TURUN YLIOPISTO
UNIVERSITY OF TURKU

UNPREDICTABILITY OF MATERNAL SENSORY SIGNALS: ENTROPY AS A NOVEL METRIC OF CAREGIVING BEHAVIOR

The FinnBrain Birth Cohort Study

Eeva Holmberg

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University of Turku

Faculty of Social Sciences
Department of Psychology and Speech-Language Pathology
Psychology, Doctoral Programme in Clinical Research

Supervised by

Professor, Riikka Korja
Department of Psychology and Speech-Language Pathology
University of Turku, Finland

Professor, Elysia Poggi Davis
Department of Psychology
University of Denver, Colorado, United States

Adjunct Professor, Marjukka Pajulo
Department of Child Psychiatry
University of Turku, Finland

Reviewed by

Associate professor Kati Heinonen
The Welfare Sciences Unit/Psychology
Tampere University, Finland

Professor Anna-Maija Poikkeus
Department of Education
University of Jyväskylä, Finland

Opponent

Professor, Marian Bakermans-Kranenburg
University Institute of Psychological, Social and Life Sciences, ISPA, Lisbon, Portugal

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ABSTRACT

Emerging evidence suggests that exposure to unpredictable maternal sensory signals in caregiving behavior (characterized as entropy rate) during infancy affects child neurocognitive development. However, the research paradigm is new, and little is known regarding which parental characteristics are related to unpredictable sensory signals or how signal unpredictability is related to more traditional caregiving measurements. Moreover, the longitudinal effects of signal unpredictability on child development are understudied.

The aims of our study were 1) to examine how maternal mental health and self-regulation are associated with unpredictability of maternal sensory signals in caregiving behavior (Study I); 2) to investigate how unpredictable maternal sensory signals associate with maternal sensitivity (Study II) and 3) to explore whether unpredictable sensory signals relate to child self-regulation at 5 years of age (Study III). The study sample comprised mother-child dyads from the FinnBrain Birth Cohort Study.

The main findings showed that higher maternal anxiety symptoms during the pre- and postnatal period together with low self-regulation capacity were associated with greater signal unpredictability during infancy. During the period of infancy to toddlerhood, unpredictable sensory signals and sensitivity were modestly correlated with each other. Exposure to unpredictable sensory signals, especially at very high levels, was associated with children's poorer self-regulation at 5 years of age.

The findings suggest that the combination of high maternal anxiety symptoms and low self-regulation capacity seems to constitute a specific risk for higher unpredictability of maternal sensory signals in caregiving behavior. Results identify unpredictable sensory signals as a characteristic of parental care that is independent of quality measures, namely maternal sensitivity. Unpredictability of maternal sensory signals is a potentially important aspect of early caregiving behavior associated with the development of child self-regulation capacity.

KEYWORDS: caregiving behavior, unpredictable sensory signals, sensitivity, anxiety symptoms, depressive symptoms, self-regulation

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TIIVISTELMÄ

Kasvava tutkimusnäyttö osoittaa, että altistuminen ennustamattomille aistiärsykkeille äidin hoivakäyttäytymisessä (entropia) vauvaiän aikana on yhteydessä lapsen neurokognitiiviseen kehitykseen. Tutkimussuuntaus on kuitenkin uusi ja toistaiseksi tiedetään vähän, mitkä vanhemman ominaisuudet ovat yhteydessä ennustamattomiin aistiärsykkeisiin tai miten signaalien ennustamattomuus on yhteydessä perinteisempiin hoivakäyttäytymistä arvioiviin mittareihin. Lisäksi aistiärsykkeiden ennustamattomuuden pitkäaikaisia vaikutuksia lapsen kehitykseen on tutkittu vielä vähän.

Tutkimuksen tavoitteena oli 1) tutkia miten äidin raskausaikaiset ja synnytyksen jälkeiset ahdistus- masennusoireet ja itsesäätelykyky ovat yhteydessä ennustamattomiin aistiärsykkeisiin äidin hoivakäyttäytymisessä (Tutkimus I), 2) tutkia miten ennustamattomat aistiärsykkeet ovat yhteydessä äidin sensitiivisyyteen (Tutkimus II), ja 3) selvittää ovatko äidin ennustamattomat aistiärsykkeet yhteydessä lapsen itsesäätelyyn 5 vuoden iässä (Tutkimus III). Tutkimusotokset koostuivat FinnBrain-syntymäkohorttitutkimukseen osallistuvista äiti-lapsipareista.

Keskeisten tulosten mukaan äidin korkeat ahdistusoireet raskausaikana ja synnytyksen jälkeen yhdessä heikon itsesäätelykyvyn kanssa olivat yhteydessä korkeampaan aistiärsykkeiden ennustamattomuuteen. Vauva- ja taaperoiässä aistiärsykkeiden ennustamattomuus ja sensitiivisyys olivat kohtalaisesti yhteydessä toisiinsa. Altistuminen ennustamattomille aistiärsykkeille, erityisesti hyvin korkealle tasolle, oli yhteydessä lapsen heikompaan itsesäätelyyn 5-vuoden iässä.

Tulokset osoittavat, että korkeat ahdistusoireet yhdessä heikon itsesäätelykyvyn kanssa näyttävät olevan erityinen riskitekijä korkeammalle aistiärsykkeiden ennustamattomuudelle. Aistiärsykkeiden ennustamattomuus näyttää olevan erillinen osa-alue hoivan laatua arvioivista mittareista kuten äidin sensitiivisyydestä. Äidin ennustamattomat aistiärsykkeet ovat mahdollisesti tärkeä osa-alue hoivakäyttäytymisessä, joka on yhteydessä lapsen itsesäätelyn kehitykseen.

ASIASANAT: hoivakäyttäytyminen, ennustamattomat aistiärsykkeet, sensitiivisyys, ahdistusoireet, masennusoireet, itsesäätely

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List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Holmberg E., Teppola T., Pajulo M., Davis E. P., Nolvi S., Kataja E.-L., Sinervä E. & Korja R. Maternal Anxiety Symptoms and Self-Regulation Capacity Are Associated With the Unpredictability of Maternal Sensory Signals in Caregiving Behavior. *Frontiers in Psychology*, 2020; 11.

II Holmberg E., Kataja E-L., Davis E.P., Pajulo M., Nolvi S., Hakanen H., Karlsson L., Karlsson H. & Korja R. The Connection and Development of Unpredictability and Sensitivity in Maternal Care Across Early Childhood. *Frontiers in Psychology,* 2022; 13.

III Holmberg E., Kataja E-L., Davis E.P., Pajulo M., Nolvi S., Lahtela H., Nordenswan E., Karlsson L., Karlsson H. & Korja R. Unpredictable maternal sensory signals in caregiving behavior are associated with child effortful control. *PlosOne,* 2022; 17.

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Abbreviations

ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ATQ	The Adult Temperament Questionnaire
BIC	Bayesian Information Criterion
CBQ	The Child Behavior Questionnaire
CBQ-VSF	The Child Behavior Questionnaire very short form
CFI	Comparative Fit Index
EA	Emotional Availability
EPDS	The Edinburgh Postnatal Depression Scale
FDR	False Discovery Rate
gwk	Gestational week
LGMM	Latent Growth Mixture Modeling
MCMC	Markov chain Monte Carlo
PRAQ-R2	Pregnancy Related Anxiety Questionnaire Revised 2
QUIC	The Questionnaire of Unpredictability in Childhood
RMSEA	Root Mean Square of Error of Approximation
SCL-90	The Symptom Checklist 90
SRMR	Root Mean Square Residual

1 Introduction

Early care has profound effects on a child's cognitive and emotional development, especially during sensitive developmental periods (Easterbrooks et al., 2012; Farber et al., 2022; Razza & Raymond, 2013; Rocha et al., 2020). For example, early psychosocial deprivation is known to have detrimental effects on a child's later neurocognitive development (Bos et al., 2009; Fox et al., 2011). Decades of evidence, based on the fundamental work of Bowlby (1969), show the long-lasting effects of insensitive early care on a child's developing brain and stress regulation (Ainsworth et al., 1978; Biringen et al., 2014; Bowlby, 1969; Sroufe, 2005).

Besides quantity and quality of early care, environmental unpredictability is a known core element of early adversity influencing child cognitive and emotional development (Baram et al., 2012; Ugarte & Hastings, 2023). Environmental unpredictability may manifest as distal processes such as societal (e.g., crisis) or family environment unpredictability (e.g., residential transitions) or as a proximal process in caregiver–child relationship as a caregiver unpredictability (Ugarte & Hastings, 2023). Although unpredictability has been recognized as a specific adverse exposure there has been difficulties in conceptualizing and assessing unpredictability accurately. For example, caregiver unpredictability has been conceptualized as inconsistent responses to child initiatives or as emotional lability in interactions with a child (Ainsworth et al., 1978; Bowlby, 1969; Lyons-Ruth et al., 2019). The current thesis focuses on a totally novel study paradigm, based on the pioneering work of Davis et al., (2017, 2019), which provides an additional parameter to the caregiver unpredictability: sequences of parental sensory signals during parent–child interactions (Davis et al., 2017; Davis et al., 2019). Distal and proximal levels of environmental unpredictability have been illustrated in Figure 1.

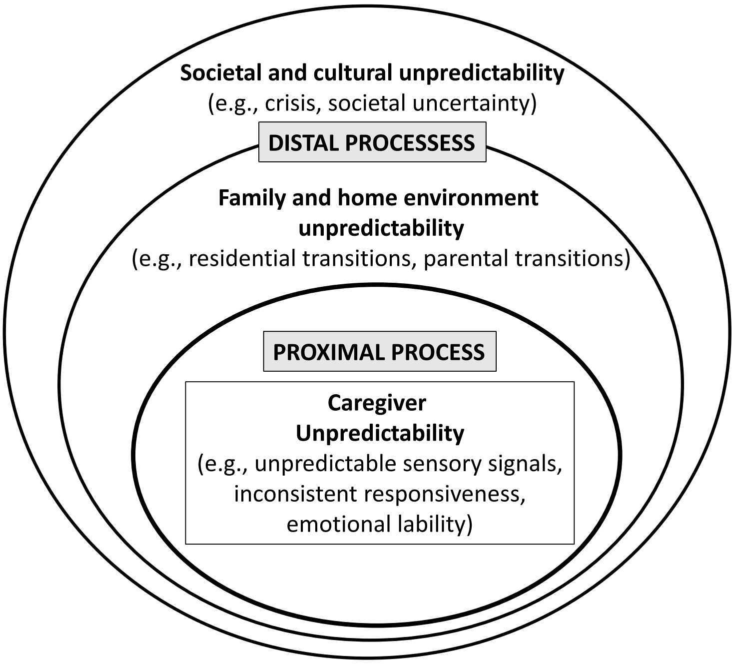

Figure 1. Distal and proximal levels of environmental unpredictability.

The paradigm examines whether parental sensory input (auditory, visual, and tactile) during interactions with a child forms predictable or unpredictable sequences (i.e., patterns), which can be characterized as entropy rate (Vegetabile et al., 2019). Emerging evidence across species demonstrates that exposure to unpredictable patterns of maternal sensory signals during sensitive periods contributes to vulnerability to later cognitive and emotional disorders (Baram et al., 2012; Davis et al., 2017; Davis et al., 2019; Davis et al., 2022; Granger et al., 2021). The model derives from the principle that neuronal circuits are shaped by patterns of sensory information during sensitive periods, which has been shown most clearly in sensory systems, such as the auditory and the visual (Espinosa & Stryker, 2012; Takesian et al., 2018). It is suggested that sensory information may shape cognitive and emotional neuronal circuits as well; and thus, predictable versus unpredictable sequences of parental sensory signals are considered a possible pathway by which early care influences child brain maturation (Birnie & Baram, 2022).

To better understand the novel metric of unpredictable sensory signals, namely entropy in caregiving behavior, this thesis aimed to increase understanding by examining the phenomena from different perspectives in a longitudinal follow-up from the prenatal period until early childhood. Specifically, we explored how maternal characteristics (i.e., maternal mental health and self-regulation) associates with unpredictable sensory signals and how the novel perspective on caregiving relates to a more traditional measurement of caregiving quality, namely maternal sensitivity. Moreover, the study examined in more detail whether early-life exposure to unpredictable sensory signals has longitudinal effects on child development, specifically self-regulation capacity, until early childhood. Overall conceptual model of the thesis is presented in Figure 2. The research was conducted as part of the FinnBrain Birth Cohort Study among mother–child pairs participating in the interaction assessments although findings are probably applicable to fathers as well.

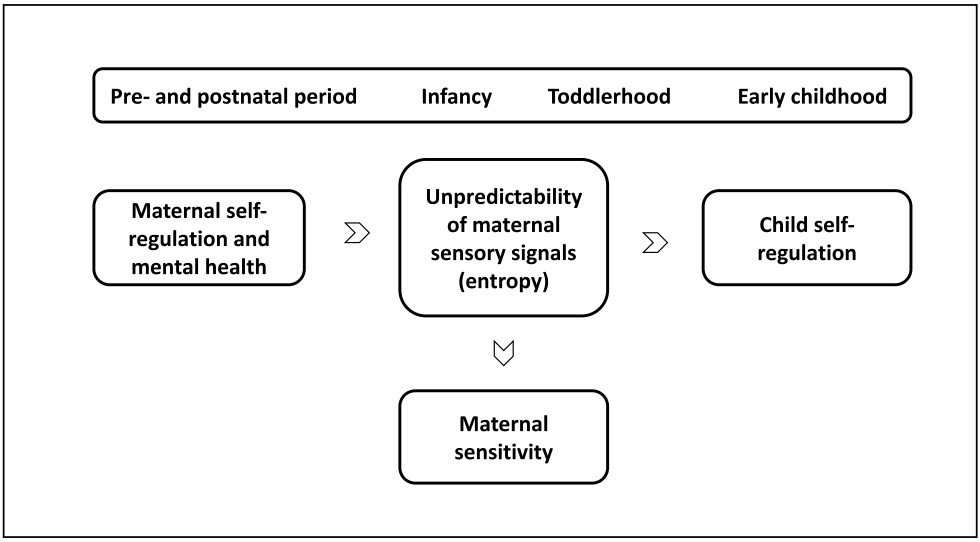

Figure 2. Overall conceptual model of the thesis.

2 Review of the Current Literature

2.1 Unpredictability of maternal sensory signals in caregiving behavior (Entropy)

2.1.1 Theory and assessment

Theoretical grounding for the novel paradigm examining unpredictability of maternal sensory signals in caregiving behavior, is based on the biological principles that neuronal circuits are shaped by sensory information from the environment during sensitive periods of development (Birnie & Baram, 2022; Espinosa & Stryker, 2012; Khazipov et al., 2004; Takesian et al., 2018). Neuronal circuits are connected via synapses, and sensory input activates and strengthens immature synaptic connections whereas inactivated connections are eliminated.

It is well-established that sensory input early in life is required for the maturation of sensory circuits (Espinosa & Stryker, 2012; Khazipov et al., 2004; Takesian et al., 2018). For example, patterns of light are critical for the normative development of the visual system, and disruption in light input is related to deficits in visual function (Espinosa & Stryker, 2012). During the sensitive period of infancy, sensory information (i.e., auditory, tactile, and visual) comes mainly from the parent, and effects of parental sensory deprivation are documented by classic work in non-human primates (Harlow, 1965). These studies establish the importance of parental sensory signals for the offspring or child development.

However, besides the importance of the quantity of parental signals, less is understood regarding the role of sequence or order of parental sensory signals. Given the impact of sensory information on the sensory circuits formation and the primacy of parental sensory signals, evaluation of the effects of parental sensory signals on the development of a child's cognitive and emotional systems has emerged as well.

In the current approach, unpredictability of maternal sensory signals in caregiving behavior is analyzed at a microlevel, based on the predictability of the transitions between maternal auditory, visual, and tactile signals while interacting with a child (Davis et al., 2017; Vegetabile et al., 2019). The sensory information from the parent to the child may be sequential (e.g., a parent may regularly follow an auditory signal with simultaneous auditory and tactile signals), or it may be inconsistent and without order (e.g., a parent may follow an auditory signal with various unpredictable sensory signals). These define the degree to which one can deduce the next parental behavior from the most recent behavior, and can be characterized by computing entropy rate (Vegetabile et al., 2019). Entropy is a metric introduced in the field of thermodynamics and information theory, which characterizes disorder and randomness. Concept of entropy has been applied now first time in behavioral sciences to assess unpredictable patterns of maternal sensory signals during caregiving behaviors (Vegetabile et al., 2019).

Rather than analyzing the quality of these signals (e.g., supportive versus unsupportive signal), only the order and consistency of these signals are calculated. In this regard, a highly predictable mother repeats a similar pattern of transitions between the signals throughout an interaction with a child, whereas an unpredictable mother shifts between signals randomly. Notably, entropy rate to characterize unpredictability can be applied across species (Davis et al., 2019).

2.1.2 Experimental rodent research

Experimental research with rodents has demonstrated, in simulated poverty experiments, that impoverished bedding conditions lead to unpredictable caregiving behavior by dams (Walker et al., 2017). The quantity of maternal care behaviors remains indistinguishable in impoverished versus routine environments, but patterns and rhythms of maternal care differ drastically; care becomes fragmented in impoverished environments. The unpredictability of the dam behavior can be characterized by computing entropy rate. Only developmental epoch for the assessment and specific caregiving behaviors assessed are different in rodent research compared to human research.

Furthermore, exposure to unpredictable patterns of dam behaviors has been shown to directly lead to offspring’s aberrant memory and emotional circuit maturation and function in the offspring (Davis et al., 2017; Ivy et al., 2008; Molet et al., 2016; Rice et al., 2008), as maternal genetic effects on offspring development have been controlled via cross-fostering. These controlled mouse and rat studies, which have been replicated repeatedly, illustrate the causal role of unpredictable caregiving behavior in shaping offspring outcomes (Walker et al., 2017).

2.2 Maternal characteristics and unpredictability of maternal sensory signals

The quality of caregiving behavior is susceptible to maternal-related factors such as maternal mental health, self-regulation capacity, and socioeconomic factors (Bridgett et al., 2015; Conger et al., 2011; Lovejoy et al., 2000; Stein et al., 2012).

However, these maternal characteristics are yet very little studied in relation to unpredictable maternal sensory signals in caregiving behavior.

2.2.1 Maternal mental health

Maternal depressive and anxiety symptoms are relatively common during the perinatal period. Prevalence estimates ranges between 10–25% for prenatal depressive symptoms (Field, 2017b), 21–25% for prenatal anxiety symptoms (Field, 2017a), 20–40% for postnatal depressive symptoms (Field, 2010) and 13–40% for postnatal anxiety symptoms (Field, 2018). Depressive and anxiety symptoms can be transient (Evans et al., 2001), whereas some may develop more chronic course of depressive and anxiety symptoms during perinatal period (Austin et al., 2007; Heron et al., 2004; Korja et al., 2018).

Maternal perinatal mental health (i.e., depressive and anxiety symptoms) constitute a well-known risk factor for quality of maternal caregiving behavior during infancy, whereas associations with unpredictability of maternal sensory signals is less studied. Depressive symptoms have been associated with lower maternal sensitivity and a higher amount of negative behavior during interactions with an infant (Easterbrooks et al., 2000; Lovejoy et al., 2000), whereas anxiety symptoms have been related to higher parental controlling behavior and intrusiveness (Hakanen et al., 2019; Stein et al., 2012). Similarly, previous studies have shown preliminary evidence that concurrent maternal postnatal depressive and anxiety symptoms associate with higher unpredictability of maternal sensory signals during interactions with an infant (Davis et al., 2017; Davis et al., 2019). These findings underscore the importance to investigate associations between maternal pre- and postnatal mental health and unpredictability of maternal sensory signals in more detail.

2.2.2 Maternal self-regulation

Recently, maternal self-regulation has gained interest as a relevant characteristic influencing caregiving behavior (Bridgett et al., 2015; Crandall et al., 2015). Individual self-regulation capacity has a biological basis and refers to the goal-directed regulation of emotion, cognition, and behavior (Rothbart & Bates, 2006). One aspect of self-regulation is effortful control, which includes the ability to flexibly inhibit, activate, or change attention and behavior according to situational needs (Eisenberg et al., 2011; Rothbart & Bates, 2006).

Optimal effortful control is related to efficient stress regulation and, consequently, it may protect from depressive and anxiety symptoms (Eisenberg et al., 2011; Marchetti et al., 2018; Stevens et al., 2015). Thus, maternal effortful control has been suggested to be an important moderator of the association between maternal mental health and quality of caregiving behavior (Stein et al., 2012; Stevens et al., 2015).

Expectedly, higher maternal effortful control has been associated with greater maternal time spent in caregiving activities and less negative caregiving behaviors with infants (Bridgett et al., 2011; Bridgett et al., 2013). In samples with older children, higher maternal effortful control has been associated with more positive reactions to school-aged children's negative emotions (Valiente et al., 2007) and more dysphoric behavior in interactions with adolescents (Davenport et al., 2011). However, there is a gap in the knowledge regarding whether maternal self-regulation is associated with the unpredictability of maternal sensory signals in caregiving behavior.

2.2.3 Socioeconomic factors and maternal age

Research proposes that low socioeconomic situation (i.e., low education level and low income level) as well as lower maternal age may be risk factors for beneficial caregiving behaviors (Camberis et al., 2016; Conger et al., 2011; Roubinov & Boyce, 2017). Low socioeconomic situation may add stress in the family, which in turn may associate with less than optimal caregiving behaviors (Conger et al., 2011; Roubinov & Boyce, 2017). Lower maternal age, in turn, may be related to lower psychological maturation and interfere with adaptation to motherhood (Camberis et al., 2016). However, these maternal characteristics have been only little studied in relation to unpredictability of maternal sensory signals. In two previous studies, mothers with lower education and income levels and younger age provided a relatively greater number of unpredictable sensory signals during interactions with their infants (Davis et al., 2017; Davis et al., 2019). Mechanisms explaining these findings are still largely undiscovered and need further exploration.

2.3 Unpredictability of maternal sensory signals in relation to quality of caregiving behavior

To better understand this novel parameter of caregiving behavior, it should be studied in relation to other aspects of caregiving behavior across child development. The key concept, with its widely used measurement to assess the quality of caregiving behavior, is maternal sensitivity (Ainsworth et al., 1978).

2.3.1 Maternal sensitivity

Sensitivity, a concept originally developed in the context of attachment theory and research, refers to the parent's ability to recognize the child's interaction cues, and to respond to them appropriately and timely enough from the child's perspective (Ainsworth et al., 1978; Bowlby, 1969). According to attachment theory, parental sensitivity is a key element of caregiving behavior, one which enhances the secure attachment pattern of a child. Securely attached children, have had repeated experiences with a caregiver, who is responsive and available when proximity and comfort are needed. In turn, children with an insecure attachment pattern may have had experiences, where proximity-seeking has been rejected, or where responses have been inconsistent.

Early attachment experiences are believed to play a crucial role in the development of psychopathology because of the internalized emotion regulation strategies developed within the parent–child attachment relationship. These strategies may be adaptive or maladaptive and challenged especially under stressful conditions (Ainsworth et al., 1978; Bowlby, 1969; Sroufe, 2005). Notably, a large body of empirical research, based on the foundational work of Bowlby, has shown that high maternal sensitivity and the secure attachment pattern of the child are associated with positive outcomes in child cognitive, emotional, and psychosocial development (Dunkel & Woodley Of Menie, 2019; Easterbrooks et al., 2012; Groh et al., 2014; Groh et al., 2012; Sroufe, 2005).

One widely used approach to evaluate maternal sensitivity in mother–child interaction from early infancy onward is the emotional availability (EA) framework (Biringen et al., 2014) operationalized as the Emotional Availability Scales (Biringen, 2008). The EA framework has its foundation in attachment theory but broadens it by taking into account dyadic and emotional features in mother–child interaction. Thus, the EA system is a relationship evaluation system considering both, the caregiver's, and the child's EA and how they emotionally affect to each other. Beyond evaluating the concept of sensitivity, the EA framework provides a multidimensional set of features to be assessed from the caregiver–child interaction (i.e., caregiver sensitivity, structuring, non-hostility, non-intrusiveness; child responsiveness and involvement). Specifically, EA sensitivity focuses on dyadic expressions of emotions and, in this sense, differs from Ainsworth's classic operationalization of sensitivity, which focuses only on the caregiver's behavior in relation to child interaction signals.

Attachment theory underscores the importance of a predictable, consistent environment for a child's healthy development. However, the attachment tradition and the novel paradigm examining maternal sensory signaling conceptualize unpredictability differently. In the attachment perspective, unpredictability is conceptualized as inconsistent parental expressions of sensitivity in relation to child interaction signals (Ainsworth et al., 1978; Bowlby, 1969). In comparison, the novel paradigm of unpredictable sensory signals evaluates only maternal behavior in interaction at a microlevel, that is, the predictability of sensory signaling input from the mother to the child. Moreover, the paradigm evaluating the unpredictability of the sensory signals focuses only on the order of the signals and not on the quality of these signals (Davis et al., 2017; Vegetabile et al., 2019).

Expectedly, analyses comparing these two study paradigms (i.e., maternal sensitivity and unpredictability of maternal sensory signals) have shown that these concepts are interrelated, but clearly separate aspects of caregiving behavior (Davis et al., 2017). In humans, maternal sensitivity as well as the degree of unpredictability of maternal sensory signals have shown to be associated with a child's overall cognitive function at age 2 years. However, of these measures, only the degree of unpredictable sensory signals was associated with memory function at the age of 6.5 years. These results showed that the unpredictability of maternal sensory signals uniquely contribute to child cognitive development, suggesting that exposure to unpredictable sensory signals could be an additional process in caregiving behavior that shapes infant brain development (Davis et al., 2017).

2.3.2 Stability of maternal sensitivity during early childhood

During infancy, caregiver–infant interaction is highly dyadic, and the infant is totally dependent upon the external regulation of the caregiver. Parent–child interaction changes when the child develops from infant to toddler and achieves motor, cognitive, and language skills and starts to seek autonomy (Edwards & Liu, 2002). These developmental achievements may challenge parents to adjust their responses to the changing developmental levels of their child. Several studies have shown that, on average, caregivers adequately adapt their responses to the developmental levels of their child and that levels of sensitivity remains stable or even increases from infancy to toddlerhood (Biringen et al., 1999; Célia et al., 2018; Kemppinen et al., 2006). It is possible that parents may better adapt to parenthood and learn parenting skills as the child develops (Whiteman et al., 2003). However, there is some evidence that developmental changes in toddlerhood may also pose a challenge to the caregiver, associated with a decrease in parental sensitivity (Bornstein et al., 2010).

At the individual level, caregiver sensitivity has repeatedly shown moderate stability throughout infancy and toddlerhood (Bornstein et al., 2010; Dallaire & Weinraub, 2005; Hall et al., 2015; Kemppinen et al., 2006). In a study of 893 mother–child pairs, the quality of mother–child interaction was assessed annually from infancy until the child age of 6 years (Dallaire & Weinraub, 2005). In the study, maternal sensitivity showed moderate stability across early childhood, showing individual-level adaption to child developmental changes.

The normative development of the unpredictability of maternal sensory signals in caregiving behavior across early childhood is largely undiscovered. Research is needed to understand whether unpredictable maternal sensory signals are a stable maternal characteristic across child development at group and individual levels and whether they follow a stability similar to that in traditional measurements of maternal sensitivity.

2.4 Unpredictability of maternal sensory signals in caregiving behavior and child development

Consistent with experimental rodent research, recent human work has shown that early exposure to unpredictable maternal sensory signals (characterized as entropy rate) while a mother interacts with her infant is associated with impairments in early childhood cognitive and emotional development, such as cognition, memory, self-regulation, and stress regulation (Davis et al., 2017; Davis et al., 2019; Granger et al., 2021; Noroña-zhou et al., 2020).

First, in a sample of 128 mother–infant dyads (USA, California), associations between exposure to unpredictable maternal sensory signals during infancy, and child cognitive development at the ages of 2 and 6.5 years, measured with the Bayley Scales of Infant Development (Bayley, 1993) and hippocampus-dependent recall-task (Sheslow & Adams, 2003), were examined (Davis et al., 2017). Exposure to unpredictable maternal sensory signals during infancy were shown to relate to poorer cognitive performance at 2 years of age and worse memory function at 6.5 years of age.

Next, exposure to unpredictable signals was investigated in relation to child self-regulation as it is known to develop in interaction with the early environment and experiences (Davis et al., 2019). Self-regulation typically refers to goal-directed activities in the regulation of cognition, behavior, and emotion (Rothbart & Bates, 2006). One aspect of self-regulation is effortful control, which refers to the temperament-based capacity to flexibly control behavior and attention (Eisenberg et al., 2011). Links between unpredictability of maternal sensory signals and child effortful control were observed in independent cohorts, from California, USA (n = 192) and Turku, Finland (n = 135) including the present sample of the thesis with very different cultures and socioeconomic situations (Davis et al., 2019). In the present Finnish sample, child effortful control was assessed with maternal reports at 1 and 2 years of age, and in the U.S. sample at 1, 5, and at 9.5 years of age. Moreover, child effortful control was assessed at 6.5 years of age with behavioral evaluation in the U.S. cohort. In both cohorts, exposure to unpredictable maternal sensory signals during infancy was associated with worse effortful control at 1 years of age, and these associations persisted until 2 years of age in the present Finnish cohort and until 9.5 years of age in the U.S. cohort.

Recently, sequences of maternal sensory signals were associated with child neurocircuit development in a U.S. sample (*n* = 69) assessed with diffusion tensor imaging (Granger et al., 2021). Exposure to unpredictability of maternal sensory signals during infancy was associated with desynchronized maturation of corticolimbic pathways, specifically the uncinate fasciculus and the cingulum, in children 9–11 years of age. In turn, imbalanced development of these two regions partially mediated the association between exposure to unpredictable signals during infancy and poor memory performance on a delayed object recognition task during childhood (Granger et al., 2021).

Moreover, emerging evidence has shown that exposure to unpredictable maternal sensory signals during infancy may affect child's stress regulation as well (Noroña-zhou et al., 2020). In a sample of 102 mother–infant pairs (USA), exposure to unpredictable signals was shown to associate with infant blunted cortisol responses to a painful (inoculation) stressor. In addition, there are preliminary findings indicating associations between exposure to unpredictable signals and child internalizing symptoms during early childhood (Aran et al., 2023, manuscript under review).

Notably, all these studies in the emerging field examining the effects of unpredictable sensory signals on child cognitive and emotional development have shown that the effects of exposure are independent of key, previously established predictors of child development, including socioeconomic factors, maternal mental health, and quality of maternal care (i.e., maternal sensitivity). This underscores the importance of considering maternal sensory signals in caregiving behavior as an additional source of early adversity contributing to child brain development. From among the developmental outcomes studied thus far, child self-regulation capacity is known to be an important contributor to later mental health (Eisenberg et al., 2004; Moffitt et al., 2011), and thus, relevant associations should be studied in more detail in longitudinal designs. The previous cross-cultural research including cohorts from California, USA and the present cohort from Turku, Finland (Davis et al., 2019) explored associations between unpredictable sensory signals and child self-regulation (i.e., effortful control) as far as the data was collected, until 9.5 years of age in California cohort and until 2 years of age in the present Turku cohort. This thesis continues this previous work by exploring associations between exposure to unpredictable sensory signals in infancy and child self-regulation (i.e., effortful control) at the age of 5 years in Finnish cohort.

2.4.1 Sex differences

Sex differences in relation to exposure to unpredictable sensory signals are largely undiscovered. However, exposure to early-life stress is known to have sex-specific responses (Glover & Hill, 2012; Hicks et al., 2019). Moreover, there may be some sex-differentiated pathways between early care and child developmental outcomes (Amicarelli et al., 2018; Chang et al., 2011; Fearon et al., 2010; Morawska, 2020). There is evidence that males could be more sensitive to the harmful effects of non-optimal caregiving quality in relation to developmental outcomes, such as externalizing symptoms and self-regulation difficulties (Amicarelli et al., 2018; Chang et al., 2011; Fearon et al., 2010). However, the methodologies used vary widely, and a systematic approach is needed to examine whether early care may influence differently in the development of males and females, and specifically, in relation to exposure to unpredictable sensory signals.

2.5 Summary of the current literature

A novel study paradigm examining unpredictable maternal sensory signals in caregiving behavior has recently emerged. Deriving from the biological principle that sensory input during sensitive developmental periods is crucial for the child brain maturation, the paradigm suggests that sequences of parental sensory input could be important for the child cognitive and emotional development as well (Birnie & Baram, 2022; Davis et al., 2022). Cross-species research has shown that exposure to unpredictable patterns of sensory signals in caregiving behavior associates with vulnerabilities in cognitive and emotional functions and, thus, is a potent source of early-life adversity (Baram et al., 2012; Davis et al., 2022).

Thus far, less is known about maternal characteristics explaining unpredictable sensory signals in caregiving behavior and how this novel measurement of caregiving behavior associates with more traditional measurements of caregiving quality, such as maternal sensitivity. Moreover, there is little knowledge about methodological aspects of the measurement, such as its stability across early childhood. In addition, there is a need for further research examining the effects of exposure to unpredictable sensory signals for child development. Thus far, there is little understanding of longitudinal effects or possible sex differences in the exposure. In addition, it is not yet known whether exposure to very high levels of unpredictability in the pattern of maternal sensory signaling may form a specific risk group in relation to child developmental outcomes.

3 Aims of the Current Study

The aims of the current study were, first, to explore how maternal characteristics, namely maternal mental health, maternal self-regulation (i.e., effortful control), socioeconomic factors and maternal age, relate to unpredictability of maternal sensory signals during infancy and toddlerhood. Second, to examine how unpredictability of maternal sensory signals associate with a more traditional measurement of caregiving quality, specifically maternal sensitivity, and whether there are changes in these caregiving aspects across early childhood. Third, to investigate whether unpredictability of maternal sensory signals has longitudinal effects on child self-regulation (i.e., effortful control) at 5 years of age, and whether child sex moderates any associations. In addition, it was examined whether exposure to very high versus low/moderate levels of unpredictable sensory signals relate to child self-regulation (i.e., effortful control).

Specifically, the aims were:

1) Maternal characteristics and sensory signaling in infancy and toddlerhood:

    a) To examine how maternal pre- and postnatal anxiety and depressive symptoms and self-regulation (i.e., effortful control) are associated with unpredictability of maternal sensory signals in caregiving behavior during infancy (Study I)

    b) To explore whether elevated maternal anxiety and depressive symptoms relate to maternal unpredictable sensory signals and sensitivity during toddlerhood (Study II)

2) Maternal sensory signaling and sensitivity in infancy and toddlerhood: To investigate how unpredictability of maternal sensory signals associate with maternal sensitivity during infancy and toddlerhood and whether there are changes in these caregiving aspects across early childhood at individual and group levels (Study II)

3) Unpredictability in maternal sensory signaling and child self-regulation at 5 years of age: To explore, whether unpredictable maternal sensory signals during infancy relate to child self-regulation (i.e., effortful control) at 5 years of age, and whether child sex moderates any associations, and further to examine whether exposure to high versus low/moderate levels of unpredictable sensory signals is related to child effortful control (Study III)

4 Materials and Methods

4.1 Study design and participants

The present study sample was drawn from families participating in the FinnBrain Birth Cohort Study (Karlsson et al., 2018). The main aim of the FinnBrain study is to prospectively investigate the effects of prenatal and early-life stress on child health and brain development. Recruitment for the cohort took place during the first trimester free-of-charge ultrasound (gestational week 12) by a research nurse between December 2011 and April 2015 in the South-Western Hospital District and Åland Islands in Finland. Of those informed about the study, 66% (n = 3808) participated. The FinnBrain Birth Cohort resembles the general Finnish population with exceptions of lower prevalence of multiparous, younger, and smoking women, along with the prevalence of preterm births being lower in the cohort than among all deliveries at Turku University Hospital. More detailed description of the cohort can be found in Karlsson et al., (2018).

Most participants in the current study were part of the nested case-control population (i.e., the Focus Cohort). The Focus Cohort was established to examine in more detail the effects of prenatal stress exposure on child development and comprised of mothers who self-reported high levels of prenatal anxiety or depressive symptoms (cases) versus lower levels of prenatal anxiety and depressive symptoms (controls) and their infants. The criteria for the Focus Cohort were established by using the anxiety and depressive symptoms questionnaire data of the first 500 participant mothers to establish cutoffs for the approximately highest and lowest 25th percentiles of maternal symptoms during pregnancy. The total sum score for the cutoff points for "cases" and "controls" were as follows: ≥ 12 and ≤ 6 for the Edinburgh Postnatal Depression Scale (EPDS) (Cox et al., 1987), ≥ 10 and ≤ 4 for the Symptom Checklist-90 (SCL-90) (Derogatis et al., 1973) anxiety subscale, and ≥34 and ≤ 25 points for Pregnancy Related Anxiety Questionnaire Revised 2 (PRAQ-R2) (Huizink et al., 2015). Participants were classified as a case if they scored at least once above the selected threshold on two different questionnaires or if they scored above the selected threshold at least twice on the same instrument during pregnancy.

Focus Cohort families and other actively participating families were invited to the FinnBrain Child Development and Parental Functioning Lab assessments when the child was 8 and 30 months and 5 years old. In addition, questionnaires concerning maternal anxiety and depressive symptoms, maternal and child self-regulation, and socioeconomic information was sent to the whole cohort. A flowchart of the mother–child pairs in the studies I–III is presented in Figure 3.

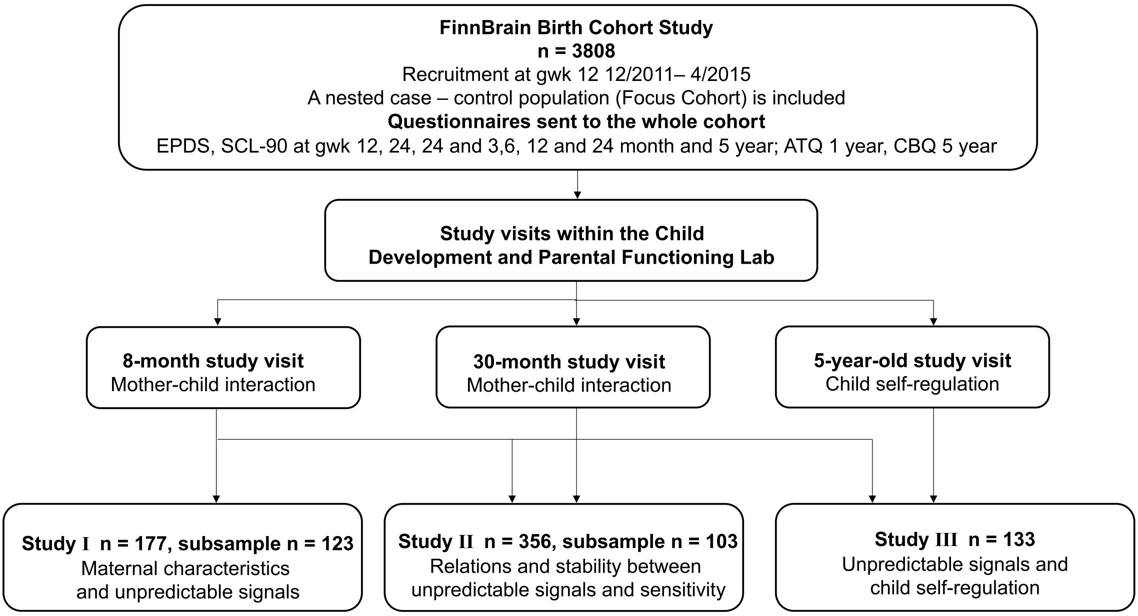

Figure 3. Flowchart of the participants in the studies I–III.

4.1.1 Participants in studies I–III

In Study I, 354 families from the Focus Cohort were contacted during the recruitment process and invited to Child Development and Parental Functioning Lab study visits by the 8-month-old infants and their mothers. From among the contacted families, 58% participated (*n* = 204) in the study visit. From these, 195, took part in mother–child interaction assessment. The non-participating mothers had a lower education level ($\chi 2(2) = 14.07$, $p < 0.001$) and they were younger ($t(313) = 2.35$, $p = 0.020$) compared to the participating mothers. From the video-recorded play situations, altogether 180 demonstrated high enough quality to be analyzed using an interaction coding system. Videos were excluded if the father was in the video instead of the mother or if the video was too short (less than 7 min). Moreover, in the sample of Study I, three mothers had missing values for their socioeconomic information and were thus left out from the analyses. The final sample consisted of 177 mother–infant pairs. In addition, the sample included a subsample of 123 mother–infant pairs, where mothers had also completed the self-regulation questionnaire. Demographics are presented in Table 1.

Study II included the sample of mother–infant pairs who participated in the mother–infant interaction assessment at infant age of 8 months (see above Study I). In addition, participants of the 30-month study visits were included in Study II. For the study visit at 30 months, 1042 families were invited, 415 of whom participated (39.8%) in the interaction evaluation. Non-participating mothers had lower education levels ($\chi2(2) = 23.38$, $p < 0.001$), had lower monthly income ($t\ (995) = 3.576$, $p < 0.001$), and were younger ($t\ (1040) = 4.154$, $p < 0.001$) compared to participating mothers. For the interaction video recordings, 377 were able to be coded using two different coding strategies namely, unpredictability of maternal sensory signals and maternal sensitivity. Videotapes were excluded due to the following reasons: inadequate videotape, having participating fathers instead of mothers, and two outliers in the unpredictability data. Moreover, at the 30-month time point, 21 participants were excluded due to missing data on background information for socioeconomic situation and child health (i.e., education, income, birthweight, Apgar scores). The final sample in Study II consisted of 356 mother–child dyads. In addition, the sample included a subsample of 103 mother–child pairs, who also had interaction data available at 8 months of age. Demographics are presented in Table 1.

Study III consisted of participants in mother–infant interaction assessment (see above Study I) at 8 months. In addition, the sample included participants (*n* = 133) who had mother reports for child self-regulation (i.e., effortful control) at 5 years of age, filled out at home online (*n* = 109) or during study visits for 5-year-old children (*n* = 24). Mothers who did not fill out the child self-regulation questionnaire at home online had lower education levels ($\chi^2(2) = 103.89$, $p < .001$), had lower monthly incomes ($\chi^2(3) = 23.37$, $p < .001$), and were younger ($t\ (3268) = 8.304$, $p < .001$) than mothers who completed the online questionnaire. For the 5-year-old study visit, 1288 families were contacted, and 545 (42.3%) of them participated. Similarly, non-participating mothers had lower education levels ($\chi^2(2) = 30.94$, $p < .001$), had lower monthly incomes ($\chi^2(3) = 11.65$, $p = .009$) and were younger ($t\ (1286) = -4.130$, $p < .001$) than the participating mothers. Demographics are presented in Table 1.

Table 1. Demographic characteristics of the samples in the studies I–III.

	Study I (*n* = 177)	**Study II (*n* = 356)**	**Study III (*n* = 133)**
Education (%)			
High school/ secondary education	23.7	25.8	20.5
Polytechnical diploma	37.9	31.2	39.4
University degree	38.4	43	40.2
Monthly income (%) *			
1500 or less	33.9	32.9	32.6
1501–2500	56.5	53.4	56.8
> 2500	9.6	13.8	10.6
Primiparous (%)	58.2	51.4	58.3
Maternal age at delivery M (SD)	31.18 (4.01)	31.04 (4.51)	31.42 (3.86)

* In euros

4.2 Procedure

Mothers filled out a background information questionnaire at gwk 14, including education level, monthly income, economic satisfaction, and parity. Information on maternal age and perinatal status (gestational weeks at birth, Apgar scores, birth weight, and infant biological sex at birth) was gained from the national birth registries (data from national birth registries, National Institute for Health and Welfare). Depressive symptoms questionnaires were filled out at gwk 14, 24, and 34 and at 3, 6, 12, and 24 months and 5 years postpartum and anxiety questionnaires at gwk 14, 24, and 34 and at 3, 6, and 24 months and 5 years postpartum. Maternal self-regulation was assessed with a self-report questionnaire when the child was 1 year of age. Child self-regulation was assessed with a mother report when the child was 5 years of age.

The study visits were conducted by graduate students and supervised by psychologists. Mother–child interaction was assessed in a video- recorded free-play situation when the child was 8 and 30 months of age. At the 8-month study visit, the mother was given a standard set of toys and asked to play 20 min together with her child as they usually would at home. At the 30-month study visit, the play episode included a 10-min free-play and a 5-min snack time. The video-recorded free-play situations were analyzed with two different coding methods: unpredictability of maternal sensory signals and the EA Scales (see measures below). Mother–child interaction situations are presented in Figure 4 and 5.

Figure 4. Mother–infant interaction assessment at 8 months of infant age.

Figure 5. Mother–child interaction assessment at 30 months of child age.

4.3 Measures

4.3.1 Unpredictability of maternal sensory signals (Entropy rate)

Unpredictability of maternal sensory signals, characterized as entropy rate, was the main variable of interest in studies I–III and assessed when the child was 8 and 30 months of age. Maternal behaviour providing sensory signals (i.e., auditory, tactile, visual) was coded for the 10-min free-play episode continuously on a moment-by-moment basis using The Observer XT 11 (Noldus). Auditory signals included all maternal vocalizations (e.g., speech and laughter). Visual signals included the mother showing a toy while the infant was visually attending. Tactile signals involved all physical contact initiated by the mother (e.g., touching and holding). Details of the coding scheme are described in Davis et al., (2017) and available at https://contecenter.uci.edu/shared-resources/. Inter-rater agreement at 8- and 30-months assessments were calculated for 10% of the videotapes. Coders were blind to all other participant characteristics. Inter-rater agreement for independent coders averaged 86% at 8 months and 84% at 30 months.

Quantification of unpredictability of maternal sensory signals was calculated with conditional probabilities of transitioning between different combinations of maternal auditory, visual, and tactile sensory signals, considering all eight possible combinations of these signals. These eight possible combinations include only auditory, tactile, or visual signal, any combination of two signals (e.g., auditory, and tactile), all three signals simultaneously (auditory, tactile, visual), or no sensory signals at all. For example, a mother who is holding her infant is providing tactile sensory input to the infant. If the mother additionally starts to talk to the infant, she is now providing tactile and auditory sensory input simultaneously. This is considered a transition between different combinations of signals (from only tactile sensory input to a combination of tactile and auditory sensory input).

The transitions between different combinations of maternal sensory signals are modeled as changes in the state of a discrete-state first-order Markov process, and the entropy rate of the process determines the unpredictability of maternal sensory input. If one combination of sensory signals (e.g., only tactile) always follows a specific combination (e.g., tactile, and auditory simultaneously), that is considered predictable behavior (low entropy rate). In contrast, if the transition from one combination of sensory signals to the next is random, it is considered unpredictable behavior (high entropy rate). The entropy rate ranges from 0 to 2.807, with higher values indicating higher unpredictability in transitions between different combinations of sensory signals. Materials regarding the coding system and calculation of the entropy rate are provided in more detail by Davis et al., (2017) and Vegetabile et al., (2019) and available at https://contecenter.uci.edu/shared-resources/. The number of the transitions between maternal sensory signals did not correlate with the entropy rate (Study I; $r = -.048$, $p = .53$, Study II; 8 months $r = -.08$, $p = .418$, 30 months, $r = .063$, $p = .222$, Study III; $r = -.003$, $p = .972$) indicating that entropy rate is a separate construct from the number of transitions.

Unpredictability of maternal sensory signals (i.e., the entropy rate) was used as a continuous variable in the analyses in studies I–III. In addition, in Study III, entropy rate was used for the first time also as a categorical variable. The cutoffs for the entropy rate were derived from another interaction measurement (i.e., maternal sensitivity) used in Study III. The theoretically based and empirically validated cutoff for “low sensitivity” (scores 1 to 3.5) (Wurster & Biringen, 2020) consisted of 15% of the sample in Study III, and similarly, cutoffs for the entropy rate were set up to the highest 15th percentile (entropy rate: 1.080–1.348) and lowest 85th percentile (entropy rate: 0.412–1.076) to create a similar extreme group.

4.3.2 Maternal anxiety and depressive symptoms

Maternal anxiety and depressive symptoms were assessed with self-reports using the Symptom Checklist-90 (SCL-90) (Derogatis et al., 1973; Holi et al., 1998) anxiety subscale and the Edinburgh Postnatal Depression Scale (EPDS) (Cox et al., 1987). The SCL-90 is a reliable and valid measure of anxiety symptoms in both clinical and research settings (Derogatis et al., 1973; Holi et al., 1998) consisting of 10 items rated from 0 to 4. The EPDS is a widely used measure of both prenatal and postnatal depression (Cox et al., 1987) consisting of 10 items rated from 0 to 3.

In Study I, maternal prenatal anxiety and depressive symptoms were assessed at gwks 14, 24, and 34, and at 3 and 6 months postpartum and measures demonstrated good internal consistency throughout the study (.84 – .90 for SCL-90; .85 –.90 for EPDS). Anxiety and depressive symptoms were used both as continuous (pre- and postnatal anxiety and depressive symptoms and a mean of pre- and postnatal anxiety and depressive symptoms) and categorical (highest 10th percentile cutoff at each each measurement point) variables.

In Study II, anxiety symptoms were assessed repeatedly at six time points (qwk 14, 24, and 34 and at 3, 6, and 24 months postpartum) and depressive symptoms at seven time points (gwk 14, 24, and 34 and at 3, 6, 12, and 24 months postpartum). Both measures demonstrated good internal consistency throughout the study (.82–.89 for EPDS and .83–.87 for SCL-90). Since we had data from seven (EPDS) or six (SCL-90) time points during the pre- and postnatal periods, we applied latent growth mixture modeling (Muthén & Muthén, 2000) to inspect different trajectories of maternal depressive and anxiety symptoms.

In Study III, maternal anxiety and depressive symptoms were measured when the child was 5 years of age. Both measures showed good internal consistency (.89 for both the SCL-90 and the EPDS) in this sample.

4.3.3 Maternal self-regulation (Effortful control)

Maternal self-regulation was used as a predictor in Study I and as a covariate in Study III. Maternal self-regulation (i.e., effortful control) was assessed using the Adult Temperament Questionnaire (ATQ) (Evans & Rothbart, 2007) when the child was 1 year of age. The ATQ includes 77 questions consisting of factors of effortful control, negative affect, extraversion, and orienting sensitivity. The effortful control factor consists of 19 items (e.g., "I can keep performing a task even when I would rather not do it" or "When interrupted or distracted, I usually can easily shift my attention back to whatever I was doing before"). It has three subscales: activation control (7 items), attentional control (5 items), and inhibitory control (7 items). Activation control refers to the ability to perform a task despite a lack of desire to engage in the activity; attentional control refers to the ability to remain focused on a task; and inhibitory control refers to the ability to suppress an inappropriate response. The effortful control factor and its subscales were used in Study I and factor of effortful control in Study III. The effortful control factor and its subscales showed adequate internal consistency in studies I and III (Study I; .82 for effortful control, .62 –.70 for the subscales, Study III .83 for effortful control).

4.3.4 Maternal sensitivity

Maternal sensitivity was used as a main variable of interest in Study II and as a covariate in Study III and was evaluated when the child was 8 and 30 months of age. Maternal sensitivity was assessed with EA Scales (Biringen, 2008) from 15- to 20-min video-recorded free-play episodes. The EA Scales are rooted in attachment theory but expand it by emphasizing the importance of emotional expressions in interactions between a parent and a child (Biringen et al., 2014). The EA Scales have shown significant short-term test–retest reliability (Bornstein et al., 2006; Endendijk et al., 2019) and cross-context (laboratory versus home environment) reliability (Bornstein et al., 2006).

The EA Scales consist of four scales regarding parent behavior: sensitivity, structuring, non- intrusiveness, and non-hostility, and two regarding the child: child responsiveness and child involvement. In the present study, the scale for maternal sensitivity (with measurements at 8- and 30-months) was used. Maternal sensitivity characterized the parent's ability to be emotionally connected with the child, to recognize the child's interaction cues, and to respond to child appropriately and timely enough. Maternal sensitivity was evaluated from 1 to 7, where a higher score refers to higher sensitivity. Coders were blinded to all other characteristics of the participants, and inter-rater reliability was assessed for 10% of the play episodes. Intraclass correlation coefficients were .80 for maternal sensitivity at 8 months and ranged from .83 to .91 at 30 months measurement point.

Maternal sensitivity was used as a continuous variable in studies II and III. In addition, maternal sensitivity was used as a categorical variable in Study III. Scores 5.5–7 refer to "high enough" maternal sensitivity and EA of the parent; scores from 4 to 5 describes "somewhat problematic or complicated" interaction; scores from 2.5 to 3.5 indicate "detached" interaction; and scores from 1 to 2 signify "disturbed" interaction (Wurster & Biringen, 2020). In study III, 15% of the mothers scored below 3.5, which was considered the “low sensitivity group.”

4.3.5 Child self-regulation (Effortful control)

Child self-regulation was used as an outcome variable in Study III. Child self-regulation (i.e., effortful control) was assessed with mother reports using the Child Behavior Questionnaire very short form (CBQ-VSF) (Putnam & Rothbart, 2006) when the child was 5 years of age. The CBQ is a valid and reliable questionnaire for assessing child reactivity and regulation in children between 3 and 7 years (Putnam & Rothbart, 2006; Rothbart et al., 2001). The CBQ-VSF consists of 36 items including three factors: effortful control, negative affectivity, and surgency. The effortful control factor, including 12 items (e.g., “When drawing or coloring in a book, shows strong concentration” or “Is good at following instructions”), was used in Study III. Mothers rate their children’s observed behavior during the previous 6 months on a scale from 1 to 7. A higher score for each item or factor reflects a higher level of a particular behavior. The effortful control factor showed adequate internal consistency in the present study ($\alpha = .76$).

4.4 Statistical analyses

4.4.1 Study I

Study I explored associations between maternal characteristics and unpredictability of maternal sensory signals at 8 months of infant age. The analyses were run by SPSS 24, and missing data for anxiety (SCL-90) and depressive (EPDS) symptoms (for the prenatal symptom measurements <5% and for the postnatal measurements <17%) were imputed using the random forest-method (MissForest) (Stekhoven & Bühlmann, 2012) in R 3.6.1. The main variables namely, unpredictability of maternal sensory signals and maternal self-regulation (i.e., effortful control) were normally distributed, and thus, even though, the distributions of anxiety and depressive symptoms were skewed, use of linear regression modeling was allowed. The associations between background variables and the unpredictability of maternal sensory signals were analyzed with analysis of variance (ANOVA), *t*-test, and Pearson correlation, and variables associated with the outcome variable were included as covariates in the following models.

The associations between anxiety and depressive symptoms and the unpredictability of maternal sensory signals were analyzed with Spearman correlations, and *p*-values for 10 comparisons were corrected using Benjamini-Hochberg correction and the False Discovery Rate (FDR) <.10 threshold. In addition, to investigate associations between elevated levels of anxiety and depressive symptoms and maternal unpredictability, cutoffs for maternal symptoms were established on the basis of the highest 10% percentile in each measurement point (for SCL- 90 gwk 14 ≥ 10, gwk 24 ≥ 13, gwk 34 ≥ 11, 3 months ≥ 10, 6 months ≥ 10; and for EPDS gwk 14 ≥ 12, gwk 24 ≥ 13, gwk 34 ≥ 13, 3 months ≥ 11, 6 months ≥ 12). A covariance analysis (ANCOVA) was conducted to test the main effects of the elevated anxiety and depressive symptoms on unpredictability of maternal sensory signals when adjusted with significant covariates. The *p*-values of each symptom predictor across all 10 models were corrected using Benjamini-Hochberg correction and FDR <.10 threshold due to the high correlation of predictors in each model.

Next, associations between self-regulation capacity and unpredictability of maternal sensory signals were investigated with Pearson correlations. The *p*-values of four comparisons were corrected using Benjamini-Hochberg correction and FDR <.10 threshold. Additionally, associations between maternal self- regulation capacity and anxiety and depressive symptoms were examined with Spearman correlations.

Finally, to study the possible interaction effect of maternal anxiety or depressive symptoms and self-regulation capacity on unpredictability of maternal sensory signals, a linear regression model was conducted separately for anxiety and depressive symptoms and each aspect of maternal self-regulation (i.e., effortful control and its subscales: activation control, attentional control, inhibition control). For the models, mean scores for pre- (qwks 14, 24, 34) and postnatal (3 and 6 months) anxiety and depressive symptoms were used due to the high collinearity of pre- and postnatal symptom measurements and to restrict the number of regression models. In each model, the first step included the significant covariates; anxiety or depressive symptoms and self-regulation were added in the second step of the model; and the interaction term between effortful control (or subscale of it) and anxiety or depressive symptoms was added to the third step. The *p*-values for the eight interaction terms were corrected using the Benjamini-Hochberg method, and FDR <.10 threshold was used due to the correlation between the dependent variables in the models. Simple slope analysis was conducted using PROCESSMacro v3.4.

4.4.2 Study II

Study II examined associations between unpredictability of maternal sensory signals and sensitivity and changes in these indices across early childhood. Moreover, in a larger sample of mother–toddler pairs (*n* = 356), associations between maternal symptom trajectories and maternal unpredictability and sensitivity were explored. Statistical analyses were run by SPSS 25.

Associations between background variables and maternal unpredictability and sensitivity were examined with ANOVA, *t*-test, and Pearson correlation. Group mean level stability between 8- and 30-months maternal unpredictable sensory signals and sensitivity were analyzed with paired sample *t*-test and individual consistency over time with Pearson correlation. Relations between maternal unpredictable signals and sensitivity at 8- and 30-months were examined with Pearson correlation.

To examine, whether the different courses of maternal anxiety and depressive symptoms would differently influence maternal caregiving behavior, the trajectories were modeled separately for depressive and anxiety symptoms with latent growth mixture modeling LGMM in Mplus (Muthén & Muthén, 2000). In this approach, growth curves of symptoms are estimated for each individual and then prototypic growth curves are identified for the whole sample. The aim is to select the latent curves, that is, "developmental patterns," that most optimally describe the data, and effectively describe the heterogeneity in the data (as opposed to simple latent growth curve models). Also, the clinical interpretability of the latent curves is used to determine the optimal model. Individual item scores were used in the models. Participants with missing data were incorporated in the analyses with maximum likelihood under the missing-at-random assumption (Graham, 2009) in order to minimize bias (Nagin, 2005). The base data for forming the trajectories consisted of participants having interaction data at 8 and/or 30 months allowing us to retain data from N = 467 and N = 468 participants (for depressive and anxiety symptoms, respectively).

First, structural equation modeling was used to examine the factor structures of general anxiety and depressive symptom questionnaires. Model fit was evaluated by considering various descriptive goodness-of-fit indices (e.g.,(Marsh et al., 2004) the comparative fit index (CFI), the root mean square error of approximation (RMSEA), and the standardized root mean square residual (SRMR), which are reported with the traditional Chi- square statistics and the corresponding degrees of freedom. For the CFI, values above .90, represent an adequate model fit (Hu & Bentler, 1999). SRMR and RMSEA values below .06 and .08, respectively, reflect a good and acceptable fit to the data (Hu & Bentler, 1999). However, since the statistics provide various goodness-of-fit indices and the cutoff criteria for model fit evaluation are not clear-cut, researchers are recommended to simultaneously take different goodness-of-fit indices into account and treat the respective cutoff criteria as guidelines instead of golden rules (Vinni-Laakso et al., 2019).

The longitudinal Confirmatory Factor Analysis of the EPDS and SCL-90 showed adequate fit with the data [SCL-90: $\chi 2(24) = 69.50$, $p > .05$, CFI = .89, root mean square error of approximation = .04, with a slightly poor fit assessed by standardized root mean square residual (SRMR) = .08. The items 2 and 3, 3 and 6, and 5 and 10, and 7 and 10 were allowed to correlate to increase model fit; EPDS: $\chi 2$ (15) = 112.77, *p* >.05, CFI = .90, root mean square error of approximation = .04, standardized root mean square residual = .07. Consecutive Items 1 and 2, 4 and 5, and 8 and 9 were allowed to correlate to improve model fit.] We note that the CFI value for SCL- 90 was slightly below the recommended .90. This is likely related to the fact that the follow-up period was very long (from early pregnancy to 2 years postpartum), and also the intervals between some measurement time points were long and infrequent (i.e., pregnancy weeks 12, 24, 34, and 3, 6, and 24 months postpartum for SCL-90 scores). However, we decided to accept both longitudinal CFA models as most of the indices indicated adequate or good model fit.

Second, the number of latent growth curves using LGMM models and by comparing fit indices of the models with increasing number of subgroups was studied. The following criteria were used for the decision about the optimal number of groups: Bayesian information criteria (BIC, where lower value indicates better model fit; (Nylund et al., 2007), the posterior probability for each trajectory group (referring to the probability of an individual belonging to a group; here a score of >.80 is preferred; (Nagin, 2005), and entropy rate indexing classification accuracy (>.80 indicating excellent accuracy; Lubke & Muthen, 2007). Also, theoretical, and clinical interpretability of the class solutions were used when selecting the best model.

For EPDS LGMM, the statistical indices continued to improve and/or were satisfactory up to a 3-group model, but the latent group sizes were larger and thus more suitable for the subsequent analyses in the 2-group model and thus it was chosen for the analyses. The two EPDS groups were labelled as “Low and stable” (*n* = 370, estimate of intercept = 2.95, estimate of slope = –.14, *p* = .31), and “High and slightly decreasing” (*n* = 97, estimate of intercept = 11.24, estimate of slope = –.41, p < .01). For SCL-90 LGMM, the 2-, 3-, and 4-group solutions were all acceptable. However, the 2-group model showed excellent fit with the data, and the group sizes were sufficient for subsequent analyses, and therefore it was chosen to depict the trajectories of anxiety from early pregnancy to 2 years postpartum. We labelled the groups, based on the courses of symptoms, “Low and slightly decreasing” (*n* = 414, estimate of intercept = 2.39, estimate of slope = –.09, p = .01) and “High and stable” (n = 54, estimate of intercept = 11.17, estimate of slope = .22, p = .44). Hence, the trajectories used in the current study analyses to describe the level and courses of psychiatric symptoms were the following for depressive symptoms “High and slightly decreasing” (mean levels for EPDS symptom scores ranged from 8.7 to 11.6)/ “Low and stable” and for anxiety symptoms “High and stable” (mean levels for SCL symptom scores ranged from 9.9 to 13.7)/ “Low and decreasing.”

Relations between maternal depressive and anxiety symptom trajectories and maternal unpredictable sensory signals and sensitivity at 30 months were analyzed with *t*-tests. Finally, general linear models were conducted to test if the associations remain when significant covariates are accounted for.

4.4.3 Study III

Study III examined whether unpredictability of maternal sensory signals is associated with child self-regulation (i.e., effortful control) at 5 years of age and whether child sex moderates any associations. In addition, it was explored whether exposure to high versus low/moderate unpredictability of maternal sensory signals is associated with child self-regulation. Analyses were run by SPSS 28.0. Missing data (<10%) for maternal anxiety (the SCL-90) and depressive (the EPDS) symptoms at 5 years of child age were imputed using the random forest method (MissForest) (Stekhoven & Bühlmann, 2012) in R 3.6.1, and missing data for maternal effortful control (20%) and background information (i.e., education, income, economic satisfaction, and parity; 1%) were imputed using multiple imputation (10 imputations) using the Markov chain Monte Carlo (MCMC) protocol. According to Little's MCAR test, data were missing at random ($\chi^2(2) = 4.949$, $p = .084$). Unpredictability (i.e., the entropy rate) and child self-regulation showed normal distributions.

First, associations between possible confounding variables and child self-regulation (i.e., effortful control) were examined using Pearson correlation and *t*-test. Confounding factors yielding at least a small effect size ($r > .10$) or significant association with the outcome variable were included as covariates. Associations between unpredictability of maternal sensory signals and child self-regulation (i.e., effortful control) were examined using Pearson correlation. Linear regression (stepwise) was conducted to see whether the associations remain significant after adjustment for economic satisfaction (step 1), maternal effortful control (step 2), and maternal sensitivity and child sex (step 3).

The interaction effect between unpredictable maternal sensory signals and child sex was explored with a standard linear regression. In the first step, covariates (economic satisfaction, maternal effortful control, and maternal sensitivity) were added to the model. In the second step, the main effects of unpredictable sensory signals and child sex were entered in the model. Finally, the interaction term between unpredictable sensory signals and child sex was entered in the model. The interaction effect was further explored using Pearson correlation.

Group comparisons using categorical cutoffs for unpredictable sensory signals were assessed using a *t*-test. Next, a general linear model was used to test whether the association remained when significant covariates (economic satisfaction, maternal effortful control, categorical maternal sensitivity, and child sex) were included. Finally, the interaction effect between categorical unpredictable sensory signals and child sex was tested.

4.5 Ethical considerations

The Ethics Committee of the Hospital District of Southwest Finland approved the study protocol. Written informed consent was provided to the parents prior to the study visits, also on behalf of their child. The register-keeping organization gave their permission to use the data drawn from national birth registries (National Institute for Health and Welfare, www.thl.fi), according to the Finnish data protection legislation. All participants were informed about the confidentiality of the study as well as their voluntary participation and a right to interrupt the study visit without any specific reason.

Coders for the unpredictability of maternal sensory signals were trained in collaboration with developers of the method, Elysia Davis's research group, and active contact was maintained with their group to discuss possible questions and problems raised up during the coding process. Coders for emotional availability (sensitivity) went through authorized online training and got certified for the method (www.emotionalavailability.com).

5 Results

5.1 Maternal characteristics (mental health, self-regulation) and unpredictability of maternal sensory signals during infancy and toddlerhood (Study I and II)

In study I, we examined how maternal characteristics namely, maternal mental health and self-regulation (i.e., effortful control), associate with unpredictability of maternal sensory signals during infancy (at 8 months) in the sample of a 177 mother–infant pairs. Descriptive statistics for Study I are presented in Table 2.

First, associations between socioeconomic factors, child health, and unpredictability of maternal sensory signals were examined. Maternal education level associated significantly with unpredictability of maternal sensory signals (F (2,174) = 3.520, p = .032): mothers of the middle education group (polytechnical diploma) provided a significantly greater number of unpredictable sensory signals in interaction with an infant, *M (SD)* = 0.94 (0.17), compared to the mothers in the high education group (university degree), *M (SD)* = 0.86 (0.15), p = .011. Moreover, lower monthly income level (r = −.160, p = .033) and lower maternal age (r = −.184, p = .014) were associated with higher maternal unpredictability. Child health–related variables (gestational weeks, birth weight), child sex, or parity did not associate significantly to unpredictability of maternal signals. Subsequently, maternal education, income, and age were chosen as covariates in the further analyses.

Table 2. Descriptive statistics for Study I.

	Study I (*n* = 177) ***Mean (SD)***
Unpredictability of maternal sensory signals (8 mo) *theoretical range* 0–2.807	0.90 (0.17)
Maternal effortful control (1 y) *theoretical range* 1–7	4.62 (0.74)
Anxiety and depressive symptoms First trimester	
SCL-90 *theoretical range* 0–40	3.53 (4.40)
EPDS *theoretical range* 0–30	4.98 (4.40)
Second trimester	
SCL-90	4.42 (5.40)
EPDS	5.03 (4.92)
Third trimester	
SCL-90	3.45 (4.72)
EPDS	5.04 (4.90)
Postpartum 3 months	
SCL-90	3.15 (4.04)
EPDS	4.60 (4.13)
Postpartum 6 months	
SCL-90	3.60 (4.95)
EPDS	5.20 (5.00)
SCL-90 pre- and postnatal mean	3.63 (4.05)
EPDS pre- and postnatal mean	4.97 (3.95)

Second, main effects of maternal pre-and postnatal anxiety and depressive symptoms on unpredictability of maternal sensory signals were examined. In the correlational analyses, we found that only higher maternal anxiety symptoms 3 months postpartum related significantly to higher unpredictability of maternal sensory signals ($r = .148$, $p = .049$, FDR = .49). In the examination of these pre- and postnatal measurement points with categorical classifications (highest 10th percentile), it was found that mothers reporting elevated levels of prenatal anxiety symptoms at gwk 24 versus mothers with lower symptoms exhibited higher unpredictability in interaction with an infant (t (175) = −2.87, $p = .005$, FDR = .05) and other significant differences were not observed between elevated anxiety or depressive symptoms and unpredictability of maternal sensory signals (see, Table 3).

Table 3. The unpredictability of maternal sensory signals in elevated (highest 10th percentile) versus lower level (90th percentile) of anxiety and depressive symptom groups.

	Anxiety (SCL-90) *M (SD) n*	*t* **(df)**	**Depression (EPDS)** *M (SD) n*	*t* **(df)**
gwk 14 highest 10th percentile	0.93 (0.16) 22	−1.04 (175)	0.90 (0.16) 19	−0.08 (175)
90th percentile	0.89 (0.17) 155		0.90 (0.17) 158	
gwk 24 highest 10th percentile	1.00 (0.18) 20	−2.87 (175) **	0.92 (0.16) 18	−0.56 (175)
90th percentile	0.88 (0.17) 157		0.89 (0.17) 159	
gwk 34 highest 10th percentile	0.93 (0.18) 23	−.99 (175)	0.91 (0.18) 18	−0.42 (175)
90th percentile	0.89 (0.17) 154		0.89 (0.17) 159	
3 months highest 10th percentile	0.92 (0.19) 20	−.53 (175)	0.95 (0.19) 18	−1.48 (175)
90th percentile	0.89 (0.17) 158		0.89 (0.17) 159	
6 months highest 10th percentile	0.92 (0.21) 19	−.71 (175)	0.90 (0.18) 17	−0.16 (175)
90th percentile	0.89 (0.17) 158		0.90 (0.17) 160	

** p < .01

Based on the significant association between elevated prenatal anxiety symptoms (at gwk 24), a covariance analysis (ANCOVA) was conducted to test whether the association remained significant after significant covariates (i.e., education, income, maternal age) were accounted for. Elevated levels of prenatal anxiety symptoms ($\beta = 0.197$, $p = .007$) remained associated with higher unpredictability in the adjusted model. In addition, the lower level of education ($\beta = 0.173$, $p = .035$) and a younger maternal age ($\beta = -0.168$, $p = .028$) were also significantly associated with higher unpredictability (see Table 4).

Table 4. ANCOVA for prenatal anxiety predicting unpredictability of maternal sensory signals.

	$F_{(df)}$	β
Highest 10th percentile prenatal anxiety	$7.408_{(1,171)}$*	0.197**
Education level	$4.082_{(2,171)}$*	
Low vs. high		−0.061
Middle vs. high		0.173*
Monthly income	$1.573_{(1,171)}$	−0.096
Maternal age	$4.908_{(1,171)}$*	−0.168*

* < .05 ** < .01

Third, main effects of maternal self-regulation (i.e., effortful control) on unpredictability of maternal sensory signals was explored in correlational analyses. The main factor of effortful control was not related to unpredictable sensory signals. From the subscales, lower attentional control associated significantly with the higher unpredictability of maternal sensory signals ($r = -.180$, $p = .046$, FDR = .116).

Finally, the interaction effects of pre- and postnatal anxiety and depressive symptoms (mean score) and maternal self-regulation (i.e., effortful control) on unpredictability of maternal sensory signals were explored. All four scales (main factor; effortful control and subscales; activation control, attentional control, and inhibition control) of maternal self-regulation were modestly correlated to lower anxiety and depressive symptoms throughout the pre- and postnatal period and pre- and postnatal mean symptom scores ($r = –.266$ to $–.525$, $p < .01$). We did not observe a significant interaction effect between effortful control (main factor) and anxiety or depressive symptoms (mean value) on unpredictability of maternal sensory signals. However, when focusing on the subscales, there was a significant interaction effect between activation control and anxiety symptoms (mean value) in predicting unpredictability of maternal signals (β = −1.074, $p = .008$, FDR = .064) (see Table 5). There were no significant interactions for the subscales of attentional control and inhibitory control. Simple slope analysis for the maternal anxiety symptoms (mean value) and unpredictability of maternal sensory signals among those with low (−1SD), average (0 SD), or high (+ 1SD) activation control showed that the association between maternal anxiety symptoms and unpredictability was significant only when the level of maternal activation control was low (β = 0.009, 95% CI [0.001, 0.018], $p = .033$, p adjusted for covariates = .062), and not when the level of activation control was average [β = −0.001, 95% CI = (−0.009, 0.008), $p = .905$] or high [β = −0.011, 95% CI (−0.024, 0.003), $p = .129$]. Figure 6 illustrates the interaction effect.

Table 5. Standard linear regression model for unpredictability of maternal sensory signals.

	β	R^2 (adj)	ΔR^2
Step 1		.019	.052
Education			
Low vs. high	–0.064		
Middle vs. high	0.167		
Monthly income	–0.084		
Maternal age	–0.037		
Step 2		.041	.036
Education			
Low vs. high	–0.072		
Middle vs. high	0.175		
Monthly income	–0.006		
Maternal age	–0.002		
Pre- and postnatal anxiety mean	0.079		
Activation control	–0.150		
Step 3		.091*	.055**
Education			
Low vs. high	–0.068		
Middle vs. high	–0.162		
Monthly income	–0.042		
Maternal age	–0.104		
Pre- and postnatal anxiety mean	1.182**		
Activation control	0.049		
Pre- and postnatal anxiety mean by activation control	–1.074**		

* < .05 ** < .01

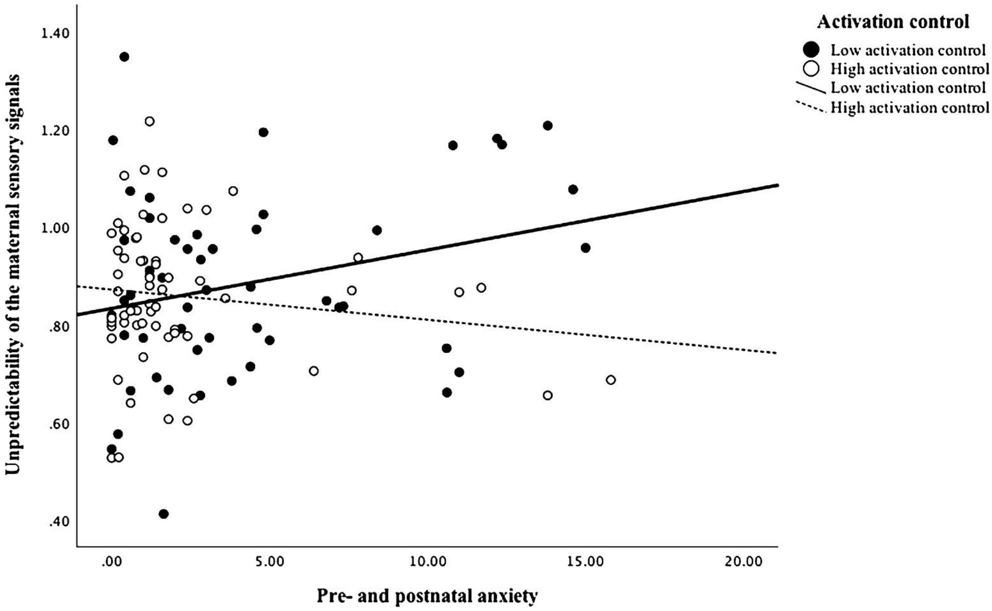

Figure 6. Maternal anxiety predicting for unpredictability of maternal sensory signals in low and high activation control groups (groups divided by median value 4.57 of activation control).

In study II, we explored whether different trajectory classes of maternal anxiety and depressive symptoms are related to unpredictability of maternal sensory signals or maternal sensitivity during toddlerhood in a larger sample (at 30 months) of 356 mother–child pairs. First, associations between background factors and unpredictable sensory signals and sensitivity were explored. Higher education level ($F_{2,353}$ = 4.570, *p* = .011) and higher maternal age were associated with lower unpredictability of sensory signals (*r* = –.107, *p* = .044) whereas higher education level ($F_{2,353}$ = 7.465, *p* = .001) and higher monthly income ($F_{3,353}$ = 3.060, *p* = .028) were related to higher maternal sensitivity at 30 months of child age. In addition, mothers were more sensitive in interactions with girls compared to boys at the 30-month time point (*t* (354) = –2.767, *p* = .006), but there were no sex differences in relation to unpredictable sensory signals. Primiparity, gestational weeks, birth weight, and Apgar scores were unrelated to unpredictability of maternal sensory signals and sensitivity at the 30-month measurement point.

The trajectory classes of anxiety (“high and stable” / “low and decreasing”) or depressive symptoms (“high and slightly decreasing” / “low and stable”) were not associated with unpredictability of maternal sensory signals in interactions with a toddler. However, the trajectory class of “high and stable” anxiety symptoms throughout pre- and postnatal periods (*n* = 33) related to lower maternal sensitivity at the 30-month time point *M(SD)* = 4.79(1.32), (*t* (354) = –2.013, *p* = .045) compared to the class of "low and decreasing" anxiety symptoms (*n* = 323) *M(SD)* 5.21(1.14). Similarly, the trajectory class of "high and slightly decreasing" depressive symptoms throughout pre- and postnatal periods (*n* = 68) was related to lower maternal sensitivity, *M(SD)* = 4.66 (1.24), (*t* (354) = –4.132, *p* < .001), at 30 months of child age compared to the class of "low and stable" depressive symptoms (*n* = 288), *M(SD)* 5.30(1.11).

Further, general linear models were conducted to see whether elevated anxiety or depressive symptoms associate with maternal sensitivity at 30 months of child age when relevant covariates (i.e., education, income, infant sex) are accounted for. Elevated anxiety symptoms were associated with lower maternal sensitivity (β = –0.416, *p* = .046) when covariates were included. Moreover, higher education (low vs. high β = –0.419, *p* = .002; middle vs. high β = –0.326, *p* = .024) associated with higher sensitivity and infant sex (male) (β = –0.318, *p* = .009) was related to lower maternal sensitivity (see Table 6). Moreover, elevated depressive symptoms associated significantly with lower maternal sensitivity (β = –0.603, *p* < .001) even after the inclusion of covariates. Similarly, in this model, higher education (low vs. high β = –0.488, *p* = .002; middle vs. high β = –0.306, *p* = .032) was associated with higher sensitivity and infant sex (male) (β = –0.288, *p* < .016) to lower sensitivity (see Table 7).

Table 6. Trajectory classes of maternal anxiety symptoms predicting maternal sensitivity at 30 months of child age.

	β	**p**	**95% CI**	**Partial ETA^2**
Education				
Low	–0.419	.002	–0.803, –0.179	.027
Middle	–0.326	.024	–0.610, –0.042	.014
High	0[a]			
Income				
1500 or less	–0.161	.736	–1.098, 0.776	.000
1501-2500	0.128	.785	–0.796, 1.052	.000
2501-3500	–0.188	.702	–1.154, 0.778	.000
>3500	0[a]			
Infant sex (male)	–0.318	.009	–0.556, –0.079	.019
SCL				
High	–0.416	.046	–0.824, –0.007	.011
Low	0[a]			

Table 7. Trajectory classes of maternal depressive symptoms predicting maternal sensitivity at 30 months of child age.

	β	p	95% CI	Partial ETA^2
Education				
Low	–0.488	.002	–0.795, –0.182	.027
Middle	–0.306	.032	–0.585, –0.027	.013
High	0[a]			
Income				
1500 or less	–0.194	.679	–1.114, 0.726	.000
1501-2500	0.103	.824	–0.805, 1.010	.000
2501-3500	–0.212	.661	–1.161, 0.738	.001
>3500	0[a]			
Infant sex (male)	–0.288	.016	–0.522, –0.054	.017
EPDS				
High	–0.603	<.001	–0.897,–0.309	.045
Low	0[a]			

5.2 Relations and stability of unpredictability of maternal sensory signals and maternal sensitivity during infancy and toddlerhood (Study II)

In Study II, in a smaller subsample of 103 mother–child dyads with interaction data available from both 8- and 30-month measurement points, we examined how unpredictability of maternal sensory signals and sensitivity relate to each other and how these aspects of caregiving behavior develop during infancy and toddlerhood at group mean level and individual correlational levels.

Correlational analyses revealed that higher maternal unpredictability was associated with lower maternal sensitivity moderately at the 8-month (r = –.279, p = .004) and modestly at the 30-month (r = –.146, p = .006) measurement points.

In the group-level comparisons, we found that mothers provided less unpredictable sensory signals at 30 months compared to the 8-month measurement point (t (102) = 4.737, p < .001). In contrast, there was no significant mean level change in maternal sensitivity between 8- and 30-month measurement points; see Table 8. In individual-level analyses, we found that unpredictability (r = .296, p = .002) and maternal sensitivity (r = .293, p = .003) were moderately consistent between the 8- and 30-month measurement points.

Table 8. Group comparisons for maternal unpredictable sensory signals and sensitivity at 8- and 30-month measurement points.

	8-month mother–child interaction *M (SD)*	30-month mother–child interaction *M (SD)*	*t (df)*
Unpredictable sensory signals (entropy rate)	0.87 (0.16)	0.79 (0.13)	4.737 (102), $p < .001$
Sensitivity	5.36 (1.32)	5.27 (1.05)	0.658 (102), $p = .512$

5.3 Unpredictability of maternal sensory signals and child self-regulation (Study III)

In study III, we examined how exposure to unpredictable maternal sensory signals during infancy relates to child self-regulation (i.e., effortful control) at 5 years of age in a sample of 133 mother–child pairs. Descriptive statistics are presented in Table 9.

Table 9. Descriptive statistics for Study III.

	M(SD)	Theoretical range
Child sex (% female)	47.4	
Unpredictability of maternal sensory signals (child 8 mo)	0.89 (0.17)	0–2.807
Males	0.91 (0.16)	
Females	0.88 (0.19)	
Child effortful control, CBQ (5y)	5.46 (0.74)	1–7
Males	5.25 (0.75)	
Females	5.69 (0.66)	
Maternal effortful control, ATQ (child 1 y)	4.64 (0.76)	1–7
Maternal sensitivity, EA (child 8 mo)	5.34 (1.40)	1–7

Associations between background factors and child self-regulation (i.e., effortful control) were examined first. Maternal economic satisfaction ($r = .126$, $p = .151$), maternal effortful control ($r = .136$, $p = .160$), and maternal sensitivity ($r = .128$, $p = .141$) exhibited modest positive associations ($r > .10$) with child effortful control and, thus, were included in the main analyses as covariates. Moreover, child sex was significantly related to effortful control, with males displaying poorer effortful control compared to females ($t\ (131) = -3.569$, $p < .001$, $d = .62$), and was included in the models as well. Maternal anxiety ($r = -.054$, $p = .540$) and depressive symptoms (r = −.058, p = .511) at 5 years of child age did not meet the criteria for inclusion as a covariate and thus were left out from the main analyses.

In correlational analyses, we found that higher unpredictability of maternal sensory signals was associated with lower child self-regulation (i.e., effortful control) at 5 years of age (r = −.172, p = .048). In the adjusted models (see Table 10), the association between unpredictability and child effortful control, remained at a trend-level after adjustments for economic satisfaction (β = −0.167, p = .052.) The associations weakened after adjustments for economic satisfaction and maternal effortful control (β = −0.156, p = .077), and diminished after adjustments for economic satisfaction, maternal effortful control, maternal sensitivity, and child sex (β = −0.118, p = .175). Child sex was also significantly associated with child effortful control (β = 0.275, p = .001).

Table 10. Standard linear regression for child effortful control.

	β (stand.)	β (unstand.)	p	95% CI	R^2(adj)
Step 1					.029
Unpredictable sensory signals	−0.167	−0.707	.052	−1.419, 0.005	
Economic satisfaction	0.119	0.038	.167	−0.016, 0.092	
Step 2					.027
Unpredictable sensory signals	−0.156	−0.659	.077	−1.389, 0.072	
Economic satisfaction	0.090	0.029	.344	−0.031, .089	
Maternal effortful control	0.071	0.070	.501	−.134, .274	
Step 3					.095
Unpredictable sensory signals	−0.118	−0.499	.175	−1.219, 0.221	
Economic satisfaction	0.083	0.026	.369	−0.031, 0.084	
Maternal effortful control	0.019	0.019	.848	−0.176, 0.214	
Maternal sensitivity	0.103	0.055	.228	−0.034, 0.143	
Child sex (male)	0.275	0.406	.001	0.161, 0.652	

Next, it was examined whether child sex moderates associations between unpredictability of maternal sensory signals and child self-regulation (i.e., effortful control) (see Table 11). The test of the moderating role of child sex revealed that exposure to unpredictable sensory signals was differently related to child effortful control among male and female infants, although the association did not reach standard statistical significance after adjustments for economic satisfaction, maternal effortful control, and maternal sensitivity (β = 0.902, p = .062, see model step 3).

Additional analyses showed negative correlations between infant exposure to unpredictable maternal sensory signals and child effortful control at 5 years of age among males ($r = -.289$, $p = .015$), but not among females ($r = -.007$, $p = .959$); see Figure 7.

Table 11. Standard linear regression for child effortful control with interaction effect of child sex.

	β (stand.)	β (unstand.)	p	95% CI	R^2 (adj)
Step 1					.018
Economic satisfaction	0.092	0.029	.338	–0.031, 0.089	
Maternal effortful control	0.087	0.085	.404	–0.116, 0.286	
Maternal sensitivity	0.120	0.064	.166	–0.027, 0.154	
Step 2					.096
Economic satisfaction	0.083	0.026	.369	–0.031, 0.084	
Maternal effortful control	0.019	0.019	.848	–0.176, 0.214	
Maternal sensitivity	0.103	0.055	.228	–0.034, 0.143	
Unpredictable sensory signals	–0.118	–0.499	.175	–1.219, 0.221	
Child sex (male)	0.275	0.406	.001	0.161, 0.652	
Step 3					.112
Economic satisfaction	0.071	0.023	.439	–0.035, 0.080	
Maternal effortful control	0.031	0.023	.812	–0.168, 0.214	
Maternal sensitivity	0.113	0.060	.183	–0.028, 0.148	
Unpredictable sensory signals	–0.591	–2.499	.027	–4.718, –0.280	
Child sex (male)	–0.517	–0.764	.232	–2.017, 0.489	
Unpredictable sensory signals by child sex	0.902	1.311	.062	–0.66, 2.687	

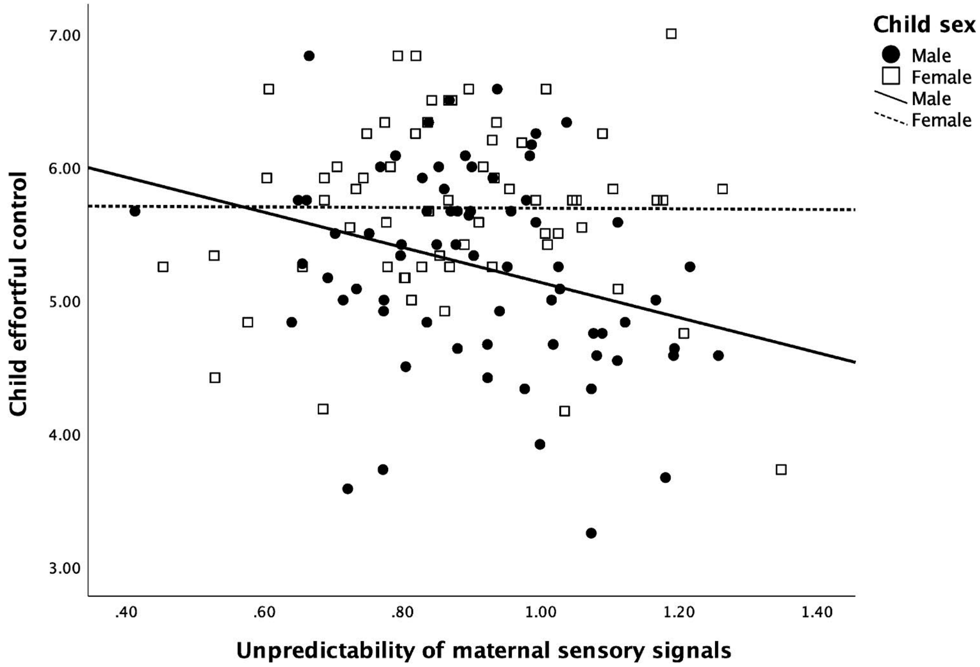

Figure 7. Among males, exposure to unpredictable maternal sensory signals related to poorer effortful control at 5 years of age.

In addition, infant exposure to high versus low/moderate unpredictability of maternal sensory signals and child self-regulation (i.e., effortful control) was explored. Exposure to high unpredictability (highest 15th percentile) was significantly associated with child poorer effortful control, *M (SD)* = 5.10 (0.82), at 5 years of age (t (131) = −2.413, p = .016), compared to low/moderate unpredictability (lowest 85th percentile), *M (SD)* = 5.53 (0.71). The model testing this association after adjustments for covariates (economic satisfaction, maternal effortful control, categorical maternal sensitivity, and child sex) is shown in Table 12. Exposure to high unpredictability of maternal sensory signals (the highest 15th percentile) remained related to poorer child effortful control at 5 years of age ($\beta = 0.169$, p = .047) after the inclusion of covariates. Low maternal sensitivity ($\beta = 0.175$, $p = .035$) and child sex (male) ($\beta = 0.276$, $p < .001$) were associated with poorer child effortful control as well.

Follow-up analyses showed that males exposed to high levels of unpredictable sensory signals during infancy (n =11) had poorer effortful control *M(SD)* = 4.73 (0.48) in comparison to the low/moderate unpredictability group (n = 59) *M(SD)* = 5.35(0.75). Similarly, females (n = 9) exposed to high levels of unpredictable sensory signals during infancy had poorer effortful control *M(SD)* = 5.55 (0.94) in comparison to the low/moderate unpredictability group (n = 54) *M(SD)* = 5.72

(0.62). However, there was no significant interaction effect between categorical unpredictability and child sex in predicting child effortful control.

Table 12. The general linear model for child effortful control (using categorical cutoffs).

	β (stand.)	β (unstand.)	p	95% CI
Economic satisfaction	0.070	0.022	.439	–0.034, 0.079
Maternal effortful control	0.014	–0.004	.968	–0.195, 0.187
Maternal sensitivity				
Lowest 15th percentile	0.175	–0.360	.035	–0.696, –0.025
Highest 15th percentile	0[a]			
Unpredictable sensory signals				
Highest 15th percentile	0.169	–0.349	.047	–0.694, –0.004
Lowest 85th percentile	0[a]			
Child sex (male)	0.276	–0.407	.001	–0.647, –0.167

5.4 Summary of the results

Study I

- Elevated prenatal maternal anxiety symptoms were associated with higher unpredictability of maternal sensory signals in caregiving behavior during infancy. Depressive symptoms were found unrelated to unpredictability of maternal sensory signals.
- Maternal self-regulation capacity moderated the association between maternal pre- and postnatal anxiety symptoms and higher unpredictability of maternal sensory signals during infancy. Mothers with higher anxiety symptoms and poorer self-regulation exhibited higher unpredictability of sensory signals in caregiving behavior.

Study II

- Elevated maternal anxiety and depressive symptoms during pre- and postnatal period were not found related to unpredictability of maternal sensory signals in interaction with a toddler. Instead, they were found related to lower maternal sensitivity.
- Mean level of unpredictability of maternal sensory signals in caregiving behavior decreased between infancy and toddlerhood whereas maternal sensitivity did not change.

- Both unpredictability of maternal sensory signals in caregiving behavior and maternal sensitivity showed some consistency within individuals.
- Unpredictability of maternal sensory signals and maternal sensitivity were modestly to moderately correlated throughout infancy and toddlerhood.

Study III

- Higher unpredictability of maternal sensory signals had a modest association with poorer self-regulation at 5 years of age. However, the association weakened after adjustment for economic satisfaction and maternal self-regulation and diminished after further adjustment for maternal sensitivity and child sex.
- A trend-level finding showed a moderating role of child sex: Among males, infant exposure to unpredictable maternal sensory signals in infancy was related to poorer self-regulation at 5 years of age, whereas no such association was found among females.
- Exposure to very high unpredictability (highest 15th percentile) was associated with poorer self-regulation at 5 years of age compared to the rest of the study group. The association remained significant after adjustment for possible confounding factors (i.e., economic satisfaction, maternal self-regulation, maternal sensitivity, and child sex).

6 Discussion

In the present study, a novel method to assess unpredictability of maternal sensory signals in caregiving behavior was used to analyze maternal interaction behavior with an infant at a microlevel. The first aim was to examine how maternal characteristics associate with unpredictability of maternal sensory signals in caregiving behavior during infancy and toddlerhood. The second aim was to explore how unpredictability of maternal sensory signals in caregiving behavior and maternal sensitivity develop and relate to each other during the child's infancy and toddlerhood. The third aim was to examine how exposure to unpredictable maternal sensory signals during infancy associates with child self-regulation at 5 years of age, and whether child sex moderates these associations.

6.1 Maternal characteristics and unpredictability of maternal sensory signals across early childhood

Maternal characteristics explaining higher unpredictability of maternal sensory signals in caregiving behavior are still largely undiscovered. In Study I, we examined how maternal pre- and postnatal anxiety and depressive symptoms and maternal self-regulation (i.e., effortful control) relate to unpredictability of maternal sensory signals in interaction with an infant. In Study II, we further examined whether elevated anxiety and depressive symptoms from pregnancy to the postnatal period associate with unpredictability of maternal sensory signals in a second assessment point, in interaction with a toddler.

In study I, we found that elevated maternal prenatal anxiety symptoms (gwk 24) were related to higher unpredictability of maternal sensory signals and remained significant after adjustment for socioeconomic factors (i.e., education, income, and maternal age). Only elevated prenatal anxiety symptoms were significantly related to unpredictability of maternal sensory signals, even though there was a trend-level relation between elevated anxiety symptoms and unpredictability of maternal signals throughout the pre- and postnatal period. In contrast, elevated depressive symptoms during the pre- and postnatal period, were not found to be associated with unpredictability of maternal signals in interaction with an infant. In Study II, elevated anxiety or depressive symptoms were not found to be associated with higher unpredictability of maternal signals during toddlerhood. In contrast, elevated maternal anxiety, and depressive symptoms, modeled longitudinally throughout pre- and postnatal periods, were associated with lower maternal sensitivity in interaction with a toddler and remained significant predictors after adjustment for possible confounding factors (i.e., education, income, and infant sex).

An interesting finding in our study was that anxiety, as a hypervigilant state (Glover, 2011; Goodwin et al., 2017), associated with higher unpredictability of maternal signals whereas depressive symptoms, considered more passive dimensions of behavior, were unrelated to unpredictable signals. Although results should be interpreted with cautious as associations were observed only during prenatal period. Anxiety is known to interfere with attentional capacity, which may be related to decrease in quality of mother–child interactions such as increased maternal control (Stein et al., 2012). It could be suggested that anxiety symptoms may interfere with fluent caregiving behavior, with mothers with anxiety symptoms exhibiting more unpredictable sensory signals as well. Moreover, prenatal mood disturbances (e.g., anxiety) may interfere with the psychological transition to motherhood via straight biological effects on the expectant mother's brain functions (Brunton & Russell, 2008; Hillerer et al., 2014) and via disturbing the natural development of the mother–fetal bond (Ahlqvist-Björkroth et al., 2016; Dayton et al., 2010). In addition, prenatal stress such as anxiety may also have effects on fetal development, which may affect for the quality of postnatal mother–infant interaction (Sandman et al., 2011).

Interestingly, in study II, mothers with elevated anxiety or depressive symptoms throughout the pre- and postnatal period did not provide more unpredictable sensory signals in interaction with a toddler compared to mothers with no anxiety or depressive symptoms. This was in contrast to the prior findings regarding unpredictability of maternal sensory signals during infancy (Davis et al., 2017; Davis et al., 2019). In comparison, elevated anxiety and depressive symptoms throughout pre- and postnatal period were both associated with lower maternal sensitivity during toddlerhood, as hypothesized (Lovejoy et al., 2000; Stein et al., 2012). However, previous studies have investigated current anxiety and depressive symptoms in relation to unpredictable maternal sensory signals only during infancy. To our knowledge, this is the first study to explore unpredictable maternal sensory signals in interactions with a toddler-aged child, and no previous knowledge exists about this age period in relation to the evaluation of unpredictable sensory signals. However, our finding suggest that unpredictability of maternal sensory signals may be less influenced by maternal mood than the traditional measurement of caregiving quality, that is, maternal sensitivity.

In study I, it was revealed that maternal self-regulation (i.e., effortful control) capacity was not independently related to unpredictability of maternal sensory signals after adjustments. However, maternal self-regulation capacity, more specifically activation control, moderated the association between maternal anxiety symptoms during the pre- and postnatal period and higher unpredictability of maternal sensory signals during infancy. Mothers with higher pre- and postnatal anxiety symptoms together with lower self-regulation capacity provided more unpredictable sensory signals in interaction with an infant.

There are several possible explanations for this finding. First, high self-regulation capacity may buffer from anxiety or depressive symptoms, and further on, the detrimental effects they may have on unpredictability of maternal signals in caregiving behavior (Bakker et al., 2011; Stevens et al., 2015). Second, anxiety symptoms may disrupt efficient maternal self-regulation, which in turn increases the risk for higher unpredictability of maternal signals in caregiving behavior (Diamond, 2013; Liston et al., 2009). In addition, the mechanisms explaining why the interaction effect was found only with the activation control subscale remain unclear at this stage. Activation control describes the ability to perform a task despite a lack of desire to engage in the activity (Eisenberg et al., 2011). Caregiving behavior may pose many such challenges for the parent, and hence, it could be suggested that activation control is specifically related to fluent and coherent behavior in caregiving situations, especially in the stressful conditions.

Although not the main focus of the present study, we also found that socioeconomic factors, namely lower maternal education, income, and age, were related to higher unpredictability of maternal sensory signals in caregiving behavior. Our results are in line with previous research focusing on the caregiving quality and showing that low socioeconomic situation and lower maternal age at delivery may be risk factors for beneficial caregiving behaviors (Camberis et al., 2016; Conger et al., 2011; Roubinov & Boyce, 2017).

Our findings added knowledge about maternal and contextual factors associating with unpredictability of sensory signals in caregiving behavior during infancy and toddlerhood. To our knowledge, we were the first to explore whether maternal self-regulation (i.e., effortful control) associates with unpredictable sensory signals opening up a novel field of research and starting point for future studies. Our findings show that unpredictability of sensory signals is a multifactorial and complex system affected by several maternal and contextual factors such as maternal mental health, maternal self-regulation and socioeconomic situation. These associations should be studied further and in greater detail to understand the phenomena more comprehensively.

6.2 Relations and stability of unpredictability of maternal sensory signals and maternal sensitivity across early childhood

Very little is known regarding how unpredictable maternal signals associate with more traditional measurements of maternal sensitivity. Moreover, there is no previous knowledge about normative pathways of unpredictability of maternal sensory signals in caregiving behavior across child development. In Study II, we addressed this knowledge gap and examined how these different aspects of maternal caregiving behaviors associate with one another and change, at group (mean level) and individual levels (correlational analysis), when an infant develops to a toddler.

We found that unpredictable maternal signals and sensitivity were modestly to moderately associated with each other throughout infancy and toddlerhood, which is in line with one previous study showing similar relationships between these aspects of caregiving behavior (Davis et al., 2017). In Davis et al.'s, (2017) study, mothers who were less sensitive in interactions with their infants also exhibited higher unpredictability in sensory signals. However, of these measures, only exposure to unpredictable signals was related to child cognitive outcomes at 6.5 years of age. Our results also suggest that unpredictable maternal signals and sensitivity are partly overlapping but clearly separate aspects of caregiving, as hypothesized. Additionally, our findings from Study III shows that low maternal sensitivity and exposure to a high degree of sensory signal unpredictability have independent effects for poorer self-regulation in children. Our results support previous findings that both unpredictable sensory signals and maternal sensitivity have significant and independent associations with child development.

To our knowledge, this is the first study to measure unpredictable maternal signals across early childhood; further, previous research has focused on other aspects of caregiving behavior such as sensitivity. In group-level comparisons, we found that, on average (mean level), unpredictability of maternal sensory signals decreased among mothers when the infant developed to a toddler, whereas maternal sensitivity did not change. The finding supports the possibility that the quality of maternal caregiving behavior may improve across child development (Biringen et al., 1999; Kemppinen et al., 2006) as the mother better adapts to motherhood and acquires parenting skills. The change in unpredictable maternal signals could also be related to the child’s improved skills in language, self-regulation, and executive functions, which might increase the fluency and coherence of caregiving behaviors. In comparison, maternal sensitivity did not change between infancy and toddlerhood, which is consistent with some previous results showing that maternal sensitivity may also be stable across the first years of a child’s life (Célia et al., 2018). However, our results did not support the view that maternal caregiving quality could decrease in the face of the parenting challenges caused by toddlerhood behavioral development (Bornstein et al., 2010).

In individual-level analyses (correlational analyses), we found that both sensitivity and unpredictable maternal signals showed some consistency within an individual from infancy to toddlerhood, as hypothesized (Bornstein et al., 2010; Dallaire & Weinraub, 2005; Hall et al., 2015; Kemppinen et al., 2006). Our results replicate the previous results that quality of maternal care, once established in infancy, may be a relatively stable maternal characteristic across the child's early years. Our results also showed for the first time that unpredictability of maternal sensory signals in caregiving behavior may follow the same pathway of individual stability as other aspects of caregiving behavior. However, future studies should further investigate the normative development of unpredictability of maternal sensory signals across child development.

6.3 Unpredictability of maternal sensory signals in caregiving behavior and child self-regulation

In Study III, we examined whether exposure to unpredictable sensory signals during infancy relates to child developmental outcomes, specifically self-regulation (i.e., effortful control) at 5 years of age, after adjustments for possible confounding factors (i.e., economic satisfaction, maternal effortful control, maternal sensitivity, and child sex). We used a categorical variable (highest 15%) to explore whether exposure to high versus low/moderate unpredictability of maternal sensory signals was associated with child self-regulation. In addition, possible sex differences were investigated.

We found that exposure to higher unpredictability of maternal sensory signals in infancy was modestly associated with poorer child self-regulation (i.e., effortful control) at 5 years of age. However, the association weakened after adjustment for economic satisfaction and maternal effortful control and diminished after further adjustment for maternal sensitivity and child sex. In addition, we found some preliminary evidence that exposure to high versus low/moderate unpredictability of maternal sensory signals during infancy may play a specific role regarding child development. High versus low/moderate unpredictability was associated with poorer child self-regulation (i.e., effortful control) at 5 years of age and remained significant after possible confounding factors (i.e., economic satisfaction, maternal effortful control, maternal sensitivity, and child sex) were accounted for.

Our finding that exposure to unpredictable maternal sensory signals during infancy, especially at very high levels, is related to children's poorer self-regulation (i.e., effortful control) is in line with findings in a previous study (Davis et al., 2019) that showed infant exposure to higher unpredictability of maternal sensory signals is associated with poorer emerging self-regulation capacities of the 1-year-old infants in a USA cohort and in the present Finnish sample. Moreover, longitudinal analyses revealed that associations persisted as far as the data was collected i.e., until 9.5 years of age in the U.S. sample and until 2 years of age in the present Finnish sample. Our present findings indicated that associations persisted at least until early childhood (at 5 years of age) as well in the Finnish sample. However, the association did not remain significant when possible confounding factors were accounted for (i.e., economic satisfaction, maternal effortful control, maternal sensitivity, and child sex), showing that several aspects affect the development of child self-regulation (i.e., effortful control) in early childhood.

Exposure to very high levels of unpredictable sensory signals during infancy was associated with poorer child self-regulation (i.e., effortful control) at 5 years of age even after adjustments for the possible confounding factors (i.e., economic satisfaction, maternal effortful control, maternal sensitivity, and child sex). This finding suggests that the association between maternal unpredictable sensory signals and child developmental outcomes may not be linear; rather, exposure to very high levels (the highest 15% percentile) of unpredictable sensory signals may be more harmful for child brain maturation in comparison to exposure to moderate or low levels of unpredictable sensory signals. However, our analysis was exploratory, and more studies are needed to validate and adjust these cutoffs.

Interestingly, we found that unpredictable sensory signals associated differently with males and females, although the interaction effect did not reach standard statistical significance when possible confounding factors were included. A trend-level finding suggested that exposure to unpredictable maternal sensory signals was related to poorer child self-regulation (i.e., effortful control) in early childhood among males, but not among females. Several possible explanations may exist. First, there are known to be innate differences in neural functioning between males and females, which may underlie early behavioral differences between them (Manoli & Tollkuhn, 2018). Second, exposure to early-life stress has shown sex-specific effects (Glover & Hill, 2012; Hicks et al., 2019). Third, caregiving quality may influence males and females differently; males may be more vulnerable to the effects of low caregiving quality (Amicarelli et al., 2018; Chang et al., 2011; Fearon et al., 2010). Finally, males have a lower effortful control capacity from early childhood on, compared to females (Else-Quest et al., 2006). Our findings suggest that there may be sex differences in how infants respond to unpredictable sensory signals in terms of their effortful control development, and that males may be especially susceptible to such environmental exposure. However, the findings are preliminary, as the moderating role of child sex remained at a trend-level only, after including several covariates. These findings should be replicated and further investigated.

In conclusion, exposure to unpredictable sensory signals during infancy is potentially one pathway by which the early environment shapes child brain development and, further, the development of child self-regulation capacity. Recent research has suggested that poor cognitive function in children exposed to unpredictable maternal sensory signals during infancy, could be explained by the desynchronized maturation of corticolimbic pathways (Granger et al., 2021). Our results are in line with this evolving knowledge in suggesting that child self-regulation development may also be affected by exposure to unpredictable sensory signals. However, given the paucity of research on this topic, replications and further studies are needed to understand which areas in child development are affected by exposure to such signals and what are the specific underlying biological mechanisms explaining poorer cognitive and emotional outcomes.

6.4 Clinical implications

Evolving knowledge indicates that unpredictable maternal sensory signals in caregiving behavior constitute a specific source of early adversity that influences child brain maturation and neurocognitive development (Davis et al., 2017; Davis et al., 2019; Granger et al., 2021). Based on consequences of exposure to unpredictable sensory signals, there is a need to develop early screening tools for identifying mother–child pairs at risk. Entropy measurement itself is not a clinically feasible tool as it is a very time-consuming coding system requiring a specific coding program and statistical knowledge in calculating entropy rates.

To this end, a retrospective self-report measurement for the adults, the Questionnaire of Unpredictability in Childhood (QUIC) (Glynn et al., 2019), has been developed and validated to evaluate unpredictable early experiences in home environments before the age of 18 years. QUIC consists of 38 items including unpredictable experiences in social (e.g., “I had a bedtime routine [e.g., my parents tucked me in, my parents read me a book, I took a bath]”), emotional (e.g., “One of my parents could go from calm to furious in an instant”), and physical domains (e.g., “I moved frequently”). Its validation showed that adults who scored higher on QUIC had been exposed to higher unpredictability of maternal sensory signals during their infancy. These two measurements (i.e., the self-report questionnaire QUIC and microlevel assessment of unpredictable sensory signals) were found to correlate moderately. Moreover, those who reported higher unpredictability in their childhood on QUIC had higher symptoms of anxiety and depression as an adult. Thus, QUIC is a promising instrument for capturing early experiences of unpredictable home environment and in predicting mental health outcomes. Additionally, a five-item short-version (QUIC-5) has recently been developed for screening purposes (Lindert et al., 2022). Screening is especially important, as an unpredictable home environment is a form of early-life adversity that may be amenable to prevention efforts. Previously, maintenance of family routines has been shown to have a buffering role in child psychosocial adjustment (Evans et al., 2005; Glynn et al., 2021; Manczak et al., 2017), suggesting that unpredictability of the home environment could be an actionable form of early-life adversity.

The present study also shed a new light on the maternal characteristics relevant to unpredictability of sensory signals and underscores that maternal mental health should be a special focus in the clinical settings already during pregnancy. Our findings also indicate that anxiety symptoms, which are more rarely screened compared to depressive symptoms, may be a specific risk factor in relation to unpredictability of sensory signals and should be considered in the clinical context.

However, to this end, there is still a lack of a feasible instrument for clinical contexts to identify microlevel unpredictability (i.e., entropy) in caregiving behavior. More research is needed to understand, more comprehensively, which maternal characteristics may pose a risk for high unpredictable sensory signals in caregiving behavior and how this microlevel unpredictability could be identified in daily parenting practices and in clinical settings.

6.5 Strengths and limitations of the study

A major strength of the present study was a longitudinal study design from the prenatal period to child age of 5 years exploring a novel study paradigm of unpredictability of maternal sensory signals in caregiving behavior. Despite the novelty of the measurement, unpredictable maternal sensory signals were observed with high inter-rater agreements. Another strength was the assessment of mother–child interactions with two different, laborious observational assessment methods (i.e., unpredictability of maternal sensory signals and maternal sensitivity). These measurements derive from different research traditions, adding interdisciplinary value to the study. Importantly, we were able to compare unpredictability of maternal sensory signals with maternal sensitivity, at two assessment points (infancy and toddlerhood), which offers totally new basic methodological information about unpredictable sensory signals. Moreover, we considered several relevant confounding factors (i.e., socioeconomic situation, maternal effortful control, maternal sensitivity, and child sex) when examining the associations between unpredictability of sensory signals and child self-regulation development.

Another strength includes repeated measurements of maternal anxiety and depressive symptoms, which enabled us to assess independently the effects of pre- and postnatal symptoms and to use latent growth mixture modeling in the assessment of maternal anxiety and depressive symptoms trajectories. However, levels of anxiety and depressive symptoms were somewhat modest in the present study, and psychiatric diagnostic criteria were not used, which may affect the variance and limit the generalizability to clinical populations. In addition, despite of our relatively large sample size for depressive and anxiety symptoms, latent growth mixture modeling was not able to detect large enough samples to study subtle differences in the trajectories of symptoms. Also, some fit indices in the longitudinal confirmatory factor analysis of the symptom scores were slightly below adequate, though most showed adequate or good fit. This was likely related to our long follow-up period with infrequent assessment points toward the end of the follow-up. However, we see merit in this longitudinal modeling strategy making use of maximal amount of data.

The present study has also clear limitations. In Study I, maternal self-regulation (i.e., effortful control) was assessed only at one time point, (at 1 year of infant age), after the outcome (unpredictable sensory signals) variable. However, effortful control has been shown to be a stable characteristic during adulthood, proving a strong rationale to use it even after the outcome variable (Laverdière et al., 2010; Putnam, 2011; Tortella-Feliu et al., 2013). Consistency is further supported by the pattern of correlations between maternal effortful control and maternal anxiety and depressive symptoms, which remained very similar in our study across the follow-up (gwk 14 to 6 months postpartum *r* ranging from .30 to .40), even though mothers undergo pregnancy and postpartum, which were major periods of change in their lives.

Additionally, limitations regarding the measurement of child self-regulation should be noted. Child self-regulation (i.e., effortful control) was assessed only with mother reports, which may increase the risk of reporter bias. This concern was mitigated by showing that maternal current anxiety or depressive symptoms were not associated with the mother reports of child effortful control. However, the CBQ (Putnam & Rothbart, 2006) is designed to characterize how a child responds in specific situations, rather than subjective ratings of the child.

Importantly, our attrition analyses indicated that the participating mothers had a higher socioeconomic status compared to non-participating mothers. Hence, it is important to be cautious in generalizing the present results to clinical samples or otherwise more disadvantageous populations. In addition, the results are specific to the cultural context and not necessarily generalizable to other countries or cultures.

Finally, we were not able to control for any genetic influence for mother or child behavior during interaction situations. Moreover, the assessment of unpredictable sensory signals did not capture child behavior or its possible effects on the mother's behavior, which should be considered a possible limitation of the method evaluating unpredictable sensory signals.

6.6 Future directions

The limitations of the current study raise suggestions for the future research. First, as measuring unpredictable maternal sensory signals in caregiving is such a novel method, the basic methodological information about the measurement is needed. It is still largely unrevealed whether the current metric is dyadic or only parent-related aspect of caregiving behavior and future studies should consider the possible influence of child characteristics and behavior, such as temperament and interaction abilities, on measuring sequences of parental sensory signals. Moreover, normative trajectories of unpredictable sensory signals are still largely undiscovered. In the future studies, ecological validity of the measurement should be in the focus as setting (free play versus difficult task) or situation (laboratory versus home environment) may affect caregiver's entropy rate. Moreover, more methodological research is needed regarding relations of unpredictable sensory signals to other measurements of parent–child interactions to explore whether unpredictable sensory signals overlap with some other domains of caregiving behavior.

Second, it is important that future studies be conducted in different populations. Preliminary evidence shows similar findings across cultures with different socioeconomic situations (Davis et al., 2019). However, more research is needed to understand whether the assessment of unpredictable sensory signals is valid and reliable measurement across cultures. Moreover, future studies should be conducted in clinical samples as well to acquire more knowledge about the generalizability of the findings to clinical populations.

Although the current study has added knowledge about parental characteristics, which are possibly related to unpredictable signals, future studies should examine these more comprehensively. For example, the possible effects of the parent's cognition or trauma history in unpredictable signals are still undiscovered. Importantly, the parent's sex should be considered to explore the applicability of the findings to the fathers as well.

Finally, future research should further examine more the significance of exposure to unpredictable sensory signals on child development. The research has started by focusing on child's cognitive development (Davis et al., 2017; Davis et al., 2019), and preliminary findings also show associations with child emotional development (Aran et al., 2023, manuscript under review). However, many areas in child development are still undiscovered, such as executive function and emotion and stress regulation and related neural correlates. Moreover, little is known as to whether associations between exposure to unpredictable sensory signals and child developmental outcomes are linear, and future studies should examine the possibility of, for example, U-shaped associations. Additionally, possible sex differences should be studied further. Moreover, specific biological mechanisms by which unpredictable sensory signals influence child development can be further probed in experimental animal work and human brain imaging studies.

7 Conclusion

Unpredictability has been recognized as a specific source of environmental adverse experience for developing child (Baram et al., 2012; Ugarte & Hastings, 2023). However, conceptualizing and measuring unpredictable experiences has been diverse. Distal processes of unpredictability have included societal and family environment where more proximal process of caregiver unpredictability manifests. However, caregiver unpredictability has included different ways of assessment such as caregiver's inconsistent sensitivity or emotional lability. This thesis focused on a novel parameter of caregiver unpredictability: sequences of sensory signals (entropy) (Davis et al., 2019, 2017). The paradigm applies metric of entropy, traditionally used in the fields of natural sciences, to behavioral human research and in specific, in early caregiving behavior research. Thus, providing a totally novel way to approach early caregiving behavior.

The thesis approached the novel metric from different perspectives to get more comprehensive picture of the phenomena and explored whether the novel metric of entropy associates with maternal factors, traditional way to assess caregiving quality and child self-regulation during early childhood. Importantly, our study adds knowledge about relevant underlying maternal characteristics suggesting that unpredictable signaling is a multifactorial system and that several aspects, such as maternal anxiety symptoms, self-regulation capacity, and socioeconomic factors, are related to such signaling. Moreover, the current study replicates the previous finding that unpredictable signals only partly overlap the traditional measurement of maternal sensitivity and suggest it to be a separate aspect of caregiving behavior (Davis et al., 2017). Additionally, the current study suggests that unpredictable signals show some individual consistency across early childhood whereas, on average, unpredictable sensory signals decrease during the child's first years, thus providing novel methodological information about the measurement. The current study supports the previous findings (Davis et al., 2019) that exposure to unpredictable sensory signals, especially at very high levels, during infancy may be harmful to the development of child self-regulation capacity, and it adds knowledge that males are possibly more vulnerable to such exposure.

The research field concerning unpredictable sensory signals (entropy) in caregiving behavior has recently emerged based on the pioneering work of Davis's research group (2017, 2019). The novel paradigm provides a promising metric to capture caregiver's unpredictability on a microlevel among the complex research field assessing environmental unpredictability. Evolving knowledge suggests that exposure to unpredictable signals is, potentially, a specific source of early-life adversity influencing child cognitive and emotional development (Aran et al., 2023, manuscript under review; Davis et al., 2022). Thus, future studies should investigate in greater detail its significance for child development, underlying biological mechanisms, and possible clinical implications.

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