condition. Outliers smaller or larger than three times the standard deviation were identified and winsorized (Tukey, 1977). Missing data was not imputed. Preliminary group comparisons were performed between children with and without colic, using independent sample t-tests for normally and Mann-Whitney U tests for non-normally distributed variables, as well as chi-square tests for categorical variables.

As per Aim 1, Spearman correlations among the variables of the CSHQ (Total Sleeping Problems, Night Waking, and Atypical Sleep Duration) from age 2.5 through 10, and the PSQI (Total Sleeping Problems, Sleep Disturbances, and Sleep Duration in hours per day) from age 12.5 through 16.5 were computed.

As per Aim 2, differences between infants with and without colic were assessed using multilevel growth curve models. Analyses were performed three times for the CSHQ (Total Sleeping Problems, Night Waking, and Atypical Sleep Duration) as well as for the PSQI (Total Sleeping Problems, Sleep Disturbances,

and Sleep Duration in hours per day). We corrected for this repetition of tests using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). First, the intercept was added as a random effect. Linear time (biological age) was added as a fixed effect. Contrary to the pre-registration, the slope was not added as a random effect, as it prevented model convergence and did not explain sufficient variance. In addition to linear time, we tested whether adding quadratic time (age*age) significantly decreased the Watanabe-Akaike Information Criterion (WAIC) (Hamaker et al., 2011). Potential covariates child sex, parity, and the highest level of maternal education at birth were added to the model in a build-up fashion if they lead to a decrease in the WAIC. Condition (colic vs. non-colic) was added as a fixed effect. The interaction of condition and time was only added in case of a decreased WAIC. Residuals of all final models were normally distributed.

For the exploratory moderation analyses, room sharing and the interaction of room sharing with condition were added to the models. Additional sensitivity analyses were performed including all participants excluded due to health conditions or medication. We ran additional exploratory dose-response analyses using a continuous measure of infant crying (i.e., mean daily minutes of crying) as the continuous duration of crying may better capture colic effects than a cutoff (Brett et al., 2024; Zeevenhooven et al., 2017).

Results

Descriptive and preliminary analyses

Of the 185 children included in this study, 125 still participated at age 16.5. Due to chronic illness of the connective tissue from age 2.5 through 16.5, one participant was excluded from the analyses on the CSHQ as well as the PSQI. Another 16 participants were excluded from the analyses on the PSQI due to chronic illness (e.g., diabetes, $N=1$; kidney disease, $N=1$; neurological injury, $N=1$) or medication intake (e.g., Thyroxine, $N=1$; Dexamethasone, $N=1$; Melatonin, $N=1$; Risperidone and/or Methylphenidate, $N=10$) between age 12.5 and 16.5. Binomial logistic regressions indicated that excluded participants did not differ from included participants in sex ($p = .65$), birth order ($p = .10$), maternal education ($p = .50$), average daily crying ($p = .99$) or colic ($p = .42$). Table 1 displays sample characteristics and the number of included participants per study variable.

The following outliers were identified and winsorized: CSHQ Total Sleeping Problems at 2.5 ($N=4$) and 10 years ($N=3$); CSHQ Night Waking at 2.5 ($N=2$), 6 ($N=3$) and 10 years ($N=2$); CSHQ Atypical Sleep Duration at 2.5 ($N=8$), 6 ($N=4$) and 10 years ($N=3$); PSQI Total Sleeping Problems at 14 ($N=1$) and 16.5 years ($N=2$); PSQI Sleep Disturbances at 14 ($N=2$) and 16.5 years ($N=1$); PSQI Sleep Duration in hours per day at 12.5 ($N=2$), and 16.5 years ($N=1$).

Table 1. Descriptive statistics and preliminary comparisons of study variables

	Total Sample		Colic		Non-Colic		Stat.
	<i>N</i>	<i>M</i> (SD) or %	<i>M</i> (SD) or %	<i>N</i>	<i>M</i> (SD) or %	<i>N</i>	
Sex (% girls)	185	46%	49%	39	44%	129	.10 ^f
Firstborn (% yes)	185	60%	59%	39	64%	129	.11 ^f
Maternal education ^a	179	6.72 (1.41)	6.86 (1.27)	37	6.66 (1.45)	126	2179 ^g
Weeks room sharing	172	11.19 (10.06)	10.14 (10.30)	37	11.53 (10.00)	120	2430 ^g
Colic (% yes)	168	23%					
Average daily crying (min.)	168	140.91 (56.76)	218.48 (32.40)	39	117.45 (38.77)	129	-16.27 ^{h***}
Total Sleeping Problems CSHQ^{b,d,i}							
2.5 years	176	38.99 (5.21)	39.71 (4.14)	39	38.73 (5.03)	121	2105 ^g
6 years	160	40.18 (4.86)	40.85 (5.76)	34	39.99 (4.48)	111	1785.5 ^g
10 years	149	40.72 (5.33)	40.78 (5.46)	34	40.44 (4.87)	101	1680 ^g
Total Sleeping Problems PSQI^{c,d,i}							
12.5 years	129	4.58 (2.52)	5.09 (2.61)	32	4.38 (2.52)	87	1186.5 ^g
14 years	124	5.15 (2.61)	6.23 (2.67)	27	4.95 (2.56)	86	832 ^{g*}
16.5 years	110	6.16 (2.41)	6.87 (2.48)	27	5.95 (2.38)	75	797.5 ^g
Night Waking CSHQ^{b,d,i}							
2.5 years	176	3.65 (1.20)	3.74 (1.21)	39	3.62 (1.19)	121	2280 ^g
6 years	160	3.49 (0.92)	3.51 (0.86)	34	3.44 (0.90)	111	1748 ^g
10 years	149	3.60 (0.93)	3.47 (0.83)	34	3.62 (0.94)	101	1860 ^g
Sleep Disturbances PSQI^{c,d,i}							
12.5 years	129	3.49 (2.81)	3.31 (2.58)	32	3.48 (2.88)	87	1414 ^g
14 years	124	3.41 (2.80)	3.45 (2.63)	27	3.33 (2.77)	86	1100.5 ^g
16.5 years	110	4.58 (2.96)	4.78 (3.33)	27	4.53 (2.90)	75	1002 ^g

Table 1. Continued

	Total Sample		Colic		Non-Colic		Stat.
	N	M (SD) or %	M (SD) or %	N	M (SD) or %	N	
Atypical Sleep Duration CSHQ^{b,d,i}							
2.5 years	176	3.21 (0.53)	3.28 (0.56)	39	3.21 (0.50)	121	2225 ^g
6 years	160	3.32 (0.65)	3.40 (0.69)	34	3.29 (0.64)	111	1718 ^g
10 years	149	3.59 (0.87)	3.38 (0.74)	34	3.66 (0.94)	101	1992 ^g
Sleep Duration in hours per day PSQI^{c,e,i}							
12.5 years	129	8.83 (1.08)	8.67 (1.28)	32	8.91 (1.03)	87	1567.5 ^g
14 years	124	8.24 (1.04)	7.79 (1.09)	27	8.32 (0.99)	86	1478.5^g*
16.5 years	110	7.48 (0.98)	7.42 (0.91)	27	7.47 (1.04)	75	1087 ^g

Note. ^a Ordinal score ranging from 1 = primary school to 8 = University or higher. ^b Children's Sleep Habits Questionnaire (CSHQ). ^c Pittsburgh Sleep Quality Index (PSQI). ^d Higher scores indicate more problems. ^e Average sleep duration in hours. Higher scores indicate longer sleep durations. ^f χ^2 for chi-square tests on categorical data. ^g *U* for Mann-Whitney *U* tests on non-normally distributed data. ^h *T*-statistic for *t*-tests on normally distributed data. ⁱ Winsorized data. ^{*}*p* < .10, ^{*}*p* < .05, ^{**}*p* < .01, ^{***}*p* < .001.

Association of sleeping problems from toddlerhood through adolescence

Correlations of sleeping problems from toddlerhood through adolescence are displayed in Table 2. We found weak to moderate correlations of Total Sleeping Problems, Night Waking/Sleep Disturbances, as well as Atypical Sleep Duration/Sleep duration in hours per day from ages 2.5 through 16.5 years.

Association of infant colic with sleeping problems

Results of the final models are presented in Table 3. For analyses on the CSHQ from age 2.5 through 10, there was no association of infant colic with Total Sleeping Problems, Night Waking, or Atypical Sleep Duration. Notably, there was a significant main effect of age for Total Sleeping Problems and Atypical Sleep Duration, indicating that sleeping problems increased with increasing age.

For analyses on the PSQI from age 12.5 through 16.5, after correction for multiple testing, there was a significant main effect of colic, with participants with a history of infant colic showing higher scores of Total Sleeping Problems compared to those without (Figure 1a). For analyses on the PSQI, we found significant main effects of age in all three analyses, indicating that, with increasing age, Total Sleeping Problems and Sleep Disturbances increased, and Sleep Duration in hours decreased. Finally, boys showed fewer Total Sleeping Problems than girls.

Table 2. Spearman correlations among study variables across the entire study group

Variables	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.
Total Sleeping Problems																			
1. 2.5 years ^{a,c}																			
2. 6 years ^{b,c}	.38^{***}																		
3. 10 years ^{a,c}	.23^{**}	.46^{***}																	
4. 12.5 years ^{b,c}	.22[*]	.28^{**}	.29^{**}																
5. 14 years ^{b,c}	.23[*]	.30^{***}	.23[*]	.44^{***}															
6. 16.5 years ^{b,c}	.05	.27^{**}	.25[*]	.31^{**}	.47^{***}														
Night Waking/Sleep Disturbances																			
7. 2.5 years ^{a,c}	.48^{***}	.19[*]	.09	.12	.16 [*]	.01													
8. 6 years ^{a,c}	.14[*]	.36^{***}	.21[*]	.02	.03	.11	.32^{***}												
9. 10 years ^{a,c}	.21[*]	.06	.43^{***}	.08	<.01	-.09	.22^{**}	.24^{**}											
10. 12.5 years ^{b,c}	.17 [*]	.19[*]	.13	.63^{***}	.12	.14	.06	.12	.01										
11. 14 years ^{b,c}	.16 [*]	.40^{***}	.33^{***}	.38^{***}	.50^{***}	.29^{**}	.15	.04	.10	.42^{***}									
12. 16.5 years ^{b,c}	-.05	.23[*]	.22[*]	.22[*]	.36^{***}	.47^{***}	-.09	.20[*]	.05	.35^{***}	.47^{***}								
Sleep Duration																			
13. 2.5 years ^{a,c}	.25^{***}	.01	.02	.27^{**}	.23[*]	.04	.07	-.02	-.04	.12	.04	.02							
14. 6 years ^{a,c}	.40^{***}	.49^{***}	.29^{***}	.23^{**}	.22[*]	.09	.23^{**}	.09	.13	.10	.26^{**}	.10	.11						
15. 10 years ^{a,c}	.22^{**}	.23^{**}	.58^{***}	.20[*]	.10	.12	.15 [*]	.04	.11	.11	.10	.03	.08	.16 [*]					
16. 12.5 years ^d	-.11	-.16 [*]	-.20 [*]	-.52^{***}	-.32^{***}	-.27^{**}	-.12	.01	.06	-.23^{**}	-.10	-.03	-.22[*]	-.13	-.25^{**}				
17. 14 years ^d	-.11	-.18 [*]	-.28 [*]	-.34^{***}	-.64^{***}	.40^{***}	-.10	-.02	-.03	.01	-.14	-.25[*]	-.22[*]	-.14	-.15	.33^{***}			
18. 16.5 years ^d	.07	-.09	-.15	-.06	-.23[*]	-.56^{***}	.06	.01	.07	.16 [*]	.01	-.12	-.14	.03	-.19[*]	.31^{**}	.27^{**}		
19. Daily min. crying	.17[*]	.05	.07	.11	.11	.06	.10	.13	.09	.01	.07	-.08	.06	.11	-.03	-.01	-.12	-.08	
20. Weeks room sharing	-.17[*]	.02	.07	.00	.06	.01	.01	.08	-.08	-.08	.04	.12	.00	.02	.01	.01	-.15	-.04	-.10

Note. Min., Minutes. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI). ^c Higher scores indicate more problems. ^d Higher scores indicate longer sleep durations. ^{*} $p < .10$, ^{**} $p < .05$, ^{***} $p < .001$.

Table 3. Best fitting models on the association of infant colic and sleeping problems

1. Total Sleeping Problems				2. Night Waking/Sleep Disturbances				3. Sleep Duration				
B	SE	P	95% CI	B	SE	P	95% CI	B	SE	P	95% CI	
CSHQ at 2.5, 6 and 10 years ^a												
Intercept	39.69	0.33	<.001	[39.03,40.34]	3.57	0.07	<.001	[3.43,3.70]	3.38	0.04	<.001	[3.29,3.46]
Age	<0.001	<0.001	.002	[<0.01,<0.01]	<-0.001	<0.001	.48	[<-0.01,<0.01]	0.001	<0.001	<.001	[<0.01,<0.01]
Colic [0 = no]	0.59	0.68	.39	[-0.76,1.93]	-0.03	0.14	.86	[-0.30,0.25]	-0.04	0.09	.64	[-0.21,0.13]
PSQI at 12.5, 14 and 16.5 years ^b												
Intercept	5.70	0.27	<.001	[5.18,6.23]	4.45	0.30	<.001	[3.85,5.04]	8.27	0.08	<.001	[8.11,8.43]
Age	0.001	<0.001	<.001	[<0.01,<0.01]	0.001	<0.001	<.001	[<0.01,<0.01]	<-0.001	<0.001	<.001	[<-0.01,<-0.01]
Child sex	-1.22	0.34	<.001	[-1.90,-0.54]	-1.28	0.39	.001	[-2.05,-0.51]	/	/	/	/
Colic [0 = no]	0.89	0.39	0.03^c	[0.11,1.67]	0.03	0.44	.94	[-0.85,0.91]	-0.25	0.16	.12	[-0.57,0.07]

Note. B, Effect size; SE, Standard Error. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI). ^c p-value significant after Benjamini-Hochberg correction for multiple testing (p<.033).

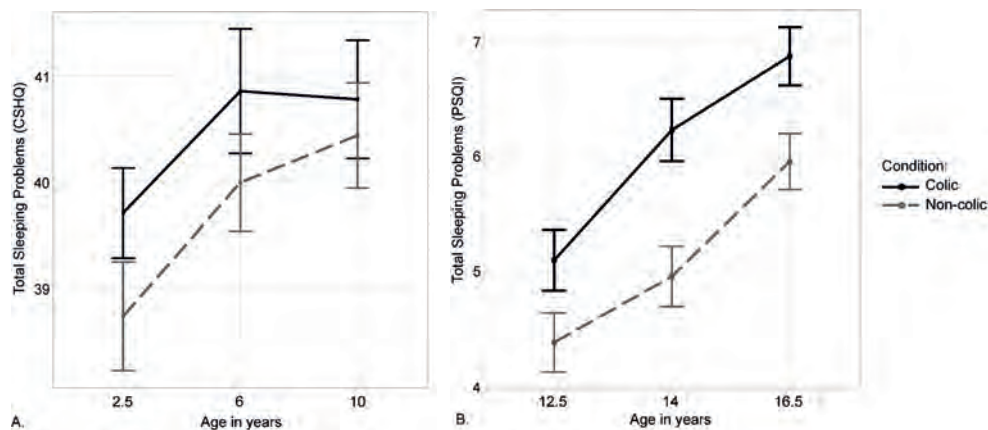


Figure 1. Average score of Total Sleeping Problems of A. the Children's Sleep Habits Questionnaire from age 2.5 through 10 (maternal report) and B. the Pittsburgh Sleep Quality Index from age 12.5 through 16.5 (self-report)

Moderation by room sharing

The final models on the moderation of the association of infant colic with sleeping problems by room sharing are displayed in Table 4. No significant interaction effects were found.

Sensitivity analyses

Analyses on the association of infant colic with sleeping problems including children who were excluded due to health conditions or medication were insignificant (see Supplementary information S1-S2). Also, no significant effects were found in dose-response analyses using the average score of crying in minutes (see Supplementary Information S3-S4).

Table 4. Best fitting models on the moderation of room sharing for the association of infant colic and sleeping problems

1. Total Sleeping Problems					2. Night Waking/Sleep Disturbances					3. Sleep Duration				
B	SE	P	95% CI		B	SE	P	95% CI		B	SE	P	95% CI	
CSHQ at 2.5, 6 and 10 years^a														
Intercept	39.63	0.35	<.001	[38.95,40.32]	3.59	0.07	<.001	[3.45,3.73]		3.37	0.04	<.001	[3.28,3.45]	
Age	<0.001	<0.001	.01	[<0.01,<0.01]	<-0.001	<0.001	.45	[<-0.01,<0.01]		<0.001	<0.001	<.001	[<0.01,<0.01]	
Colic [0 = no]	0.71	0.71	.32	[-0.68,2.10]	-0.05	0.15	.71	[-0.35,0.24]		-0.02	0.09	.86	[-0.19,0.16]	
Room sharing	-0.02	0.04	.60	[-0.09,0.05]	0.003	0.007	.67	[-0.01,0.02]		-0.001	0.004	.85	[-0.01,0.01]	
Room sharing x Colic	0.04	0.07	.61	[-0.10,0.17]	-0.005	0.01	.75	[-0.03,0.02]		0.009	0.009	.32	[-0.01,0.03]	
PSQI at 12.5, 14 and 16.5 years^b														
Intercept	5.70	0.29	<.001	[5.14,6.27]	4.52	0.32	<.001	[3.90,5.15]		8.28	0.09	<.001	[8.11,8.45]	
Age	0.001	<0.001	<.001	[<0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]		<-0.001	<0.001	<.001	[<-0.01,<-0.01]	
Child sex	-1.27	0.37	.001	[-1.99,-0.54]	-1.42	0.41	<.001	[-2.23,-0.62]		/	/	/	/	
Colic [0 = no]	0.96	0.41	.02	[0.15,1.77]	0.13	0.45	.78	[-0.77,1.02]		-0.27	0.16	.11	[-0.59,0.06]	
Room sharing	-0.007	0.02	.75	[-0.05,0.04]	-0.001	0.02	.98	[-0.05,0.05]		-0.007	0.009	.46	[-0.02,0.01]	
Room sharing x Colic	0.02	0.04	.67	[-0.06,0.09]	-0.003	0.04	.94	[-0.09,0.08]		0.002	0.02	.89	[-0.03,0.03]	

Note. B, Effect size; SE, Standard Error. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI).

Discussion

This study investigated the development of sleeping problems from 2.5 till 16.5 years, whether infant colic was associated with more sleeping problems, and whether parent-infant room sharing in the first six months of life moderates this association.

As hypothesized, the Total Scores of Sleeping Problems as well as subscales on Night Waking/Sleep Disturbances and (Atypical) Sleep Duration persisted from early and middle childhood into adolescence. Current findings are in line with studies reporting associations of sleeping problems between ages nine and 18 (Hysing et al., 2018; Shimizu et al., 2021). Notably, in our study, scores of Total Sleeping Problems also increased with rising age. Since insufficient sleep during childhood has a myriad of consequences for physical and psychological development (Matricciani et al., 2019; Shimizu et al., 2021; Tarokh et al., 2016; Tsao et al., 2021; Vriend et al., 2015; Zhou et al., 2015), future studies may focus on strengthening programs for resolving persistent sleeping problems already in early childhood.

Supporting our hypothesis, children with a history of colic reported more Total Sleeping Problems between 12.5 and 16.5 years. Their mothers also reported slightly more sleeping problems between the ages of 2.5 and 10 (Figure 1), however, these differences were insignificant. Hence, the association between infant colic and later sleeping problems may become stronger in adolescence. Alternatively, mothers may be less aware of their child's sleeping behavior, leading to more pronounced group differences with self-report in adolescence. Note, however, that maternal report during early childhood correlated with adolescent self-report (Table 2), supporting our first explanation. Importantly, a cross-sectional study found that reports of mothers and their children aged nine to 17 were equally valid in predicting polysomnography measures (Combs et al., 2019).

While previous evidence on associations of infant colic with childhood sleeping problems (studied up till age 10) is conflicting, a large body of research has shown associations of colic with childhood regulatory problems (e.g., externalizing and internalizing behavior) (Canivet et al., 2000; Galling et al., 2023; Indrio et al., 2023; Zeevenhooven et al., 2022) and in the current cohort, colic was also associated with altered cortisol circadian rhythms until the age of 10 (Brett et al., 2024). The current results suggest that

sleeping problems in children with a history of colic are more pronounced during adolescence. Potentially, previously found regulatory difficulties and altered circadian rhythms during early childhood are a precursor of sleeping problems in adolescence. During adolescence, the circadian rhythm shifts due to delayed melatonin secretion (Agostini & Centofanti, 2021), school-times are misaligned with adolescents' rhythms (Tarokh et al., 2016), and Delta EEG power during non-rapid eye movement sleep declines drastically, signifying physiological reorganization (Feinberg & Campbell, 2010). This reorganization of sleep physiology during adolescence might be especially challenging for children with pre-existing regulatory difficulties.

Contrary to our hypotheses, we found no differences in the PSQI subscales Sleep Disturbance and Sleep Duration in our main analyses. However, preliminary analyses showed significantly shorter sleep durations in children with a history of colic at age 14. Notably, subscale scores of the PSQI rely on fewer items, and are possibly more subjective than the overall score of Total Sleeping Problems. Future studies using polysomnography may help identify underlying mechanisms (e.g. sleep stages and microstructure) of the subjectively reported sleeping problems in adolescents with a history of colic.

We did not find a moderating role of the association of infant colic with sleeping problems by room sharing. However, in line with studies showing beneficial associations of room sharing with later childhood outcomes (Barry, 2019; Beijers et al., 2019; Tollenaar et al., 2012), room sharing correlated negatively with sleeping problems at age 2.5. Although current results suggest that the development of sleeping problems in adolescents with a history of colic is not prevented by parent-infant room sharing during the first six months, the current study might have been underpowered to assess this association, as a large proportion of infants received less than two weeks of room sharing. Future studies in populations where room sharing is more common are of interest.

To our knowledge, the current study was the first to assess sleep development in association with colic prospectively up to adolescence. Another strength were the prospective diaries on colic and room sharing in the form of simple logbooks, which reduce reporting biases compared to retrospective recall or brief questionnaires (Trull & Ebner-Priemer, 2009; Zeevenhooen et al., 2017). A limitation is that the observational nature of the study and the subjective sleep report do not allow us to identify underlying mechanisms of the association

between colic and sleeping problems. Future research employing objective measures (e.g., polysomnography), as well as randomized-controlled intervention trials are recommended. Lastly, our sample was highly educated and mostly Dutch. As sleep development and the evaluation of sleeping quality are subject to cultural differences (Schlieber & Han, 2021), the field would benefit from studies on samples with diverse demographic backgrounds.

Conclusion

The current study found that sleeping problems developing in early and middle childhood persist into adolescence, and that infants with colic were prone to develop sleeping problems during adolescence. Considering that sleeping problems tend to be underdiagnosed during routine well-child visits (Bathory & Tomopoulos, 2017), and in the light of consequences of insufficient sleep for child development (Mason et al., 2021; Matricciani et al., 2019; Schlieber & Han, 2021; Shimizu et al., 2021; Tarokh et al., 2016; Tsao et al., 2021; Vriend et al., 2015; Zhou et al., 2015), these findings should aid in raising awareness towards the importance of early childhood programs aimed at preventing and resolving sleeping problems.

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Supplementary information

Tables S-1 and S-2: Results of the analyses on the association of infant colic with sleeping problems including children who were excluded due to health conditions or medication were insignificant.

Table S-1. Best fitting models on the association of infant colic and sleeping problems including participants with health issues and medication

1. Total Sleeping Problems					2. Night Waking/Sleep Disturbances					3. Sleep Duration				
B	SE	P	95% CI		B	SE	P	95% CI		B	SE	P	95% CI	
CSHQ at 2.5, 6 and 10 years^a														
Intercept	39.97	0.33	<.001	[39.07,40.38]	3.57	0.07	<.001	[3.43,3.70]		3.37	0.04	<.001	[3.29,3.46]	
Age	<0.001	<0.001	.004	[<0.01,<0.01]	<-0.001	<0.001	.44	[<-0.01,<0.01]		<0.001	<0.001	<.001	[<0.01,<0.01]	
Colic [0 = no]	0.54	0.68	.43	[-0.80,1.89]	-0.02	0.14	.87	[-0.30,0.25]		-0.04	.09	.65	[-0.21,0.13]	
PSQI at 12.5, 14 and 16.5 years^b														
Intercept	5.96	0.28	<.001	[5.41,6.50]	4.62	0.29	<.001	[4.05,5.20]		8.23	0.08	<.001	[8.07,8.38]	
Age	0.001	<0.001	<.001	[<0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]		<-0.001	<0.001	<.001	[<-0.01,<-0.01]	
Child sex	-1.37	0.35	<.001	[-2.06,-0.67]	-1.42	0.37	<.001	[-2.15,-0.68]		/	/	/	/	
Colic [0 = no]	0.69	0.41	.09	[-0.11,1.50]	-0.11	0.43	.80	[-0.96,0.74]		-0.18	0.16	.24	[-0.49,0.12]	

Note. B, Effect size; SE, Standard Error. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI).

Table S-2. Best fitting models on the moderation of room sharing for the association of infant colic and sleeping problems including participants with health issues and medication

1. Total Sleeping Problems				2. Night Waking/Sleep Disturbances				3. Sleep Duration				
B	SE	P	95% CI	B	SE	P	95% CI	B	SE	P	95% CI	
CSHQ at 2.5, 6 and 10 years ^a												
Intercept	39.68	0.35	<.001	[39.00,40.36]	3.59	0.07	<.001	[3.44,3.73]	3.37	0.04	<.001	[3.28,3.45]
Age	<0.001	<0.001	.02	[<0.01,<0.01]	<-0.001	<0.001	.41	[<-0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]
Colic [0 = no]	0.66	0.71	.35	[-0.73,2.06]	-0.05	0.15	.73	[-0.34,0.24]	-0.01	0.09	.87	[-0.19,0.16]
Room sharing	-0.01	0.04	.77	[-0.08,0.06]	0.002	0.007	.71	[-0.01,0.02]	<-0.001	0.004	.84	[<-0.01,<0.01]
Room sharing x Colic	0.03	0.07	.69	[-0.11,0.16]	-0.004	0.01	.77	[-0.03,0.02]	0.009	0.009	.31	[<-0.01,0.03]
PSQI at 12.5, 14 and 16.5 years ^b												
Intercept	5.96	0.30	<.001	[5.38,6.55]	4.70	0.31	<.001	[4.09,5.30]	8.23	0.08	<.001	[8.07,8.39]
Age	0.001	<0.001	<.001	[<0.01,<0.01]	0.001	<0.001	<.001	[<0.01,<0.01]	-0.001	<0.001	<.001	[<-0.01,<-0.01]
Child sex	-1.39	0.37	<.001	[-2.13,-0.65]	-1.54	0.39	<.001	[-2.31,-0.78]	/	/	/	/
Colic [0 = no]	0.75	0.42	.08	[-0.09,1.58]	-0.04	0.44	.93	[-0.90,0.83]	-0.19	0.16	.22	[-0.51,0.12]
Room sharing	-0.02	0.02	.50	[-0.06,0.03]	-0.01	0.02	.64	[-0.06,0.03]	-0.003	0.008	.70	[-0.02,0.01]
Room sharing x Colic	0.03	0.04	.45	[-0.05,0.11]	<-0.001	0.04	.99	[-0.08,0.08]	<-0.001	0.02	>.99	[-0.03,0.03]

Note. B, Effect size; SE, Standard Error. ^aChildren's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI).

Tables S-3 and S-4: Results of the dose-response analyses using the average score of crying in minutes.

Table S-3. Exploratory dose-response analyses on the association of infant crying and sleeping problems																	
1. Total Sleeping Problems					2. Night Waking/Sleep Disturbances					3. Sleep Duration							
	B	SE	P	95% CI	B	SE	P	95% CI	B	SE	P	95% CI					
CSHQ at 2.5, 6 and 10 years ^a																	
Intercept	38.85	0.78	<.001	[36.98,40.07]	3.37	0.16	<.001	[3.05,3.69]	3.31	0.10	<.001	[3.11,3.51]					
Age	<0.001	<0.001	.002	[<0.01,<0.01]	<-0.001	<0.001	.46	[<-0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]					
Average Crying (min.)	0.009	0.005	.08	[<-0.01,0.02]	0.001	0.001	.21	[<-0.01,<0.01]	<0.001	<0.001	.55	[<-0.01,<0.01]					
PSQI at 12.5, 14 and 16.5 years ^b																	
Intercept	5.14	0.50	<.001	[4.16,6.13]	4.36	0.56	<.001	[3.26,5.46]	8.33	0.20	<.001	[7.93,8.72]					
Age	0.001	<.001	<.001	[<0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]	<-0.001	<0.001	<.001	[<-0.01,<-0.01]					
Child sex	-1.30	0.35	<.001	[-1.99,-0.60]	-1.29	0.39	.001	[-2.07,-0.51]	/	/	/	/					
Average Crying (min.)	0.006	0.003	.07	[<-0.01,0.01]	<0.001	0.004	.85	[<-0.01,<0.01]	<-0.001	0.001	.51	[<-0.01,<0.01]					

Note. B, Effect size; SE, Standard Error. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI). ^c p-value significant after Benjamini-Hochberg correction for multiple testing (p<.033).

Table S-4. Exploratory dose-response analyses on the moderation of room sharing for the association of infant crying and sleeping problems

1. Total Sleeping Problems				2. Night Waking/Sleep Disturbances				3. Sleep Duration				
B	SE	P	95% CI	B	SE	P	95% CI	B	SE	P	95% CI	
CSHQ at 2.5, 6 and 10 years ^a												
Intercept	38.58	0.84	<.001	[36.92,40.23]	3.43	0.18	<.001	[3.08,3.78]	3.28	0.11	<.001	[3.07,3.49]
Age	<0.001	<0.001	.01	[<0.01,<0.01]	<0.001	<0.001	.44	[<-0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]
Average Crying (min.)	0.008	0.005	.13	[<-0.01,0.02]	<0.001	0.001	.39	[<-0.01,<0.01]	<0.001	<0.001	.43	[<-0.01,<0.01]
Room sharing	0.06	0.08	.50	[-0.11,0.22]	0.03	0.02	.11	[<-0.01,0.06]	0.005	0.01	.60	[-0.02,0.03]
Room sharing x Crying	<-0.001	<0.001	.41	[<-0.01,<0.01]	<0.001	<0.001	.12	[<-0.01,<0.01]	<-0.001	<0.001	.69	[<-0.01,<0.01]
PSQI at 12.5, 14 and 16.5 years ^b												
Intercept	5.02	0.54	<.001	[3.96,6.09]	4.54	0.59	<.001	[3.37,5.71]	8.33	0.21	<.001	[7.91,8.75]
Age	0.001	<0.001	<.001	[<0.01,<0.01]	<0.001	<0.001	<.001	[<0.01,<0.01]	<-0.001	<0.001	<.001	[<-0.01,<-0.01]
Child sex	-1.35	0.37	<.001	[-2.08,-0.61]	-1.43	0.41	<.001	[-2.23,-0.62]	/	/	/	/
Average Crying (min.)	0.007	0.003	.05	[<-0.01,0.01]	<0.001	0.004	.97	[<-0.01,0.01]	-0.001	.001	.54	[<-0.01,<0.01]
Room sharing	-0.005	0.05	.93	[-0.10,0.10]	0.02	0.06	.68	[-0.09,0.13]	-0.02	0.02	.42	[-0.06,0.02]
Room sharing x Crying	<0.001	<0.001	.93	[<-0.01,0.01]	<-0.001	<0.001	.64	[<-0.01,0.01]	<0.001	<0.001	.59	[<-0.01,<0.01]

Note. B, Effect size; SE, Standard Error. ^a Children's Sleep Habits Questionnaire (CSHQ). ^b Pittsburgh Sleep Quality Index (PSQI).

Figures S-1 and S2: Figures showing group differences for the subscales of the Children's Sleep Habits Questionnaire and the Pittsburgh Sleep Quality Index.

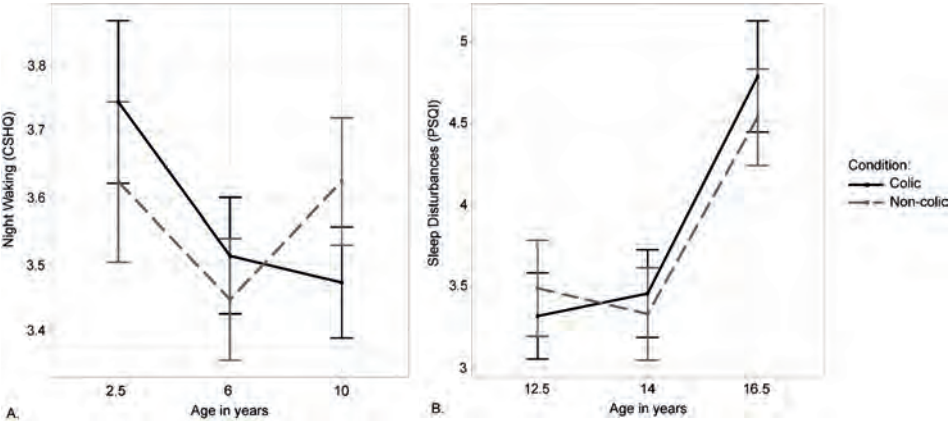


Figure S-1. Average score of A. Night Waking of the Children's Sleep Habits Questionnaire from age 2.5 through 10 (maternal report) and B. Sleep Disturbances of the Pittsburgh Sleep Quality Index from age 12.5 through 16.5 (self-report).

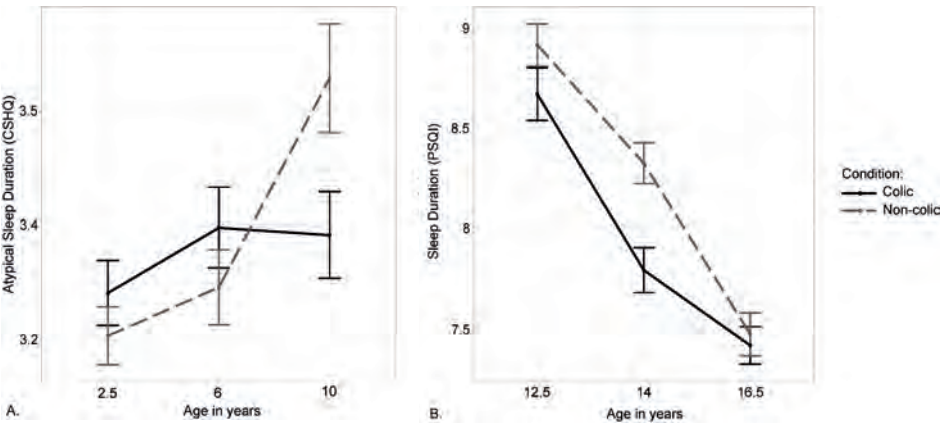
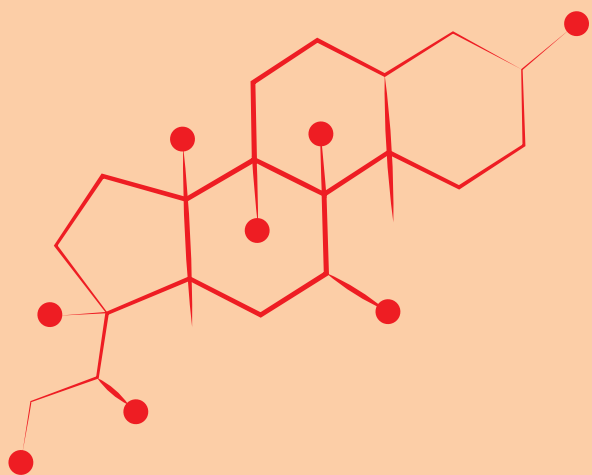


Figure S-2. Average score of A. Atypical Sleep Duration of the Children's Sleep Habits Questionnaire from age 2.5 through 10 (maternal report) and B. Average Sleep Duration in hours per day of the Pittsburgh Sleep Quality Index from age 12.5 through 16.5 (self-report).



Chapter 7

Discussion

This section starts with an extensive summary of the empirical chapters presented in this thesis. The summary is followed by a general discussion, interpreting the results in the context of the broader literature and exploring their implications for future research as well as the general society.

Summary

Self-regulation refers to the ability to adapt physiological and behavioral states in order to respond to demands and stressors within the body or in the environment (Beeghly et al., 2016; Nigg, 2017). The term encompasses both physiological aspects, such as neurobiological and circadian functioning, and behavioral and cognitive aspects, such as controlling anger and focusing on tasks (Beeghly et al., 2016; Nigg, 2017). Infants are not yet able to regulate autonomously, and hence largely rely on external regulation, most often provided by their caregivers (Feldman, 2007; Norholt, 2020; Rattaz et al., 2022). Through repeated, successful, external regulation, infants develop the ability to self-regulate (Beeghly et al., 2016; Kiel et al., 2024). Early caregiving modulates this development, with less optimal caregiving being linked to poorer outcomes for regulation (Gruhn & Compas, 2020; Gunnar & Quevedo, 2007; Loman & Gunnar, 2010). For instance, maltreatment in early childhood is associated with poorer emotion regulation, such as an increased expression of negative emotions during stressful situations between the ages of five and 18 years (see review by Gruhn & Compas, 2020). In turn, positive factors of early caregiving, such as maternal sensitivity, may facilitate the development of the child's regulatory capacities (Gunnar & Quevedo, 2007; Loman & Gunnar, 2010). Maternal sensitivity is defined as the mother's ability to respond promptly and accurately to the infant's needs (Bell & Ainsworth, 1972; Mesman & Emmen, 2013). Throughout the literature, it has been widely acknowledged that higher maternal sensitivity during infancy is associated with improved regulation of the physical and behavioral responses to stressful situations later in childhood (Albers et al., 2008; Berry et al., 2017; Borelli et al., 2021; Bosquet Enlow et al., 2014; Tsotsi et al., 2020). Identifying factors that facilitate the development of regulation is crucial for caregiving advice, policymaking, and developing interventions for infants with predisposing factors for regulatory difficulties. This thesis assessed the role of factors in early caregiving in the development of self-regulation from infancy through adolescence. The outcomes of self-regulation assessed in this thesis were the hypothalamic-pituitary-adrenal (HPA) axis, sleep, and behavior.

When an individual is distressed, the HPA axis responds with an increased production of the hormone cortisol, which can be measured in the saliva (Jansen et al., 2010; Leistner & Menke, 2020; Spiga et al., 2014). Chronic early life stress or adverse experiences, such as childhood maltreatment, are associated with a dysregulation of the HPA axis (Fogelman & Canli, 2018; Isenhour et al., 2021; Marques-Feixa et al., 2023; Murphy et al., 2022; Radley et al., 2015; Tarullo & Gunnar, 2006). This dysregulation, in turn, is linked to poorer physical and mental health later in life, highlighting the importance of the early caregiving environment for the development of well-functioning HPA axis regulation (Adam et al., 2017; Murphy et al., 2022; Zajkowska et al., 2022). Furthermore, early life plays a crucial role in the development of a healthy sleep rhythm (April-Sanders et al., 2021; Bathory & Tomopoulos, 2017; Schlieber & Han, 2021). Throughout the first years of life, children transition from a biphasic sleeping pattern, with several bouts of sleep a day to a monophasic pattern, with the majority of sleep overnight (Bathory & Tomopoulos, 2017; Iglowstein et al., 2003). Young infants largely depend on their caregivers to regulate their sleep-wake cycle and to develop a healthy sleeping pattern (Barry, 2021; Bathory & Tomopoulos, 2017). In turn, sleep in early childhood is involved in mental and physical development, including memory and learning, brain development, the immune system, physical growth, and hormonal production (Beebe, 2011; Irwin & Opp, 2017; Poluektov, 2021; Vriend et al., 2015). Also in the first year of life, infants highly rely on their caregivers to regulate their behavior, including emotional states, such as crying in response to daily stressors (Hofer, 1987; Norholt, 2020). Hereby, parents play a crucial role in infants' development of behavioral self-regulation (Feldman, 2007; Gruhn & Compas, 2020; Loman & Gunnar, 2010; Maughan et al., 2007; Norholt, 2020). Particularly toddlerhood is marked by the emergence of externalizing (e.g., anger, impulsivity) and internalizing (e.g., anxiety, withdrawal) behaviors as well as problems with executive functioning (e.g., attention, inhibition). Effective behavioral regulation, in turn, is essential for socio-emotional interactions, academic success, and overall mental health (Best & Miller, 2010; Hasty et al., 2023; Nigg, 2017). This thesis assessed associations of the described outcomes of child regulation with several factors of early caregiving. The following sections summarize the findings of this thesis per chapter.

Chapter 2

Exposure to outdoor green environments has been related to lower reported stress levels, as well as improved outcomes for mood, behavioral and socio-emotional regulation, and mental health in older children (McCormick, 2017; Moll et al., 2022; Scott et al., 2018; Taylor et al., 2002; Taylor & Butts-Wilmsmeyer, 2020). Meanwhile, the past decades have been characterized by a decreasing trend of outdoor time in children (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011). Little research has focused on **outdoor time** in infants. It is therefore unknown whether spending time outdoors has beneficial effects on the physiological and behavioral regulation of infants. We also know very little on how much time infants spend outdoors, and which demographic characteristics might facilitate or hinder outdoor time during infancy. The study presented in **Chapter 2** assessed the frequencies and durations of outdoor walking and infant carrying in mother-infant dyads, as well as infant outdoor sleeping in a stationary cot or pram, and identified associations of these activities with infant, maternal, and environmental characteristics. A nationwide online survey for mothers of 0-to-12-month-old infants was used ($N = 1275$). The survey inquired about mother-infant dyads' total weekly duration of walking in minutes, frequency of walking on weekdays as well as on weekends, and the frequency of using an infant carrier during walks. Outdoor sleeping was assessed in terms of whether the infant was put outdoors to sleep at all (yes/no), and the total weekly duration as well as the weekly frequency of outdoor sleeping. Associations of all outcome variables with a number of infant (e.g., age, sex, health), maternal (e.g., working status, age, health), and environmental (e.g., housing type, recreational areas in walking distance, city size) characteristics were assessed.

Results showed that mothers walked outdoors with their infants for approximately 201 minutes weekly, for around one to three walks over weekdays (Monday to Friday) and one to three walks on the weekend (Saturday and Sunday). Around 22% of mothers used an infant carrier for outdoor walking for at least half of the time. Among other associations, maternal enjoyment of outdoor walking, being on maternity leave or unemployed, and having more recreational areas within walking distance were positively associated with the amount of outdoor walking. The infant carrier was used more frequently during outdoor walks if the infant was younger, and if more than one child lived in the household. Roughly a third of infants regularly slept outdoors (29%), for a weekly duration of four hours and a weekly frequency of approximately one to two times. Infant outdoor sleeping was associated with younger infant

age, higher maternal education, and living in detached houses. In sum, this study identified important associations between demographic characteristics with the amount of outdoor time during infancy, which may help to identify facilitators and barriers for parents to take their infants outdoors, and in turn, facilitate future research on interventions that aim to increase outdoor time during infancy. The results can also be of interest for urban planning and the formation of new policies such as paid parental leave.

Chapter 3

Although the benefits of outdoor time for behavioral and physiological regulation are well-known in older children and adults (Larouche et al., 2023; McCormick, 2017; Moll et al., 2022; Taylor et al., 2002; Taylor & Butts-Wilmsmeyer, 2020), there is a lack of studies on the effects of **outdoor time** on infants' behavioral and physiological regulation. Next to time spent outdoors, parental closeness is beneficial for infant regulation, as it facilitates the exchange of regulatory cues (e.g. auditory, visual, thermal, olfactory) (Kiel et al., 2024; Norholt, 2020). The repeated exchange of regulatory cues, in turn, is suggested to help the biological and behavioral processes of caregiver and infant to synchronize, which is suggested to further aid infant regulation (di Lorenzo et al., 2022; Reyna & Pickler, 2009). Increased proximity, and in turn, a better exchange of regulatory cues might be achieved through **infant carrying** using a chest carrier (Hofer, 1987; Hostinar et al., 2014; Kiel et al., 2024). To date, there is a lack of studies assessing the effects of infant carrying on short-term outcomes of infant regulation. The experimental study in **Chapter 3** assessed whether being walked outdoors in a green environment compared to staying indoors, either using an infant carrier or a pram, would facilitate infants' regulation. Effects of outdoor walking and infant carrying on the following outcomes were assessed: infant sleep and cortisol recovery, maternal mood and cortisol, and mother-infant adrenocortical synchrony. The study used a cross-sectional, quasi-randomized experimental design. Mothers and their 0-5-month-old infants ($N = 101$) were invited to the laboratory. First, infants were exposed to a mild stressor (diaper change, mock bath, and weighing). Then, infants and their mothers were randomized to one of the four experimental conditions for the duration of 30 minutes: walking in an outdoor green environment, with the infant in a pram or a chest carrier; or staying indoors with the infant in a pram or a chest carrier. Infant sleep was reported by the mothers in minutes. Mothers reported on their own mood (vigor and affect) through visual analog vigor and affect scales before and after the

conditions. Five saliva samples were collected from infants and mothers to determine cortisol throughout the experiment.

After the stressor, infants who were carried showed a greater cortisol decrease compared to infants in the pram, regardless of being walked outdoors or staying indoors. Infants who were taken for a walk outdoors using a carrier or pram slept longer than infants who stayed indoors in a pram. Mothers who stayed indoors showed greater cortisol decreases compared to mothers walking outdoors. Mothers who used an infant carrier showed greater cortisol decreases compared to mothers having their infant in a pram. Lastly, mothers who stayed indoors showed a decrease in vigor, while mothers who walked outdoors showed no decrease. No difference was found for maternal affect or mother-infant adrenocortical synchrony. This study was the first to assess the combined effects of outdoor time and infant carrying. Altogether, the results show the potential of these two caregiving behaviors for infants' behavioral and physiological regulation. Hereby, this study taps into a novel field of research that might bring forward future studies on interventions for the long-term development of infant regulation. Ultimately, studies such as this are of interest to individuals who create caregiving advice, employees of childcare centers, pediatricians, as well as individuals involved in urban planning or policymaking around the postnatal phase.

Chapter 4

Skin-to-skin contact (SSC) between caregivers and infants in the first postnatal month has been shown to increase infants' sleep duration and reduce cortisol concentrations in both infants and mothers throughout infancy (Cong et al., 2015; Cooijmans et al., 2022; Hardin et al., 2020; Mörelius et al., 2015). Research on preterm infants furthermore indicated that early, repeated SSC in the first postnatal weeks can enhance the alignment of cortisol concentrations between mothers and their infants at age four months, suggesting increased adrenocortical synchrony (Mörelius et al., 2015). However, few studies have assessed the potential of SSC throughout the first postnatal month for the development of regulation in infants born full-term. The study presented in **Chapter 4** assessed the effects of one hour of SSC daily during the first month of life on full-term infants' cortisol and behavioral reactions to a stressor. The study also examined adrenocortical synchrony between mother and infant as well as the quality of the maternal caregiving behavior. The randomized-controlled trial recruited 116 mothers during late pregnancy. After birth, they were randomly assigned to either a SSC group, which was asked to provide one

hour of SSC daily until five weeks postpartum, or a care-as-usual (CAU) group with no specific SSC instructions. At five weeks of age, mothers were asked to bathe their infant during a home visit. Three saliva samples were collected from infants and mothers to determine cortisol concentrations throughout the bathing routine. The routine was videotaped to score infant behavior in terms of responsivity and involvement as well as negative mood. Additionally, the quality of the maternal caregiving behavior was rated in terms of sensitivity, cooperation, and positive as well as negative regard toward the infant.

Results showed no significant effect of SSC on infant cortisol or behavior, nor adrenocortical synchrony or the quality of the maternal caregiving behavior. This was one of the first randomized-controlled trials to assess the effects of repeated SSC in the first postnatal month on outcomes of infant physiological and behavioral regulation. The results suggest that SSC does not have the same effect on infant regulation of infants born full-term as it does in preterm infants. Possibly, preterm infants are affected more by SSC due to their developmental delay. Notably, although mothers in the SSC group of the study presented in **Chapter 4** performed significantly more SSC than mothers in the CAU group, only around one-third of mothers performed the requested SSC daily for five weeks postnatally. Further research should assess whether performing SSC more frequently or for longer durations in the first postnatal month benefits the development of early regulation of infants born full-term.

Chapter 5

Research on preterm infants who received repeated postnatal **SSC** in the first postnatal weeks has demonstrated long-term benefits for behavioral regulation from childhood through young adulthood. These benefits include improved executive functioning, fewer externalizing problems such as hyperactivity and aggressiveness, and better conversational reciprocity (Charpak et al., 2017; Feldman et al., 2014; Ropars et al., 2018). To date, few studies have investigated the long-term benefits of SSC for infants born full-term. In **Chapter 5** of this thesis, we used the randomized-controlled trial described above to investigate whether children who received one hour of daily SSC in their first postnatal month showed fewer behavioral problems and improved executive functioning at age three. Moreover, infants' development of regulation varies based on individual predisposing factors, including the potential impact of prenatal maternal mental health. Elevated **maternal stress and anxiety during pregnancy**, for instance, have been linked to poorer outcomes of behavioral regulation in offspring (Gragnic-Philippe et

al., 2014; van den Bergh et al., 2020). However, prenatal stress and anxiety might also enhance the child's plasticity, making the child more responsive to early postnatal interventions (Beijers et al., 2020; Gaignic-Philippe et al., 2014). Therefore, **Chapter 5** also examined whether infants of mothers who had experienced more prenatal stress and anxiety derived greater benefits for behavioral and cognitive regulation from the SSC intervention. Maternal stress and anxiety during pregnancy were assessed through questionnaires in gestational week 37. When the child was three years old, the mothers ($N = 103$) filled in questionnaires on the children's externalizing and internalizing behavioral problems, as well as on executive functioning.

Mothers of children of the SSC group reported significantly fewer internalizing and externalizing problems compared to the CAU group. No group differences for executive functioning and no moderating effects of maternal prenatal stress and anxiety were found. The current study delivers novel evidence that repeated SSC in the first postnatal month positively influences the development of behavioral regulation in infants born full-term. The findings underline the great potential of a cost-efficient intervention that is accessible to most parents. Current findings are restricted to maternal reports, and further studies incorporating direct behavioral observations are of interest.

Chapter 6

Infant colic is marked by excessive, unsoothable crying, lasting more than three hours per day, for at least three days a week, beginning around two weeks and peaking at about six weeks postpartum (de Weerth et al., 2013; Savino, 2007; Zeevenhooven et al., 2018). Though colic usually resolves by three months of age without intervention, the condition has been linked to altered regulatory functioning later in life (Brett et al., 2024; Canivet et al., 2000; Indrio et al., 2023; Zeevenhooven et al., 2022). Hence, infant colic may be seen as a predisposing factor for regulatory difficulties later in life (Indrio et al., 2023; Zeevenhooven et al., 2022). Results on the relationship between infant colic and sleep development are mixed. Some studies report that colic is associated with increased sleeping problems, reduced sleep duration, and more frequent night waking in children up to 10 years old (Helseth et al., 2022; Savino et al., 2005; Ståhlberg, 1984), while others found no such links (Bell et al., 2018; Canivet et al., 2000; Lehtonen et al., 1994). **Chapter 6** of this thesis assessed the link between colic at six weeks old and sleeping problems from childhood through adolescence. Furthermore, parent-infant **room sharing**, as opposed to solitary sleeping, may help parents regulate infants more

effectively at night, potentially aiding the development of self-regulation (Barry, 2019; Beijers & Cassidy, 2019; Tollenaar et al., 2012). We therefore additionally assessed whether parent-infant room sharing in the first six months can mitigate the possible association between infant colic and sleeping problems. In a longitudinal cohort study, 193 healthy mothers and their infants were followed from pregnancy through adolescence (Beijers et al., 2013). For the outcomes of **Chapter 6**, data from multiple assessment waves were used, covering the period from birth to age 16.5 years. Specifically, from birth until six months postpartum, mothers maintained a daily diary that recorded the infant's sleeping arrangements. When the infants were six weeks old, mothers completed a four-day diary documenting the infant's crying, which was used to screen for infant colic. Children's sleeping problems were assessed through maternal questionnaires at the ages of 2.5, 6, and 10 years, and child questionnaires at the ages of 12.5, 14, and 16.5 years.

Children with a history of colic reported higher total scores for Sleeping Problems between ages 12.5 and 16.5 compared to those without colic. However, no differences were found between ages 2.5 and 10, nor was there evidence that room sharing moderated these relations. As the first study to follow the development of sleeping problems in relation to infant colic beyond the age of 10, current findings should inspire future research on the sleep health of adolescents with a history of colic, as well as studies on possible early interventions.

Conclusions

- Several demographic characteristics, such as infant age, maternal employment status, maternal education, and the number of recreational areas nearby, are associated with outdoor time during infancy.
- Being walked outdoors facilitates infant sleep duration, but is not associated with infant cortisol, or mother-infant adrenocortical synchrony after a naturalistic laboratory stressor.
- Walking outdoors with the infant, as compared to staying indoors, leads to a smaller decrease of maternal cortisol concentrations, but also a smaller decrease of maternal vigor.
- Infant carrying, as compared to using a pram, decreases cortisol concentrations of infants and mothers.

- Daily mother-infant skin-to-skin contact in the first postnatal month is not associated with infants' cortisol or behavioral reactions, nor with mother-infant adrenocortical synchrony or the quality of the maternal caregiving behavior at five weeks postpartum.
- Daily mother-infant skin-to-skin contact in the first postnatal month leads to fewer internalizing and externalizing problems at three years of age but does not affect executive functioning at that age. The association is not moderated by prenatal maternal stress and anxiety.
- Children with a history of infant colic, compared to those without, experience more sleeping problems between the ages of 12.5 and 16.5 years. No differences between children with and without a history of colic emerge between the ages of 2.5 and 10 years, and the association is not moderated by the number of weeks of parent-infant room sharing in the first six months of life.

General discussion

Caregiving behavior that benefits the development of child regulation

This section explores how the findings of this thesis complement theories on the evolutionary background of caregiving behavior that may facilitate the development of child regulation. In order to identify which early caregiving behaviors might benefit child development the most, anthropologists focus on the evolutionary history of humankind and hence the environment that humans are most adapted to (Chaudhary & Swanepoel, 2023; Narvaez et al., 2013). Considering that humans lived in hunter-gatherer societies for more than 95% of their evolutionary history, research on remaining hunter-gatherer societies to date might shed light on species-typical behaviors that may benefit infant development (Chaudhary & Swanepoel, 2023; Hawkes et al., 2018; Narvaez et al., 2013). Infants in hunter-gatherer societies are consistently in physical proximity to a caregiver, being carried, breastfed on demand, and sleeping in contact or near their caregivers at night (Berez et al., 2020; Chaudhary, et al., 2024; Konner, 2017; Narvaez et al., 2013). It is suggested that continuous physical proximity enables prompt detection and reaction to the infant's needs and thereby facilitates infant regulation (Kiel et al., 2024; Norholt, 2020). At the same time, holding the infant close may also be calming for the mother, as the mother can be assured that the infant is kept safe and well-fed.

In line with the above, research by Esposito and colleagues (2015) found that short episodes of carrying decreased heart rate and crying of human infants as well as mice pups, a reaction the researchers called the Transportation Response and proposed would be innate in newborn mammals. Accordingly, the experiment presented in this thesis found that a 30-minute episode of infant carrying, compared to keeping the infant in a pram, facilitated cortisol recovery in one to five-month-old infants (*Chapter 3*). However, this study also showed that infant cortisol concentrations did not correlate with the number of steps the mothers walked. These findings suggest a calming effect of parental proximity that goes beyond the Transportation Response described by Esposito and colleagues (2015). According to Hofer's theory (1995) on hidden regulators in mammals, caregivers regulate their infants through the exchange of sensory and social cues (e.g., touch, odor, visual and auditory cues) in close proximity. This exchange of proximal cues is suggested to induce a number of psychological and physiological processes, including production of the bonding hormone oxytocin in the infant as well as the caregiver, which further facilitates co-regulation between parent and infant (Hofer, 1995; Norholt, 2020). In line with this, SSC is found to enhance the oxytocin production of infants and their parents in preterm as well as full-term infants (Ionio et al., 2021). The results of our experimental study on infant carrying described above hence support both Esposito's theory on the Transportation Response as well as Hofer's theory on hidden regulators (*Chapter 3*). Furthermore, our SSC randomized-controlled trial found fewer behavioral problems in three-year-olds who had received SSC in the first postnatal month compared to CAU (*Chapter 5*). Possibly, the repeated SSC during early infancy facilitated the exchange of regulatory cues between parent and infant, and in turn, promoted the infants' development of behavioral regulation. Notably, research in the same cohort also found decreased crying and increased sleep during infancy in the SSC group compared to the CAU group (Cooijmans et al., 2022). In addition, the experiment on infant carrying showed that carrying also decreased cortisol of the mothers (*Chapter 3*). This may reflect the mother being calmer when the infant is in proximity. This calming response of the mother may, in turn, further facilitate external regulation of the infant.

The aim of taking an evolutionary perspective is to identify species-typical caregiving behaviors that may benefit infant development around the globe (Narvaez et al., 2013; Scheidecker et al., 2022). In Western societies, infants are more often placed in playpens, highchairs, prams, or cribs than infants of hunter-gatherer societies, and therefore physical contact between infant

and caregiver has diminished (Lozoff & Brittenham, 1979), possibly resulting in less species-typical caregiving. The findings of the current thesis on the beneficial effects of infant carrying (*Chapter 3*) and skin-to-skin contact (*Chapter 5*) on infant and maternal outcomes may deliver further support for the theory that providing parental proximity is a species-typical behavior that may benefit the development of children.

As mentioned before in this thesis, another change that is taking place in modern societies is a decrease in the time children spend outdoors over the past decades (Louv, 2005; Pergams & Zaradic, 2008). Considering that humans in hunter-gatherer societies would spend most of their daytime outdoors, the sedentary indoor lifestyle of modern societies suggests a mismatch with our evolutionary roots. In accordance, the Stress Recovery Theory (Ulrich et al., 1991) proposes that humans have an innate affinity for outdoor green environments, as these come with fewer manmade stressors, and hence have a stress-decreasing effect on the human system. The findings of the experimental study on infant carrying are in line with this theory, showing that 30 minutes of being walked outdoors by the mother can facilitate infant sleep (*Chapter 3*). The effects of outdoor walking on infant sleep may have been caused by rhythmic movement while walking outdoors. However, the number of steps the mothers walked did not correlate with infants' sleep duration, suggesting that the effects are partially caused by other factors of being outdoors than increased movement. As one of the first studies assessing the direct effects of a single session of being walked outdoors on infants' regulatory outcomes, the findings should inspire future work aimed at replicating the results. In addition, future research may want to focus on the underlying mechanisms of the effect, and on studying the effects of being walked outdoors on a regular basis. Finally, outdoor walking prevented decreases in vigor (tiredness) in mothers. Hypothetically, this maintenance of vigor may benefit the quality of the mother's caregiving and hereby further facilitate the infant's regulation. This potential indirect effect of outdoor exposure on infant regulation through stress reduction of the mother is hence also of interest for future research.

In sum, our knowledge on species-typical caregiving behavior as observed in hunter-gatherer societies, the empirical and theoretical contributions of Esposito and Hofer, and the results of this thesis point in the same direction. They support the idea that it may be advisable to make parents more aware of the advantages of offering proximity in the way of carrying and skin-to-skin

contact to their newborn infants, and potentially also of spending time in the outdoors to facilitate their own vigor and their infant's sleep.

Interventions in the light of predisposing factors for regulatory difficulties

The World Health Organization (WHO) reports alarming trends towards increased mental health issues among young adults, with one in seven adolescents suffering from a mental health disorder (World Health Organization, 2021). One risk factor for later mental health issues is having regulatory difficulties early in life (Adam et al., 2017; Berardelli et al., 2020; O'Connor et al., 2020; Zajkowska et al., 2022). Interventions for regulatory difficulties in early life may help to prevent the development of later mental health issues. Results of a longitudinal study presented in this thesis showed an association of infant colic with increased sleeping problems during adolescence (*Chapter 6*). Notably, we did not find differences during early childhood. Possibly, the sleeping problems of infants with colic lie dormant throughout early childhood, until resurfacing during adolescence. Adolescence may be a challenging period, due to a re-organization of sleep physiology as well as a shift in the circadian rhythm (Agostini & Centofanti, 2021; Feinberg & Campbell, 2010; Tarokh et al., 2016). The current study did not assess sleeping problems during infancy. Future research may be of interest to determine whether the sleeping behavior of infants after the colic has resolved might help to predict which children develop increased sleeping problems during adolescence. This might lay the foundation for early interventions for infants with colic to prevent sleeping problems later in life.

As one possible caregiving behavior that may help prevent later sleeping problems in infants with colic, the current thesis assessed parent-infant room sharing (*Chapter 6*). In the same cohort, room sharing with the parents in the first six months of life had already been associated with improved cortisol regulation throughout infancy (Beijers et al., 2013; Tollenaar et al., 2012). However, this thesis could not support the hypothesis that room sharing buffers the development of later sleeping problems in infants with colic (*Chapter 6*). Nevertheless, more weeks of room sharing were associated with fewer sleeping problems at age 2.5 across the whole group. It is possible that the absence of a buffering effect of room sharing for infants with colic was due to a lack of power, since a large proportion of the infants participating in this study were sleeping solitarily throughout most of their first six months of life. Besides, the study was observational and did not correct for possible

moderators, such as parental sensitivity. Infants' regulation is suggested to highly depend on parental sensitivity, which determines how promptly and accurately a parent reacts to the needs of the infant (Albers et al., 2008; Bell & Ainsworth, 1972). Hence, room sharing with more sensitive parents might be more effective than room sharing with less sensitive parents. Accordingly, one study in the same cohort of this thesis (*Chapter 6*) found that the association of more weeks of room sharing during the first six months of life with improved cortisol regulation at age 12 months is moderated by maternal sensitivity (Beijers et al., 2013). Notably, Beijers and colleagues (2013) assessed maternal sensitivity during a bathing stressor at age five weeks, suggesting that especially sensitivity during stressful situations may moderate the association of room sharing and positive outcomes of child regulation. Future work should assess whether parental sensitivity assessed during the night may be a potential moderator of the effectiveness of room sharing on infant regulation.

Next to infant colic as a predisposing factor for regulatory difficulties, the randomized-controlled trial presented in this thesis also assessed whether SSC is especially beneficial for infants of mothers who experienced more prenatal stress and anxiety (*Chapter 4*). We did not find this moderation, suggesting that SSC was equally beneficial regardless of prenatal maternal mental health. Notably, however, we did not assess prenatal stress and anxiety in a clinical sample, as mothers with severe mental health issues were excluded from the study during recruitment. A recent study has shown that interventions for mothers with postpartum depression prevented regulatory problems in the offspring (Amani et al., 2024). Whether SSC can prevent the association of stress and anxiety with increased regulatory difficulties in the offspring of mothers with clinical mental health complaints remains to be assessed in future research.

Lastly, the results of the experimental study of this thesis suggest that infant carrying and walking with the infant outdoors can facilitate cortisol and sleep regulation as well as maintain maternal vigor (*Chapter 3*). Although the study focused on a sample of overall healthy infants and mothers, the results may inspire future work using infant carrying and outdoor walking as an intervention for infants with a predisposition for regulatory difficulties. One prior study in a clinical population found decreased maternal postnatal depression after a 12-week period of pram walking sessions in a group setting (Armstrong & Edwards, 2004). This study did not assess outcomes for the

infants. Since maternal mental health is also linked to outcomes of regulatory difficulties in infants (Maughan et al., 2007), studies employing outdoor walking interventions for infants of mothers with mental health issues might also be beneficial for the infants.

Facilitating the implementation of caregiving advice

Implementing caregiving advice, such as providing constant proximity and outdoor time, may be difficult for parents of newborn infants. In this section, I elaborate on possible underlying difficulties of implementing caregiving advice in light of the findings of this thesis.

One reason for the difficulty of implementing outdoor time and proximity in the daily routine might be a lack of time. Research on older children showed that children of parents who are employed spend less time outdoors (Boxberger & Reimers, 2019; Tandon et al., 2012). Accordingly, in the nationwide survey of the current thesis, almost 50% of the mothers (*Chapter 2*) would have liked to go for outdoor walks more often with their infant. Similar to previous studies in older children, mothers with a paid job reported spending less time on outdoor walking as compared to mothers on maternity leave or unemployed. In addition, employed mothers reported significantly lower daily hours of infant carrying (*Chapter 2*). These findings suggest that maternal employment may result in a lack of time to walk outdoors with the infant and to carry the infant. With a rise in workforce engagement of women, attendance of children at childcare facilities has increased. The current thesis did not document the amount of outdoor time and proximity infants receive in childcare centers. However, a large child-caregiver ratio (3:1 in the Netherlands) suggests that infants may be carried and held less often than at home. Future studies should assess the amount of time infants spend outdoors and in proximity to caregivers in center-based childcare and identify factors that might predict these caregiving behaviors by childcare staff.

Paid parental leave in the first postnatal year might give mothers more time with their infants, facilitating more time spent outdoors and in close proximity, which, in turn, may benefit the infants' development. In many European countries, such as Sweden, Norway, Bulgaria, and Germany, paid parental leave is legally established for mothers throughout the first postnatal year (OECD, 2024). Research has shown that extended parental leave is associated with positive outcomes for children's physical and mental health (Khan, 2020; Ruhm, 2000; Van Niel et al., 2020) and maternal physical and mental health,

including decreased maternal postnatal distress (Aitken et al., 2015; Heshmati et al., 2023; van Niel et al., 2020). However, extended parental leave alone might not be sufficient to increase time spent in close proximity and outdoors. Indeed, as shown in the randomized-controlled trial of this thesis (*Chapters 4 and 5*), which was performed during maternity leave in the first postnatal month, less than 30% of mothers performed the requested amount of 60 minutes of SSC a day during the intervention period. While underlying reasons were not documented systematically in our study, the literature shows that one of the most commonly reported barriers to performing SSC with preterm and full-term infants is a lack of time and a lack of support with SSC or other responsibilities (Chan et al., 2016; Seidman et al., 2015).

Despite increased workforce engagement, mothers still cover two-thirds of the care and household tasks in the home (Bird, 1999; Peristera et al., 2018; Seedat & Rondon, 2021). Considering this twofold responsibility, providing caregiving advice may unintentionally induce a higher burden on mothers in particular. One solution may be to engage fathers (or the other legal guardian) more in the caregiving role. In some countries, fathers can also take up paid parental leave (Heshmati et al., 2023), and this has been associated with improved paternal mental health (Barry et al., 2023; Heshmati et al., 2023). In Germany, it is even possible for both parents to receive parental leave simultaneously (OECD, 2024). Although there is yet a lack of research on the benefits, simultaneous parental leave might allow parents to spend time together as a family, sharing responsibility for household tasks, and in return, having more time to implement positive caregiving behaviors, such as spending more time outdoors as well as in close proximity to their child. Unfortunately, a study in Sweden reported that only a small amount of fathers take up the available paid paternity leave (Haas & Hwang, 2019). Results from quantitative interviews showed that especially the workplace culture, a lack of social support from managers, and gender roles prevent fathers from taking parental leave (Haas & Hwang, 2019). These findings are concerning, considering that many mothers around the globe face the challenge of combining work with household and caregiving responsibilities. This might create an overload of responsibilities, which may result in poorer maternal mental health as well as reduced quality of caregiving. Therefore, it is not surprising that mothers of the recent generation coined the term 'mental load'. Mental load colloquially refers to the often-overlooked effort of mothers to manage household tasks, family schedules, and emotional as well as practical needs of the family (Dean et al., 2021; Robertson et al., 2019). This load is typically not confined

to physical tasks, but also contains the mental anticipation and planning in order to suffice the needs of the family. While it has become a popular topic in modern society, maternal mental load should also receive increased attention in policymaking around parental leave. Furthermore, also researchers may contribute to the alleviation of maternal mental load, for instance by assessing fathers' support in household and family responsibilities and its effects on the development of children. Communicating such findings to policymakers and society at large might help create a shift in modern gender roles, and in turn, improve the caregiving environment of infants.

Another solution to allow for more outdoor time as well as caregiver proximity for infants might be expanding the caregiving network beyond the core family. In hunter-gatherer societies, other adults from the village are highly involved in raising infants – a practice called alloparenting (Chaudhary et al., 2024; Konner, 2017). In modern societies, families often live further away from extended family members (e.g., grandparents, aunts and uncles) and the number of single-parent households has increased over the past decades (OECD, 2024; McLanahan & Percheski, 2008). Therefore, alloparenting may not be feasible in many societies around the globe. However, in several countries alternative projects are arising. These combine center-based childcare with care for the elderly in retirement homes, enabling elderly people to participate in caregiving and to spend time with infants. This may provide infants with extra one-on-one contact, while also giving the elderly tasks that benefit their own mental and physical health (Campbell et al., 2016). These promising initiatives should become subject of scientific research, especially in terms of their benefits as well as their feasibility, and whether they are well-received in the care system.

Another aspect that might make implementing caregiving advice difficult might be safety concerns. While in hunter-gatherer societies, the increased outdoor time might benefit the child's stress regulation, the child is also exposed to increased threats, such as animals or extreme temperatures. Although outdoor environments that modern societies live in may contain fewer natural threats, there might be factors that are less accommodating, such as high levels of pollution, traffic noise and accidents, as well as crime rates (Clements, 2004; Gao et al., 2022; Lambert et al., 2019). Likewise, providing proximity in the form of infant carrying might not be safe for all infants or mothers, for instance, due to recovery from birth or other health issues. Although some studies have assessed the safety of using an infant carrier (Grisham et al., 2023), there

is a lack of studies assessing the safety for infants with special needs (e.g. very low birthweight, very preterm infants, spine issues, hernia). Hence, researchers in the field of pediatric health should aim towards assessing the risks and possibilities of using infant carriers with infants with special needs.

Next to safety concerns, also a lack of access might influence whether parents implement caregiving advice. The nationwide survey of the current thesis found that mothers walked less with their infants outdoors when there were fewer recreational areas within walking distance (*Chapter 2*). Furthermore, mothers were less likely to put their infant outdoors to sleep when they lived in non-detached houses. On the other hand, the study also found that mothers walked more outdoors with their infants when they lived in larger cities, potentially due to the possibility of reaching destinations on foot (e.g. nearby supermarkets or childcare centers). This suggests that living in the city does not necessarily hinder outdoor time for infants, especially if sufficient recreational areas are provided. Furthermore, not all mothers might be equally aware of the benefits of outdoor walking and parental contact for their infants. The survey of this thesis found that lower maternal education predicted less outdoor sleeping and less infant carrying (*Chapter 2*). Also, only 30% of mothers of the longitudinal cohort assessed in this thesis (*Chapter 6*) performed parent-infant room sharing throughout the first six months of life (Beijers et al., 2013). Possibly, there is a lack of science-based communication to the general public about the importance of outdoor time and parental proximity during infancy. Meanwhile, companies with a commercial interest might be more successful in influencing parents' caregiving behavior. For instance, a recent review reported concerns about the milk formula industry causing lower rates of breastfeeding (Rollins et al., 2023). Furthermore, promotion of devices that simulate parental proximity, such as motorized cradles or remote-controlled swings, may result in less real contact between parents and infants. Also, in both adults and children, a negative association has been found between social media use as well as screen time and the time spent physically active (Bozzola et al., 2022; Nakshine et al., 2022; Purba et al., 2023). This might indirectly influence the caregiving of young infants, as parents might also spend less time outdoors with their infants as a consequence of increased screen time. Additionally, one study has shown that parental phone use causes an immediate increase in negative affect in infants (Stockdale et al., 2020), possibly because the parent is emotionally less available while using the phone. Undoubtedly, companies with a commercial interest are equipped with sufficient marketing skills and finances to successfully promote their products. Inspired by commercial

marketing, the public sector employs so-called 'social marketing' strategies, with the aim of changing citizen's behavior for the benefit of their own health (e.g., eating five fruits a day) or for the benefit of their society (e.g., recycling). This further highlights the need for increased emphasis on science communication. Possibly, scientific findings as presented in this thesis may collectively inspire future social marketing campaigns that promote outdoor walking with infants as well as infant carrying and SSC.

Strengths and limitations of the studies presented in this thesis

A strength of this thesis is the diversity of designs employed in the studies presented, which allowed for assessing the role of the early caregiving environment in the development of child regulation from multiple angles. Firstly, the nationwide survey allowed us to assess a large number of mothers throughout the Netherlands, enabling well-powered analyses on the associations of demographic factors with infant outdoor time (*Chapter 2*). Secondly, the experimental design of the cross-sectional study on outdoor walking and infant carrying permitted the study of immediate effects on outcomes of regulation (*Chapter 3*). Next, the randomized-controlled trial on SSC was one of the first fully randomized studies on the effects of SSC on full-term infants' regulation (*Chapter 4*). The follow-up on this cohort at age three further delivered valuable evidence on the longevity of the effects of SSC early in life on regulation in toddlerhood (*Chapter 5*). Lastly, the longitudinal cohort study followed children from pregnancy through adolescence (*Chapter 6*). Through elaborate and prospective documentation of early life factors as well as repeated extensive follow-up rounds throughout childhood, this study was able to deliver novel, longitudinal information on the development of sleeping problems in adolescents with a history of colic.

Nevertheless, the individual studies also had some limitations. Observational studies such as the nationwide survey (*Chapter 2*) and the cohort study (*Chapter 6*) cannot shed light on the directionality of the found associations. Furthermore, during the experimental study on outdoor walking and infant carrying, weather conditions (e.g., precipitation, heat waves) did not allow for full randomization. Further, although the study on SSC was fully randomized, a low protocol adherence within the SSC group might have decreased the strength of the effect, possibly causing the absence of an effect on infant's stress reactions at age five weeks (*Chapter 4*). Lastly, mothers of all studies were mostly highly educated with an HBO diploma (higher professional education, equal to a college degree) or higher. This restricts

the generalizability of our findings. Although we made considerable efforts to increase participation of lower educated mothers in the studies of *Chapters 2 and 3*, such as by means of social media advertisement and printed flyers in the community (e.g, supermarkets and childcare centers), highly educated mothers still made up approximately 70% of the sample, which is still not entirely representative of the Dutch population of women between the age of 25 and 34 (60%, Centraal Bureau voor de Statistiek, 2023).

Conclusion

This thesis emphasizes the role of the early caregiving environment for the development of child regulation. The results of the empirical chapters suggest that being walked outdoors and receiving increased proximity in the form of infant carrying and SSC may benefit the development of child regulation. The thesis also shows links of early predisposing factors with later regulatory difficulties, such as the association of infant colic with sleeping problems in adolescence, and hereby generates important insights for pediatric care. Furthermore, topics of interest for future research on possible early interventions can be derived, such as increased attention towards the feasibility of implementing caregiving advice in daily life. Lastly, the chapters presented in this thesis are of interest for urban planning as well as policymaking around parental leave. Altogether, future research might utilize the knowledge generated by this thesis in order to improve the early caregiving environment and, in turn, benefit the development of regulation in children.

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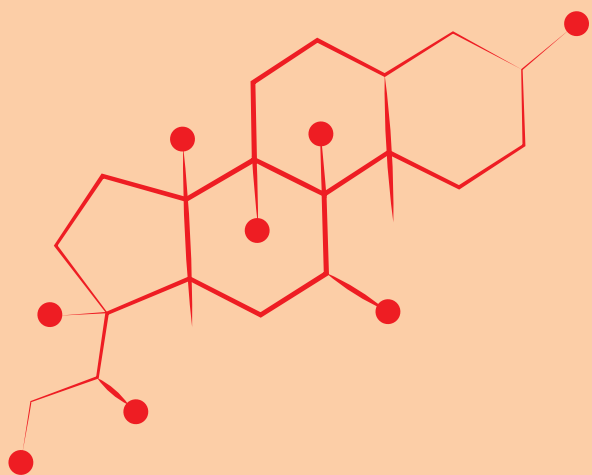
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Appendix

**Dutch summary
(Nederlandse samenvatting)
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Acknowledgements
Curriculum Vitae
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Dutch summary (Nederlandse samenvatting)

Zelfregulatie verwijst naar het vermogen om fysiologische en gedragstoestanden aan te passen om te reageren op eisen en stressoren in het lichaam of in de omgeving (Beeghly et al., 2016; Nigg, 2017). De term omvat zowel fysiologische aspecten, zoals neurobiologische en circadiaanse functies, als gedrags- en cognitieve aspecten, zoals het omgaan met woede en het focussen op taken (Beeghly et al., 2016; Nigg, 2017). Baby's zijn nog niet in staat om zich zelfstandig te reguleren en zijn daarom grotendeels afhankelijk van externe regulatie, meestal geboden door hun verzorgers (Feldman, 2007; Norholt, 2020; Rattaz et al., 2022). Door herhaalde, succesvolle externe regulatie ontwikkelen baby's het vermogen tot zelfregulatie (Beeghly et al., 2016; Kiel et al., 2024). De vroege zorgomgeving beïnvloedt deze ontwikkeling, waarbij minder optimale zorg in verband wordt gebracht met slechtere uitkomsten voor de regulatie (Gruhn & Compas, 2020; Gunnar & Quevedo, 2007; Loman & Gunnar, 2010). Mishandeling in de vroege kindertijd wordt bijvoorbeeld geassocieerd met een slechtere emotieregulatie, zoals een verhoogde expressie van negatieve emoties tijdens stressvolle situaties tussen de leeftijd van vijf en 18 jaar (zie review door Gruhn & Compas, 2020). Positieve factoren in de vroege zorgomgeving, zoals hoge maternale sensitiviteit, kunnen de ontwikkeling van het regulatievermogen van het kind juist bevorderen (Gunnar & Quevedo, 2007; Loman & Gunnar, 2010). Maternale sensitiviteit wordt gedefinieerd als het vermogen van de moeder om snel en accuraat te reageren op de behoeften van de baby (Bell & Ainsworth, 1972; Mesman & Emmen, 2013). In de literatuur wordt algemeen erkend dat een hogere maternale sensitiviteit tijdens de babytijd geassocieerd is met een betere regulatie van de fysieke en gedragsmatige reacties op stressvolle situaties later in de kindertijd (Albers et al., 2008; Berry et al., 2017; Borelli et al., 2021; Bosquet Enlow et al., 2014; Tsotsi et al., 2020). Het identificeren van factoren die de ontwikkeling van regulatie faciliteren is cruciaal voor zorgadvies, beleidsvorming en het ontwikkelen van interventies voor baby's met predisponerende factoren voor regulatieproblemen. Deze dissertatie onderzocht de rol van de vroege zorgomgeving in de ontwikkeling van zelfregulatie vanaf de babytijd tot aan de adolescentie. De onderwerpen met betrekking tot zelfregulatie die in dit proefschrift werden onderzocht waren de hypothalamus-hypofyse-bijnier-as (HPA-as), slaap en gedrag.

Wanneer een individu wordt blootgesteld aan een stressvolle situatie, reageert de HPA-as met een verhoogde productie van het hormoon cortisol.

Dit kan worden gemeten in het speeksel (Jansen et al., 2010; Leistner & Menke, 2020; Spiga et al., 2014). Chronische stress of ongunstige ervaringen in het vroege leven, zoals mishandeling in de kindertijd, worden geassocieerd met een ontregeling van de HPA-as (Fogelman & Canli, 2018; Isenhour et al., 2021; Marques-Feixa et al., 2023; Murphy et al., 2022; Radley et al., 2015; Tarullo & Gunnar, 2006). Deze ontregeling is wederom gekoppeld aan een slechtere fysieke en mentale gezondheid op latere leeftijd, wat het belang van de vroege zorgomgeving voor de ontwikkeling van een goed functionerende HPA-as benadrukt (Adam et al., 2017; Murphy et al., 2022; Zajkowska et al., 2022). Verder speelt het vroege leven een cruciale rol in de ontwikkeling van een gezond slaapritme (April-Sanders et al., 2021; Bathory & Tomopoulos, 2017; Schlieber & Han, 2021). Gedurende de eerste levensjaren maken kinderen de overgang van een bifasisch slaappatroon, met meerdere slaaperioden per dag, naar een monofasisch patroon, met de meeste slaap 's nachts (Bathory & Tomopoulos, 2017; Iglowstein et al., 2003). Jonge baby's zijn grotendeels afhankelijk van hun verzorgers om hun slaap-waakcyclus te reguleren en een gezond slaappatroon te ontwikkelen (Barry, 2021; Bathory & Tomopoulos, 2017). Een gezond slaappatroon in de vroege kindertijd is belangrijk, aangezien slaap betrokken is bij de mentale en fysieke ontwikkeling, waaronder geheugen en leren, hersenontwikkeling, het immuunsysteem, fysieke groei en de productie van hormonen (Beebe, 2011; Irwin & Opp, 2017; Poluektov, 2021; Vriend et al., 2015). Baby's zijn daarnaast ook in hoge mate afhankelijk van hun verzorgers om hun gedrag te reguleren, inclusief emotionele toestanden, zoals huilen als reactie op dagelijkse stressoren (Hofer, 1987; Norholt, 2020). Ouders spelen hierbij een cruciale rol in de ontwikkeling van de zelfregulatie van het gedrag (Feldman, 2007; Gruhn & Compas, 2020; Loman & Gunnar, 2010; Maughan et al., 2007; Norholt, 2020). Vooral de peutersjaren wordt gekenmerkt door de opkomst van externaliserend (bijv. woede, impulsiviteit) en internaliserend (bijv. angst, terugtrekking) gedrag, evenals problemen met executief functioneren (bijv. aandacht, inhibitie). Effectieve gedragsregulatie is essentieel voor sociaal-emotionele interacties, een succesvolle studieloopbaan en algehele mentale gezondheid (Best & Miller, 2010; Hasty et al., 2023; Nigg, 2017). Dit proefschrift onderzocht de associaties tussen de beschreven maten van regulatie en verschillende factoren van vroege zorgverlening. In de volgende paragrafen worden de bevindingen van deze thesis per hoofdstuk samengevat.

Hoofdstuk 2

Blootstelling aan groene buitenomgevingen is in verband gebracht met lagere gerapporteerde stressniveaus, evenals verbeterde resultaten voor stemming, gedrags- en sociaal-emotionele regulatie, en mentale gezondheid bij oudere kinderen (McCormick, 2017; Moll et al., 2022; Scott et al., 2018; Taylor & Butts-Wilmsmeyer, 2020; Taylor et al., 2002). Tegelijkertijd worden de afgelopen decennia gekenmerkt door een dalende trend van buitentijd bij kinderen (Dinkel et al., 2019; Gray et al., 2015; Gubbels et al., 2011). Weinig onderzoek heeft zich gericht op buitentijd bij baby's. Het is daarom onbekend of tijd buiten doorbrengen gunstige effecten heeft op de fysiologische en gedragsregulatie van baby's. We weten daarnaast heel weinig over de hoeveelheid tijd die baby's buiten doorbrengen en welke demografische kenmerken dit zouden kunnen vergemakkelijken of belemmeren. Het onderzoek van **Hoofdstuk 2** onderzocht de frequenties en duur van buiten wandelen van moeders met hun baby's, het dragen van baby's, evenals het buitenslapen van baby's in een stilstaande wieg of kinderwagen. Daarnaast identificeerde het onderzoek verbanden tussen deze activiteiten en kenmerken van de baby, de moeder en de omgeving. Er werd gebruikgemaakt van een landelijke online enquête voor moeders van baby's van 0 tot 12 maanden oud ($N = 1275$). In de enquête werd gevraagd naar de totale wekelijkse duur van wandelen buitenshuis van moeder en kind in minuten, de frequentie van wandelen op weekdays en in het weekend, en de frequentie van het gebruik van een draagzak tijdens wandelingen. Het buitenslapen werd onderzocht aan de hand van de vraag of de baby überhaupt buiten werd gelegd om te slapen (ja/nee), de totale wekelijkse duur en de wekelijkse frequentie van buitenslapen. Associaties tussen alle uitkomstvariabelen en een aantal kenmerken van de baby (bijv. leeftijd, geslacht, gezondheid), moeder (bijv. werkstatus, leeftijd, gezondheid) en omgeving (bijv. woningtype, recreatiegebieden op loopafstand, stadsgrootte) werden onderzocht.

De resultaten toonden aan dat moeders wekelijks ongeveer 201 minuten buiten wandelden met hun baby. Ze gingen ongeveer één tot drie keer met hun baby wandelen op weekdays (maandag tot vrijdag) en één tot drie keer in het weekend (zaterdag en zondag). Ongeveer 22% van de moeders gebruikte minstens de helft van de tijd een draagzak om buiten te wandelen. Onder andere het plezier dat moeders beleven aan buiten wandelen, het feit dat ze met zwangerschapsverlof of werkloos waren, en het feit dat er meer recreatiegebieden op loopafstand waren, hielden positief verband met de hoeveelheid buiten wandelen met de baby. De draagzak werd vaker gebruikt

tijdens wandelingen als de baby jonger was en als er meer dan één kind in het huishouden woonde. Ongeveer een derde van de baby's sliep regelmatig buiten (29%), voor een wekelijkse duur van vier uur en een wekelijkse frequentie van ongeveer één tot twee keer. Buitenslapen werd in verband gebracht met een jongere leeftijd van de baby, een hogere opleiding van de moeder en het wonen in vrijstaande huizen. Kortom, deze studie identificeerde belangrijke associaties tussen demografische kenmerken en de hoeveelheid tijd die baby's buiten doorbrengen, wat kan helpen bij het identificeren van bevorderende en belemmerende factoren voor ouders om hun baby's mee naar buiten te nemen. Dit kan vervolgens inspiratie geven voor toekomstig onderzoek naar interventies die gericht zijn op de buitentijd van baby's. De resultaten kunnen ook van belang zijn voor stedelijke ontwikkeling en het maken van nieuw beleid rondom bijvoorbeeld betaald ouderschapsverlof.

Hoofdstuk 3

Hoewel de voordelen van tijd buitenshuis voor gedrags- en fysiologische regulatie bekend zijn voor oudere kinderen en volwassenen (Larouche et al., 2023; McCormick, 2017; Moll et al., 2022; Taylor & Butts-Wilmsmeyer, 2020; Taylor et al., 2002), is er een gebrek aan studies naar de effecten van tijd buitenshuis op de gedrags- en fysiologische regulatie van baby's. Daarnaast is de nabijheid van de ouders gunstig voor de regulatie van baby's, omdat het de uitwisseling van regulerende signalen (bijv. auditief, visueel, thermisch, olfactorisch) vergemakkelijkt (Kiel et al., 2024; Norholt, 2020). De herhaalde uitwisseling van regulerende signalen zou op zijn beurt de biologische en gedragsprocessen van verzorger en kind kunnen synchroniseren, wat de regulatie van het kind verder zou bevorderen (di Lorenzo et al., 2022; Reyna & Pickler, 2009). Meer nabijheid, en de hieruit resulterende uitwisseling van regulerende signalen, kan worden bereikt door het dragen van baby's met behulp van een draagzak (Hofer, 1987; Hostinar et al., 2014; Kiel et al., 2024a). Tot op heden is er een gebrek aan studies naar de directe effecten van het dragen van baby's op hun regulatie. De experimentele studie in **Hoofdstuk 3** onderzocht of buiten wandelen in een groene omgeving in vergelijking met binnen blijven, met behulp van een draagzak of een kinderwagen, de regulatie van baby's zou bevorderen. De effecten van buiten wandelen en het dragen van de baby op de volgende uitkomsten werden onderzocht: slaap en cortisolherstel van de baby, stemming en cortisol van de moeder, en de HPA-as-synchronisatie tussen moeder en kind. Het onderzoek maakte gebruik van een cross-sectioneel, quasi-gerandomiseerd experimenteel design. Moeders en hun baby's van 0-5 maanden ($N = 101$) werden uitgenodigd voor

een bezoek in het lab. Eerst werden de baby's blootgesteld aan een milde stressor (luierverschoning, nep-badje en wegen). Daarna werden de baby's en hun moeders gerandomiseerd naar een van de vier experimentele condities voor de duur van 30 minuten: wandelen in een groene buitenomgeving, met de baby in een kinderwagen of een draagzak; of binnenblijven met de baby in een kinderwagen of een draagzak. De moeders rapporteerden de slaap van de baby in minuten. Moeders rapporteerden ook hun eigen stemming (alertheid en affect) met behulp van visuele analoge alertheid- en affectschalen voor en na de condities. Vijf speekselmonsters werden verzameld van baby's en moeders om cortisol te bepalen gedurende het experiment.

Na de stressor vertoonden baby's die gedragen werden een grotere cortisoldaling in vergelijking met baby's in de kinderwagen, ongeacht of ze buiten of binnen waren. Baby's die werden meegenomen op een buitenwandeling met de draagzak of de kinderwagen sliepen langer dan baby's die binnen in de kinderwagen bleven. Moeders die binnen bleven vertoonden grotere cortisoldalingen in vergelijking met moeders die buiten gingen wandelen. Bij moeders die een draagzak gebruikten daalde cortisol sterker dan bij moeders die hun baby in een kinderwagen lieten. Tot slot vertoonden moeders die binnen bleven een afname in alertheid, terwijl moeders die buiten liepen geen afname vertoonden. Er werd geen verschil gevonden voor de gemoedstoestand van moeders of moeder-kind HPA-as-synchronisatie. Deze studie was de eerste die de gecombineerde effecten van buiten wandelen en het dragen van baby's onderzocht. De resultaten tonen het potentieel aan van deze twee vormen van zorg voor de gedrags- en fysiologische regulatie van baby's. Hiermee boort deze studie een nieuw onderzoeksgebied aan dat toekomstige studies naar interventies voor de lange termijn ontwikkeling van de regulatie van baby's kan opleveren. Uiteindelijk zijn studies zoals deze interessant voor personen die zorgadvies geven, medewerkers van kinderdagverblijven, kinderartsen en personen die betrokken zijn bij stedelijke planning of beleidsvorming rond de postnatale fase.

Hoofdstuk 4

Huid-op-huidcontact (HHC) tussen moeders en baby's in de eerste postnatale maand blijkt de slaapduur van baby's te verhogen en cortisolconcentraties te verlagen bij zowel baby's als moeders gedurende het eerste postnatale jaar (Cong et al., 2015; Cooijmans et al., 2022; Hardin et al., 2020; Mörelius et al., 2015). Onderzoek bij premature baby's heeft bovendien aangetoond dat vroege, herhaalde HHC in de eerste postnatale weken de afstemming van

cortisolconcentraties tussen moeders en hun baby's op de leeftijd van vier maanden kan verbeteren, wat duidt op een verhoogde HPA-as-synchronisatie (Mörelus et al., 2015). Er zijn echter maar weinig studies die het potentieel van HHC gedurende de eerste postnatale maand voor de ontwikkeling van de regulatie bij voldragen baby's hebben onderzocht. De studie in **Hoofdstuk 4** beoordeelde de effecten van één uur HHC per dag gedurende de eerste postnatale maand op cortisol en gedragsreacties van voldragen baby's tijdens een stressor. De studie onderzocht ook de HPA-as-synchronisatie tussen moeder en baby en de kwaliteit van het zorggedrag van de moeder. De gerandomiseerde gecontroleerde studie wierf 116 moeders tijdens de late zwangerschap. Na de geboorte werden ze willekeurig toegewezen aan ofwel een HHC-groep, die gevraagd werd om dagelijks een uur HHC te geven tot vijf weken na de geboorte, of een 'care-as-usual' (CAU) groep zonder specifieke HHC-instructies. Op de leeftijd van vijf weken werden moeders gevraagd om hun baby in bad te doen tijdens een huisbezoek. Er werden drie speekselmonsters verzameld van baby's en moeders om de cortisolconcentraties tijdens het in bad doen te meten. Het in bad doen werd op video opgenomen om het gedrag van de baby te scoren wat betreft responsiviteit en betrokkenheid, evenals negatieve stemming. Daarnaast werd de kwaliteit van het zorggedrag van de moeder beoordeeld wat betreft gevoeligheid, samenwerking en zowel positieve als negatieve houding ten opzichte van het kind.

De resultaten toonden geen significant effect van HHC op cortisol of gedrag van de baby, noch op HPA-as-synchronisatie of de kwaliteit van het zorggedrag van de moeder. Dit was een van de eerste gerandomiseerde gecontroleerde onderzoeken naar de effecten van herhaalde HHC in de eerste postnatale maand op de fysiologische en gedragsregulatie van baby's. De resultaten suggereren dat HHC niet hetzelfde effect heeft op de regulatie van voldragen baby's als bij premature baby's. Mogelijk worden premature baby's meer beïnvloed door HHC vanwege hun ontwikkelingsachterstand. Hoewel moeders in de HHC-groep van het onderzoek in **Hoofdstuk 4** significant meer HHC gaven dan moeders in de CAU-groep, gaf slechts ongeveer een derde van de moeders de gevraagde HHC dagelijks gedurende de eerste postnatale maand. Verder onderzoek moet uitwijzen of het vaker of langer geven van HHC in de eerste postnatale maand de ontwikkeling van de vroege regulatie van voldragen baby's ten goede komt.

Hoofdstuk 5

Onderzoek bij premature kinderen die herhaaldelijk postnatale HHC ontvingen in de eerste postnatale weken heeft voordelen op de lange termijn aangetoond voor gedragsregulatie tot jonge volwassenheid. Deze voordelen omvatten verbeterd executief functioneren, minder externaliserende problemen zoals hyperactiviteit en agressiviteit, en beter communicatievermogen (Charpak et al., 2017; Feldman et al., 2014; Ropars et al., 2018). Tot op heden hebben weinig studies de lange termijn voordelen van HHC voor voldragen baby's onderzocht. In **Hoofdstuk 5** van dit proefschrift gebruikten we de hierboven beschreven gerandomiseerde gecontroleerde studie om te onderzoeken of kinderen die dagelijks een uur HHC ontvingen in hun eerste postnatale maand minder gedragsproblemen en beter executief functioneren vertoonden op driejarige leeftijd. Bovendien varieert de ontwikkeling van regulatie bij zuigelingen op basis van individuele predisponerende factoren, waaronder de mogelijke invloed van prenatale mentale gezondheid van de moeder. Zo zijn verhoogde stress en angst bij de moeder tijdens de zwangerschap in verband gebracht met slechtere uitkomsten voor de gedragsregulatie van de nakomelingen (Gaignic-Philippe et al., 2014; van den Bergh et al., 2020). Prenatale stress en angst zouden echter ook de plasticiteit van het kind kunnen versterken, waardoor het kind beter reageert op vroege postnatale interventies (Beijers et al., 2020; Gaignic-Philippe et al., 2014). Daarom werd in **Hoofdstuk 5** ook onderzocht of kinderen van moeders die meer stress en angst tijdens de zwangerschap hadden ervaren, meer baat hadden bij de HHC-interventie op het gebied van gedrags- en cognitieve regulatie. Maternale stress en angst tijdens de zwangerschap werden gemeten aan de hand van vragenlijsten in zwangerschapsweek 37. Toen het kind drie jaar oud was, vulden de moeders ($N = 103$) vragenlijsten in over de externaliserende en internaliserende gedragsproblemen van de kinderen en over executief functioneren.

Moeders van kinderen uit de HHC-groep rapporteerden significant minder externaliserende en internaliserende problemen vergeleken met de CAU-groep. Er werden geen groepsverschillen voor executief functioneren en geen moderatie door maternale stress en angst tijdens de zwangerschap gevonden. De huidige studie levert nieuw bewijs dat herhaalde HHC in de eerste postnatale maand een positieve invloed heeft op de ontwikkeling van gedragsregulatie bij voldragen kinderen. De bevindingen ondersteunen het grote potentieel van een kostenefficiënte interventie die voor de meeste ouders toegankelijk is. De huidige bevindingen zijn beperkt tot rapporten

van de moeder. Toekomstige studies met directe gedragsobservaties kunnen veelbelovende inzichten opleveren.

Hoofdstuk 6

Koliek bij baby's wordt gekenmerkt door overmatig, ontroostbaar huilen, dat meer dan drie uur per dag duurt, gedurende ten minste drie dagen per week. Koliek begint meestal rond twee weken en piekt rond zes weken na de geboorte (de Weerth et al., 2013; Savino, 2007; Zeevenhooven et al., 2018). Hoewel koliek meestal zonder interventie na drie maanden verdwijnt, zijn er studies die een verband vinden tussen het overmatige huilen en slechtere zelfregulatie later in de kindertijd (Brett et al., 2024; Canivet et al., 2000; Galling et al., 2023; Indrio et al., 2023; Zeevenhooven et al., 2022). Daarom kan koliek bij kinderen gezien worden als een predisponerende factor voor regulatieproblemen op latere leeftijd (Indrio et al., 2023; Zeevenhooven et al., 2022). De bevindingen over het verband tussen koliek bij baby's en slaapontwikkeling zijn gemengd. Sommige studies rapporteren verbanden tussen koliek en meer slaapproblemen, een kortere slaapduur en vaker wakker worden 's nachts bij kinderen tot 10 jaar (Helseth et al., 2022; Savino et al., 2005; Ståhlberg, 1984), terwijl andere studies dergelijke associaties niet vonden (Bell et al., 2018; Canivet et al., 2000; Lehtonen et al., 1994). **Hoofdstuk 6** van dit proefschrift bestudeerde het verband tussen koliek op zes weken oud en slaapproblemen van de kindertijd tot en met de adolescentie. Bovendien kan het slapen van de baby op de kamer van de ouders, in tegenstelling tot afgezonderd slapen, ouders helpen om hun baby 's nachts beter te reguleren, wat mogelijk de ontwikkeling van zelfregulatie bevordert (Barry, 2019; Beijers & Cassidy, 2019; Tollenaar et al., 2012). Daarom hebben we aanvullend onderzocht of het slapen op de kamer van de ouders in de eerste zes maanden de mogelijke associatie tussen koliek en slaapproblemen kan verminderen. In een longitudinale cohortstudie werden 193 gezonde moeders en hun baby's gevolgd vanaf de zwangerschap tot aan de adolescentie (Beijers et al., 2013). Voor de uitkomsten van **Hoofdstuk 6** werden gegevens uit meerdere meetrondes gebruikt, die de periode vanaf de geboorte tot de leeftijd van 16.5 jaar bestreken. Vanaf de geboorte tot zes maanden na de bevalling hielden moeders dagelijks een dagboek bij waarin de slaapplek van de baby werd bijgehouden. Toen de baby's zes weken oud waren, vulden de moeders een vierdaags dagboek in waarin ze het huilen van de baby noteerden. De slaapproblemen van de kinderen werden onderzocht met vragenlijsten voor de moeder op de leeftijd van 2.5, 6 en 10 jaar, en vragenlijsten voor het kind op de leeftijd van 12.5, 14 en 16.5 jaar.

Kinderen met een voorgeschiedenis van koliek rapporteerden hogere totaalscores voor slaapproblemen tussen de 12.5 en 16.5 jaar in vergelijking met kinderen zonder koliek. Er werden echter geen verschillen gevonden tussen de leeftijden 2.5 en 10 jaar, noch was er bewijs dat het slapen op de kamer van de ouders deze relaties modereerde. Dit is het eerste onderzoek dat de ontwikkeling van slaapproblemen volgt in relatie tot een voorgeschiedenis van koliek bij kinderen ouder dan 10 jaar. De huidige bevindingen zouden een inspiratiebron kunnen zijn voor toekomstig onderzoek naar de slaapgezondheid van adolescenten met een voorgeschiedenis van koliek, evenals voor onderzoek naar mogelijke vroegtijdige interventies.

Conclusies

- Verschillende demografische kenmerken, zoals de leeftijd van de baby, de werksituatie van de moeder, de opleiding van de moeder en het aantal recreatiegebieden op loopafstand, zijn geassocieerd met de tijd die baby's buiten besteden.
- Buiten wandelen met de baby, in vergelijking met binnen blijven, bevordert de slaapduur van de baby, maar is niet geassocieerd met de cortisol van de baby of de HPA-as-synchronisatie tussen moeder en baby na een stressor.
- Buiten wandelen met de baby, in vergelijking met binnen blijven, leidt tot een kleinere daling van cortisol van de moeder, maar ook tot een kleinere daling van de alertheid van de moeder.
- Het dragen van de baby, in vergelijking met het gebruik van een kinderwagen, vermindert cortisol van zowel baby's als moeders.
- Dagelijks huid-op-huidcontact tussen moeder en baby in de eerste postnatale maand is niet geassocieerd met de cortisol- of gedragsreacties van baby's, noch met de HPA-as-synchronisatie tussen moeder en kind of de kwaliteit van het zorggedrag van de moeder tijdens een stressor op vijf weken postpartum.
- Dagelijks huid-op-huidcontact tussen moeder en baby in de eerste postnatale maand leidt tot minder externaliserende en internaliserende problemen op driejarige leeftijd, maar heeft geen invloed op de executieve functies op die leeftijd. De associatie wordt niet gemodereerd door maternale stress en angst tijdens de zwangerschap.
- Kinderen met een voorgeschiedenis van koliek, vergeleken met degenen zonder, ervaren meer slaapproblemen tussen de leeftijden van 12.5 en 16.5 jaar. Er komen geen verschillen naar voren tussen kinderen met en zonder een geschiedenis van koliek tussen de leeftijden van 2.5 en 10 jaar, en de associatie wordt niet gemodereerd door het aantal weken dat baby's op de kamer van hun ouders slapen in de eerste zes maanden postpartum.

Research data management statement

Ethics and privacy

The BIBO, Skippy, and GO Baby study as well as the Online Survey were conducted in accordance with the 1964 Declaration of Helsinki and its amendments, and with relevant national legislation and regulations, guidelines, and codes of conduct.

The ethics committee of the Social Science faculty of the Radboud University, Nijmegen, the Netherlands, had no formal objections against the study protocols of the BIBO study (ECG300107/SW2017-1303-497/SW 121 2017-1303-498/ECSW-2023-046), the Skippy study (ECSW2015-2311-358/SW2017-1303-497) and the Online Survey (ECSW-2022-031R1), and issued a statement that the studies were not subject to the Dutch Medical Research Involving Human Subjects Act (WMO). The recognized Medical Ethics Review Committee 'METC Oost-Nederland' had no formal objections against the study protocol of the GO Baby study (2022-13765) and issued a statement that the study was not subject to the Dutch Medical Research Involving Human Subjects Act (WMO).

A written informed consent was obtained from all participants regarding their data usage and storage. Participants of the GO Baby study gave consent for the sharing and reuse of their data.

Data collection and storage

Online questionnaire data were collected through the secure platform Castor EDC for the BIBO study, the GO Baby study, and the Online survey, and through the secure LimeSurvey platform for the SKIPPY study. For the GO Baby and the Skippy study, tasks performed by the participants were videotaped. The privacy of the participants in all studies was warranted by the use of pseudonymization. The pseudonymized research data and the videotaped data from the BIBO study, the Skippy study as well as the Online survey, including raw, cleaned, and analyzed data, are stored in a secure network drive of the DI. Additionally, for the BIBO and the Skippy study, paper logbooks were collected, which were physically stored in a locked archive at the DI. The key file for pseudonymization is stored by the lab manager of the Developmental Psychobiology lab on the secure network drive separate of the research data of the DI and can be accessed by the lab manager.

Data sharing

The research data and documentation of the BIBO (<https://doi.org/10.34973/jary-3m91>) and Skippy (<https://doi.org/10.34973/ybcs-z395>) study as well as the Online Survey (<https://doi.org/10.34973/50mp-vk39>) are only accessible to researchers involved in these studies, and to the lab manager of the Developmental Psychobiology lab. The data are not made accessible freely, since participants were not asked for permission to share their data in a public repository. The data are archived using closed access on the Radboud Data Repository, and only the metadata is publicly visible. The pseudonymized research data of the GO Baby study can be accessed and reused through the Radboud Data Repository (<https://doi.org/10.34973/xxqp-0t66>).

In accordance with the informed consent form, all study data will be stored for a minimum of 15 years from the moment of being collected.

Acknowledgements

Embarking on this academic journey has been both great and challenging, and it would not have been possible without the support of so many incredible people. While this section cannot capture all the people who have positively contributed to my development, I would like to express my deep gratitude to everyone who has guided, supported and accompanied me throughout the last years.

Carolina, your dedication to research and to your team is absolutely inspiring. I was always impressed by how you make time and are fully invested in so many amazing projects at once! Not only did you give me a great number of opportunities during my PhD, you also guided me through all of them and taught me so much in the process. Among many other things, I greatly thank you for teaching me all about doing research, working in a team, managing time, keeping calm and overcoming hurdles. Who knows, maybe, if I had stayed for a few more years, I might have even gotten the hang of Chanco! I would also like to thank my first co-promotor. **Roseriet**, your patience and kindness helped me tremendously throughout the first years of my PhD. I was always amazed by how passionate you are about all the simultaneous projects and by your ability to remember them in detail over the course of many years. I am especially thankful that you taught me about sensitivity, not only in scoring mother-child interactions, but also in being sensitive and kind towards others as well as myself. Lastly, I greatly thank **Stefania** for taking over the role of co-promotor in the last couple of years of my PhD. Your enthusiasm and motivation for research were infectious, and your analytical thinking as well as your great attention to detail have taught me a lot about conducting research and scientific writing!

The research published in this thesis would not be possible without all the **families** who participated in the **Survey**, and the **NINO**, **Skippy**, **GO Baby** and **BIBO** study. My deepest gratitude to all of you! I would also like to thank the people who helped me to plan the NINO study - my very first research project: **Tesse** and her lovely team at the **Kinderdagverblijf Bij Ons**. Thank you for being so welcoming, for all the brainstorming sessions and for patiently teaching me how to communicate with, hold, feed, and soothe babies! I would also like to thank the **Lise Meitner Group** for sharing their fascination for environmental psychology with me, and especially **Simone** for sharing her knowledge and advice!

Many thanks also to all my colleagues of the Developmental Psychobiology (DPB) lab. **Kelly** – thank you for trusting me with a part of your Skippy study, and for patiently guiding me through the analyses. **Bonnie** – thank you for introducing me to writing and publishing. **Irene** – Thank you for always being there when I needed help and for supporting me with your impressive talent for multitasking and chaos-prevention. **Hellen** – Thank you for all the fun times, wee adventures abroad, deep conversations and conveying your passion for science and fairness. **Yvonne** – Your positive and open-minded personality is absolutely inspiring. Thank you for always being there, be it for dinners, ‘dagjes uit’, ‘BIBO kennistoetsen’ or general advice. **Nina** – Thank you for sticking through video scoring with me and for being around for all the fun lunches and travel adventures. **Henrik** – Thank you for sharing your passion for statistics and for pushing me beyond my limits during Chanco. **Ana** – Thank you for always being so lovely and considerate. **Evie** – I greatly appreciate your calm and kind attitude. **Lucia and Maddalena** – Thank you for your help in navigating the sleep data. I would also like to express deep gratitude to all the dedicated interns and student assistants who helped me throughout my PhD. **Danique, Lonneke, Larissa, Roosmarijn, Jennifer, Julie, Julia and Julia, Eva and Eva, Luka, Anke, Georgia, and Jesse** – Thank you for being such a great team. Also, many thanks to **Kathi, Majorie, Yang, Dafna, Esmee**, and all the others for the team spirit and good times – there were simply too many amazing **DPBers** to mention everyone!

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Next to the tremendous support I received from people in the Netherlands, I am also very grateful for the support I received from across the border. Thank you **Ana, Shimul, Manthan, and Anshul**, for accomplishing the challenging task of making the Niederrhein feel like a new home! Ganz lieben Dank auch an alle Mitbewohner*, Nachbar* und Freund*innen die mir den Alltag in meiner neuen Heimat bereichert haben: **Şura, Timo, Afaaf, Eva, Gerda und Frau Timmer, und Janine** sowie die ganze **Stallgemeinschaft!** Ganz herzlichen Dank auch an die lieben **Kolleg*innen vom Autismus Therapie Zentrum Niederrhein**, von denen ich viel über kollegialen Zusammenhalt sowie die Arbeit mit Kindern gelernt habe.

Zuletzt bin ich dankbar für die vielen Menschen die mich aus der Heimat unterstützt haben. **Josepha**, ich danke dir von ganzem Herzen für die unvergängliche und unentbehrliche Freundschaft. **Mama**, ich danke dir dafür, dass du mir mit bedingungsloser Hingabe nicht nur alles erlaubt, sondern auch alles ermöglicht hast, was ich mir in den Kopf gesetzt habe. **Sandra, Nadine, Michelle und Benni**, ich danke euch dafür, dass ich mich immer auf eure Unterstützung und Gesellschaft verlassen kann. **Sandra und Nadine** danke ich insbesondere auch für die linguistische Unterstützung (ich habe in diesem Dankwort ein paar Bonuskommata für euch versteckt). **Emmi** danke ich für jeden großmütterlichen Rat, und **Friedel** für seinen unvergänglichen Humor.

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Mohith, your balanced attitude to life helped me tremendously during the past years. Thank you for always listening (without a word limit), caring for Timmy when I was busy, proofreading, helping me to put things into perspective, and making sure I always enjoy my free time (and that I always eat well)! Thank you for a million other things, most of which I have probably already told you, and am planning on telling you a million times more often in the future!

Curriculum Vitae

Nicole Rheinheimer was born on June 29th, 1993 in Kaiserslautern, Germany. After completing secondary education in 2012, she studied Psychology at Radboud University Nijmegen, where she specialized in the topics of brain and cognition. She wrote her Bachelor thesis on predictive model updating in infants at the Baby Brain Group of Prof. dr. Sabine Hunnius at the Baby and Child Research Center in Nijmegen.



In 2015, Nicole started the Research Master in Cognitive Neuroscience at the Donders Graduate School in Nijmegen. She specialized in the topics perception, action and control, and wrote her Master thesis on the association of frontostriatal functional connectivity with repetitive behavior in children with autism spectrum disorder and obsessive-compulsive disorder at the Developmental Neuropsychiatry Group of Prof dr. Jan Buitelaar. After completing her Master's degree in 2017, she worked as a Therapist at the Autism Therapy Center Niederrhein in Kalkar, Germany.

In January 2020, Nicole started her PhD at the Department of Cognitive Neuroscience of the Radboudumc Nijmegen in the Developmental Psychology Lab, supervised by Prof. dr. Carolina de Weerth, Dr. Roseriet Beijers, and Dr. Stefania Vacaru. During her PhD, Nicole conducted research on the role of early caregiving in the development of child regulation.

List of publications

- Akkermans, S. E. A., **Rheinheimer**, N., Bruchhage, M. M. K., Durston, S., Brandeis, D., Banaschewski, T., Boecker-Schlier, R., Wolf, I., Williams, S. C. R., Buitelaar, J. K., van Rooij, D., Oldehinkel, M., & TACTICS consortium (2019). Fronto-striatal functional connectivity correlates with repetitive behaviour across autism spectrum disorder and obsessive-compulsive disorder. *Psychological Medicine*, 49(13), 2247–2255. <https://doi.org/10.1017/S0033291718003136>
- Rheinheimer**, N., Beijers, R., Cooijmans, K. H. M., Brett, B. E., & de Weerth, C. (2022). Effects of skin-to-skin contact on full-term infants' stress reactivity and quality of mother-infant interactions. *Developmental Psychobiology*, 64(7), e22308. <https://doi.org/10.1002/dev.22308>
- Rheinheimer**, N., Beijers, R., Bruinhof, N., Cooijmans, K. H. M., & de Weerth, C. (2023). Effects of daily full-term infant skin-to-skin contact on behavior and cognition at age three - secondary outcomes of a randomized controlled trial. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, 64(1), 136–144. <https://doi.org/10.1111/jcpp.13679>
- Rheinheimer**, N., Vacaru, S. V., van Immerseel, J. C., Kühn, S., & de Weerth, C. (2024). Infant care: Predictors of outdoor walking, infant carrying and infant outdoor sleeping. *International Journal of Environmental Research and Public Health*, 21(6), 694. <https://doi.org/10.3390/ijerph21060694>
- Rheinheimer**, N., Vacaru, S. V., Kühn, S. & de Weerth, C. Effects of outdoor walking and infant carrying on behavioral and adrenocortical outcomes in mothers and infants, under review.
- Rheinheimer**, N. & de Weerth, C. Infant colic and sleeping problems from early childhood through adolescence, under review.

Portfolio

Course participation

Internship supervision for PhD-students	2020
Schrijven voor anderstaligen	2020
Donders Graduate School Day	2020 / 2023
Donders Graduate School – Scientific integrity course	2021
Radboudumc BROK certification	2021 / 2023
Grant writing: creating a compelling narrative for your proposal	2023
Effective writing strategies	2022
Education in a nutshell	2021
Diversity and inclusion	2021
Loopbaanmanagement voor promovendi	2021
Scientific writing for PhD candidates	2021
Poster pitching	2021
Donders Institute Toolkit Advanced (f)MRI	2023
Research Integrity Round Radboudumc	2023

Supervision

Master Thesis (Biomedical Sciences) – Roosmarijn Kockelkoren <i>Title: Investigating the association between sleeping problems and biological aging in children from age 6 to 10: a longitudinal study</i>	2022
Master Thesis (Research Master Cognitive Neuroscience) – Larissa Rosalia <i>Title: Links of infant early non-parental care with cortisol circadian rhythm throughout childhood and the moderating role of room sharing</i>	2023

Conference presentations

Effects of daily skin-to-skin contact on full-term infants' cortisol reactivity and mother-infant-synchrony. <i>Symposium talk at the Society for Research in Child Development, Online Conference.</i>	2021
Effects of daily skin-to-skin contact on full-term infants' development. <i>Poster Presentation at the International Society for Developmental Psychobiology, Hybrid Annual Meeting, Chicago, USA</i>	2021
Effects of daily skin-to-skin contact on full-term infants. <i>Symposium talk at 'Beginnersgeluk', Radboudumc, Nijmegen, the Netherlands</i>	2022
The role of sleep in early development – results of the longitudinal BIBO cohort. <i>Poster Presentation at the Donders-NIN Sleep Meeting, Nijmegen, the Netherlands</i>	2023
Benefits of a forest walk for young infants and their mothers. <i>Poster presentation at the International Society for Developmental Psychobiology, Utrecht, the Netherlands</i>	2023
The role of nature in infant development. <i>Symposium talk at 'Beginnersgeluk', Radboudumc, Nijmegen, the Netherlands</i>	2023
Benefits of a forest walk for young infants and their mothers. <i>Symposium talk at the European Society for Cognitive and Affective Neuroscience, Ghent, Belgium</i>	2024
The role of sleep in infant development – results of a longitudinal study. <i>Flashtalk at Jahrestagung Psychologie und Gehirn, Hamburg, Germany</i>	2024
Risk and protective factors of postpartum stress for infants and mothers. <i>Symposium talk at the International Congress of Infant Studies (Chair and Presenter), Glasgow, Scotland</i>	2024

Other activities

Member of the Outreach Team of the Baby and Child Research Center	2020 - 2021
Coordinator of the GCP-WMO and BROK certifications for the Cognitive Neuroscience Department of Radboudumc	2020 - 2023

Donders Graduate School

For a successful research Institute, it is vital to train the next generation of scientists. To achieve this goal, the Donders Institute for Brain, Cognition and Behaviour established the Donders Graduate School in 2009. The mission of the Donders Graduate School is to guide our graduates to become skilled academics who are equipped for a wide range of professions. To achieve this, we do our utmost to ensure that our PhD candidates receive support and supervision of the highest quality.

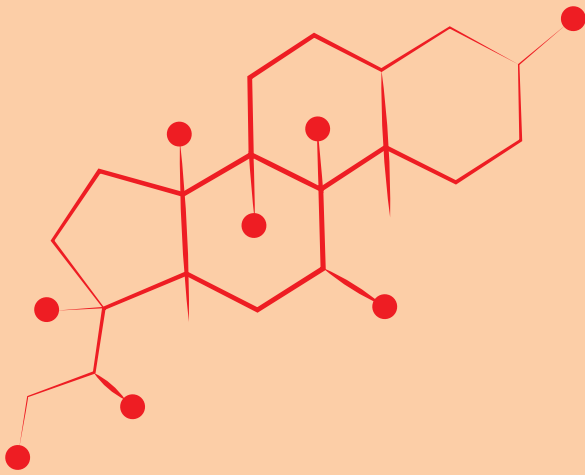
Since 2009, the Donders Graduate School has grown into a vibrant community of highly talented national and international PhD candidates, with over 500 PhD candidates enrolled. Their backgrounds cover a wide range of disciplines, from physics to psychology, medicine to psycholinguistics, and biology to artificial intelligence. Similarly, their interdisciplinary research covers genetic, molecular, and cellular processes at one end and computational, system-level neuroscience with cognitive and behavioural analysis at the other end. We ask all PhD candidates within the Donders Graduate School to publish their PhD thesis in the Donders Thesis Series. This series currently includes over 600 PhD theses from our PhD graduates and thereby provides a comprehensive overview of the diverse types of research performed at the Donders Institute. A complete overview of the Donders Thesis Series can be found on our website: <https://www.ru.nl/donders/donders-series>.

The Donders Graduate School tracks the careers of our PhD graduates carefully. In general, the PhD graduates end up at high-quality positions in different sectors, for a complete overview see <https://www.ru.nl/donders/destination-our-former-phd>. A large proportion of our PhD alumni continue in academia (>50%). Most of them first work as a postdoc before growing into more senior research positions. They work at top institutes worldwide, such as University of Oxford, University of Cambridge, Stanford University, Princeton University, UCL London, MPI Leipzig, Karolinska Institute, UC Berkeley, EPFL Lausanne, and many others. In addition, a large group of PhD graduates continue in clinical positions, sometimes combining it with academic research. Clinical positions can be divided into medical doctors, for instance, in genetics, geriatrics, psychiatry, or neurology, and in psychologists, for instance as healthcare psychologist, clinical neuropsychologist, or clinical psychologist. Furthermore, there are PhD graduates who continue to work as researchers

outside academia, for instance at non-profit or government organizations, or in pharmaceutical companies. There are also PhD graduates who work in education, such as teachers in high school, or as lecturers in higher education. Others continue in a wide range of positions, such as policy advisors, project managers, consultants, data scientists, web- or software developers, business owners, regulatory affairs specialists, engineers, managers, or IT architects. As such, the career paths of Donders PhD graduates span a broad range of sectors and professions, but the common factor is that they almost all have become successful professionals.

For more information on the Donders Graduate School, as well as past and upcoming defences please visit:

<http://www.ru.nl/donders/graduate-school/phd/>



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