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EXPLORATORY REPORT

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Maternal substance use, unpredictability of sensory signals and child cognitive development: An exploratory study

Noora Hyysalo[1] | Minna Sorsa[2,3] | Eeva Holmberg[4,5] | Riikka Korja[4,5] | Elysia Poggi Davis[6,7] | Eveliina Mykkänen[1] | Marjo Flykt[1,8]

[1]Faculty of Social Sciences, Psychology, Tampere University, Tampere, Finland

[2]Faculty of Social Sciences, Social Psychiatry (Public Health), Tampere University, Tampere, Finland

[3]Child Psychiatry, Wellbeing Services County of Pirkanmaa, Tampere, Finland

[4]FinnBrain Birth Cohort Study, Turku Brain and Mind Center, Department of Clinical Medicine, University of Turku, Turku, Finland

[5]Department of Psychology and Speech-Language Pathology, University of Turku, Turku, Finland

[6]Department of Psychology, University of Denver, Denver, Colorado, USA

[7]Department of Pediatrics, University of California-Irvine, Hewitt Hall, Irvine, California, USA

[8]Faculty of Medicine, Department of Psychology and Logopedics, University of Helsinki, Helsinki, Finland

Correspondence
Noora Hyysalo, Faculty of Social Sciences, Psychology, Tampere University, Kalevantie 5, Tampere FI-33014, Finland.
Email: noora.hyysalo@gmail.com

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Abstract

Maternal substance use and unpredictable maternal sensory signals may affect child development, but no studies have examined them together. We explored the unpredictability, frequency and duration of maternal sensory signals in 52 Caucasian mother–child dyads, 27 with and 25 without maternal substance use. We also examined the association between unpredictable maternal signals and children's cognitive development. Maternal sensory signals were evaluated with video-recorded dyadic free-play interactions at child age of 24 months. Children's cognitive development was evaluated with Bayley-III at 24 months and with WPPSI-III at 48 months. We found similar unpredictability, frequency and duration of sensory signals between substance-using and non-using mothers. Higher unpredictability of maternal sensory signals was robustly linked with poorer child cognitive development at 24 months. The link persisted, although weakened to 48 months. Unpredictability of maternal sensory signals may be a vital parenting aspect shaping children's development, but more research is needed in high-risk groups.

Highlights

- We examined unpredictability, frequency and duration of maternal sensory signals among substance-using and non-using mothers, and the associations between unpredictability and children's cognitive development.
- We assessed sensory signals with dyadic free-play interaction and children's cognitive development with standardized tests. Groups showed similar sensory signal unpredictability, frequency and duration. Unpredictable sensory signals were linked with poorer child cognitive development at 24 and 48 months.
- Unpredictability of maternal sensory signals is a potentially vital aspect of parental care in shaping children's development. More research is needed especially including high-risk mothers.

KEYWORDS

child cognitive development, exploratory, mother–child interaction, sensory signals, substance use, unpredictability

1 | INTRODUCTION

Environmental unpredictability and, more proximally, caregiver unpredictability adversely influence children's development (Baram et al., 2012; Davis & Glynn, 2024; Ellis et al., 2022; Ugarte & Hastings, 2023). A novel paradigm to observe caregiver unpredictability focuses on fine-grained aspects of caregiving behaviour, namely maternal sensory signals, encompassing *auditory*, *visual* and *tactile* signals directed toward the child (Davis et al., 2017, 2019). *Unpredictability* of these signals—inconsistent transitions between combinations of different sensory signals—is recognized as sculpting child neurodevelopment (Glynn & Baram, 2019). The *frequency* and *duration* of sensory signals in caregiving behaviour may also vary, but research is inconsistent on their role for child development and associations with caregiving risks. In animal studies, dams experiencing a limited bedding and nesting condition did not differ from dams with a typical rearing environment in their frequency and duration of sensory signals but provided unpredictable patterns of care to their offspring which led to adverse offspring outcomes (Baram et al., 2012). In human studies, maternal risks, such as depressive symptoms, may influence the frequency and duration of their sensory signals (e.g. less frequent and shorter duration of touching; Mantis et al., 2019).

Maternal substance use represents a caregiving risk factor strongly linked to cumulative adversities, including socioeconomic and psychiatric disadvantages (Barrocas et al., 2016; Conradt et al., 2023). Substance use affects mothers at neural level by altering the functioning of their stress-reward system and leading to passive and disengaged caregiving behaviour (Rutherford & Mayes, 2019). Indeed, altered quality of dyadic interaction, such as decreased sensitivity (Hatzis et al., 2017; Hyysalo et al., 2022) and behavioural incoherence, is common among substance-using (SU) mothers (Hakansson et al., 2018). Interaction difficulties associated with substance use and high psychiatric comorbidity could impact the patterns, frequency and duration of maternal sensory signals. However, maternal sensitivity and unpredictable sensory signals have independent links to offspring outcomes (Davis et al., 2017; Holmberg et al., 2022). Furthermore, as prior studies have focused on community samples, our understanding of caregiving risks, such as maternal substance use, that shape the unpredictability, frequency and duration of sensory signals remains limited.

Finally, unpredictable maternal sensory signals have been found to shape children's neurodevelopment, contributing to poor cognitive function (Baram et al., 2012; Davis et al., 2017, 2022; Granger et al., 2021). Substance exposure during pregnancy also influences neural maturation causing deficits in cognitive function (Guille & Aujla, 2019; Lin et al., 2018). Simultaneously, maternal substance use and unpredictable sensory signals may expose children to early adversities, impacting child neurocognitive maturation (Glynn & Baram, 2019; Lin et al., 2018). However, the association between unpredictable maternal sensory signals and children's cognitive development has been observed in community samples, and an evaluation of how maternal substance use contributes to this relation is missing.

In this study, our research questions were: Are there differences between SU and non-using (NU) mothers in (1) the unpredictability, and (2) the frequency or duration of maternal sensory signals? We also explore (3) the associations of maternal sensory signals and children's cognitive development across the sample.

2 | MATERIALS AND METHODS

2.1 | Participants and procedure

The study was part of a longitudinal research project that followed prenatally SU and NU mothers and their children from pregnancy (T1) to children's age of 24 (T2) and 48 months (T3). T1 information concerning pregnancy and children's first 2 years of life were collected retrospectively from health care and social services registries at children's age of 24 months. In the current study, we used longitudinal data from all study phases and included 52 mother–child dyads at children's age of 24 months ($M = 25.5$, $SD = 1.9$) and again at 48 months ($M = 49.3$, $SD = 1.7$). Twenty-seven mother–child dyads were part of the SU group and 25 dyads part of the NU group (Figure 1). Initially, there were also seven foster mother–child dyads (i.e. a substance-exposed child participating with a foster mother) in the SU group, but these dyads were excluded from this study.

2.1.1 | SU group

Data for the SU group were collected from a family health clinic specialized in families with parental substance use problems, in the southern part of Finland. Data collection of T2 took place between April 2015 and March 2018, and all families at the clinic with a 24-month-old child during data collection were invited to participate. Nurses at the clinic invited potential participants during children's 24-month health checks. Those who agreed to participate were contacted by the clinic's psychologist to schedule for T2 assessment that was held at the clinic during one or two sessions (à 45 min) depending on the child's motivation. During the assessment, the psychologist first conducted the child's cognitive assessment and then the dyadic mother–child interaction assessment (see specific measures below).

Same children were studied again at T3 (48 months) that took place between November 2017 and February 2020. At T3, the psychologist recontacted families to invite them to a child's cognitive assessment (see below) that was performed at the clinic during one session lasting 45 min.

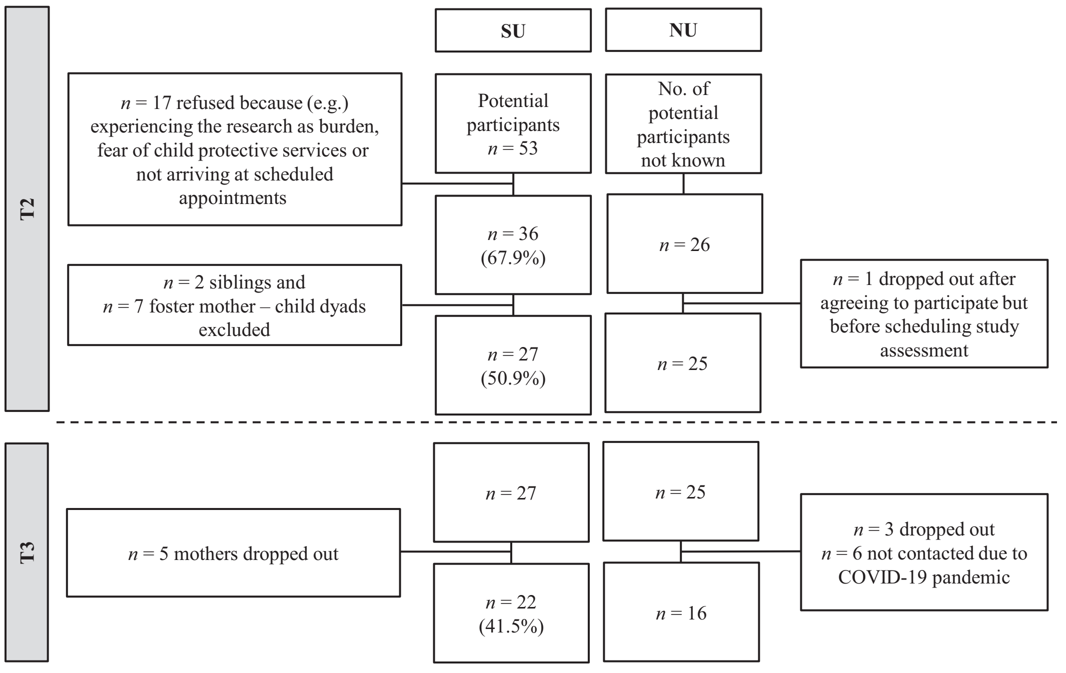

FIGURE 1 Participant flow of the current study. NU, non-using group; SU, substance-using group. T2 = children 24 months old, T3 = children 48 months old.

2.1.2 | NU group

Data for the NU group were collected from seven communal family health clinics in the southern part of Finland. Data collection of T2 took place between October 2019 and May 2021 and all families at those clinics with a 24-month-old child during data collection were invited to participate. Exclusion criteria were mother's current or previous substance use and poor Finnish language skills. Nurses were instructed to invite potential participants to the study during children's 24-month health checks and those who agreed to participate were contacted by a licensed psychologist (the first author) to schedule for study assessment. The assessment was held at the clinic, at family's home or at university laboratory during one session (à 45–90 min). The assessment followed the same structure than with the SU group. The COVID-19 pandemic caused difficulties in recruiting families, and we had to discontinue data collection for several months in 2020.

T3 data collection of the NU group took place between October 2021 and March 2022. A psychology master student recontacted all families and invited them to a child's cognitive assessment (see below) that was performed at family's home or at university laboratory during one session lasting 45 min. Six dyads who participated at T2 were not contacted due to COVID-19 pandemic.

2.1.3 | Ethical considerations

Both groups were given verbal and written information about the study by nurses in the clinic and by psychologists conducting the assessment. All participants signed an informed consent. Ethical approval to the research project was obtained from the Pirkanmaa Hospital District Ethics Committee.

2.2 | Measures

2.2.1 | Unpredictability of maternal sensory signals

The unpredictability of maternal sensory signals was evaluated from mother–child free-play situations that were video-recorded (mean duration 8.9 min, standard deviation 1.5 min). Mothers were instructed to play with their child as they normally would on a floor/mattress with age-appropriate toys.

Maternal sensory signals were coded continuously in real time with The Observer XT 11 or 14 (Noldus). Sensory signals included auditory, visual and tactile signals. Auditory signals were all mother's vocalizations to the child, for example, 'Look. Here is a book', which included two distinct vocalizations ('Look' = first, 'Here is a book' = second). Visual signals were events where (a) the mother manipulated objects, that is, held a toy or another object, or (b) the child visually attended to the mother's manipulation by looking at a toy the mother was manipulating. Tactile signals included (a) maternal touch (i.e. mother touching or stroking the child) and (b) maternal holding (i.e. mother holding the child on her lap). Four trained coders were included in coding the whole data, three of them (a psychology PhD student and two psychology master students) being blind to the group status and one being the first author who was not blind. This was expected not to influence the coding as it required marking every occurrence of a sensory signal and there was little room for interpretation. All coders achieved reliability with the method trainers. 21% of videos were double-coded and interrater agreement between coders was 83.6% ($\kappa = 0.75$). We included videos of foster mother–child dyads in the reliability coding, although these dyads were finally excluded from the analyses of this study.

After coding the data, transitions between different combinations of sensory signals were modelled as changes in the state of a discrete-state first-order Markov process. *Entropy rate* (calculated with R Statistical Software [v3.6.3; R Core Team, 2020] using remotes R package [v2.4.0; Csárdi et al., 2021]) quantifies the unpredictability of these signals and ranges from zero to 2.807, where higher rates indicate more unpredictable and inconsistent caregiving behaviour. Unpredictability refers to inconsistent transitions between the combinations of maternal sensory signals (i.e. auditory, visual, tactile). In total, there are eight possible combinations of maternal sensory signals: no behaviour, single behaviour—only auditory, visual or tactile signals—, two behaviours—any two behaviours occurring simultaneously, for example, mother talking (auditory) and showing a toy to the child (visual)—or three behaviours—for example, mother talking and showing a toy to the child and touching (tactile) the child at the same time. Mother's behaviour would be maximally predictable (indicated as an entropy rate of 0) if the mother always transitioned, for example, from a single auditory behaviour to the combination of two behaviours, such as auditory and visual. Mother's behaviour would be maximally unpredictable (indicated as an entropy rate of 2.807) if the mother's transitions between the combinations of sensory signals were completely random. Additional information on the measure and coding can be found at Davis et al. (2017) and https://contecenter.uci.edu/shared-resources/.

2.2.2 | Frequency and duration of maternal sensory signals

The frequency and duration of maternal sensory signals were obtained from the same videos and coding as the unpredictability of maternal sensory signals.

Frequency

Frequency of maternal sensory signals was illustrated as the number of each sensory signal (i.e. auditory, visual, tactile) observed during the dyadic interaction. All sensory signals could receive frequency starting from zero to as many as was observed during the interaction. As the duration of the videos varied, we scaled the frequency of each sensory signal to match the frequency that would have been observed in 10 min of interaction.

Duration

Duration of maternal sensory signals portrays the mean duration in seconds of each sensory signal (i.e. auditory, visual, tactile) during the dyadic interaction. Duration could receive any value starting from zero.

2.2.3 | Children's cognitive development

At the age of 24 months

Bayley Scales of Infant and Toddler Development—Third Edition (Bayley-III; Bayley, 2008) was used to assess children's cognitive development at the age of 24 months. Bayley-III is a widely used standardized test that evaluates infant and toddler development across three performance domains: cognitive (e.g. sensorimotor development, exploration and manipulation, memory, concept formation), language (expressive and receptive) and motor (fine and gross). Also, parent-evaluated domains of social–emotional and adaptive behaviours are included in the scale but were not used in our study. Each performance domain is evaluated separately with playful tasks and children's performance on the tasks is compared with standardized age-dependent scores that are then converted to an index score ($M = 100$, $SD = 15$). In our study, we were interested in children's cognitive and language development.

At the age of 48 months

Wechsler Preschool and Primary Scale of Intelligence—Third Edition (WPPSI-III; Wechsler, 2009) was used to assess children's cognitive development at the age of 48 months. WPPSI-III is a standardized test that evaluates preschool children's cognitive skills, and it consists of subtests that create index scores of the Verbal Intelligence Quotient (VIQ), the Performance Intelligence Quotient (PIQ), the Processing Speed Quotient and the General Language Composite. In our study, we used VIQ and PIQ. VIQ measures acquired knowledge, verbal reasoning and comprehension of verbal information. PIQ measures nonverbal reasoning, spatial processing skills, attentiveness to detail and visual-motor coordination skills. Children's performance on each subtest is compared with standardized age-dependent scores and then converted to an index score with $M = 100$ and $SD = 15$.

2.2.4 | Maternal substance use

Maternal substance use during pregnancy (T1) was assessed with mother's health care registry information that included what substances the mother had used during pregnancy. When children were 24 months old (T2), maternal substance use was assessed with a self-report questionnaire evaluating psychological and physical dependency on substances. Both were evaluated on a Likert-scale from 1 (*not at all*) to 5 (*extreme*) and included an option *don't know*. Alcohol use was assessed separately with the Alcohol Use Disorders Identification Test (AUDIT; Babor et al., 2001) at T2. Some mothers in the SU group had received or were receiving opioid replacement therapy, and this information was evaluated either with registry information (T1) or maternal self-report (T2). We report descriptive characteristics of maternal substance use in both groups.

2.3 | Analysis strategy

We used an exploratory approach in our data analysis. Following the journal guidelines, we focused on data visualization, reporting descriptive statistics and interpreting effect sizes. Analysis strategy of each research question is presented below. All analyses were carried out with R Statistical Software (v4.2.2; R Core Team, 2022), and visualizations were done with ggplot2 package (v3.4.0; Wickham, 2016).

Before the analysis, we handled missing data with multiple imputation (MI), which is currently the 'state of the art' technique for handling missingness because it increases accuracy and power (Enders, 2022; Schafer & Graham, 2002; Woods et al., 2021, 2023). MI uses a regression-based procedure to create multiple copies of the original dataset with each containing different estimates of the missing values. MI performs well in small samples and when the study groups differ in size, as well as with large missingness and non-normal distributions (Enders, 2017, 2022; Graham, 2009). Missing data rates varied from 0 to 30.8% (Table S1) with the largest missingness in T3 variables. Data were largely missing due to participant attrition (i.e. drop-out at T3). We assumed that data were missing at random meaning that the missing values were related to the observed but not to the unobserved values in the data. We performed MI by chained equations with mice package (v3.15.0; van Buuren & Groothuis-Oudshoorn, 2011). We included 15 analysis variables in the model and the two most valuable auxiliary variables that were associated with the missing and observed values of our analysis variables (T1 customer ship of child protection services [i.e. whether child protection was involved with the family: currently, previously, never] and T2 AUDIT total score). We generated 40 imputed datasets with 20 iterations. We inspected convergence visually by checking the trace plots and density plots. We also compared descriptive statistics using listwise deletion and MI. In visualizations (research questions 1, 2 and 3), we used the averaged data and illustrated the between-imputation variability with separate figures for each imputed dataset in supplementary. We also used the averaged data in the visualizations for the supplementary analyses. We chose this approach for clarity of presentation and because this did not change the results. After creating the complete datasets, descriptive statistics (research questions 1 and 2) and correlation coefficients (research question 3 and supplementary analyses) were calculated in each dataset and pooled by Rubin's rule (Rubin, 1987). See Data S1, Tables S1–S3, and Figures S1–S6 for a detailed description of the missing data analysis.

2.3.1 | Unpredictability of maternal sensory signals

We assessed the unpredictability of maternal sensory signals in both groups (SU and NU) with a rain-cloud plot that shows the scattering of entropy rate across participants and groups. We reported means and standard deviations of entropy rate in each group. We also calculated the observed effect size with Hedges' g because of unequal group sample sizes (https://www.cem.org/effect-size-calculator). We used a conventional interpretation of a small (0.2), medium (0.5) and large effect (0.8). With our sample size ($n = 52$), 80% power and alpha 0.05, we could identify medium to large effects (Cohen's $d = 0.70$, which is roughly equivalent to Hedges' g when $n > 20$; G*Power 3.1.9.4: sensitivity analysis of one-tailed independent sample t-test; Faul et al., 2007). Finally, we compared the entropy rates to previous studies among community samples.

2.3.2 | Frequency and duration of maternal sensory signals

We explored the frequency and duration of maternal auditory, visual and tactile signals with violin plots in both groups as well as with means and standard deviations. We calculated Hedges' g as effect size measures with the same interpretation than above.

2.3.3 | The unpredictability of maternal sensory signals and children's cognitive development

We reported cognitive test scores with Hedges' g by groups. We used Pearson's correlation coefficient to assess the bivariate relations between the unpredictability of maternal sensory signals and children's cognitive development across the whole sample. To illustrate our findings, we drew scatterplots. We evaluated the magnitude of an effect by converting the same limits used with g to r, where 0.1 is a small, 0.24 medium and 0.37 large effect (Perugini et al., 2018).

We also conducted two supplementary analyses to evaluate the potential influence of maternal substance use on the results. First, we calculated a partial correlation between the unpredictability of maternal sensory signals and children's cognitive development while controlling for maternal substance use. Second, we calculated the correlation between maternal sensory signal unpredictability and child cognitive development separately for SU and NU mother–child dyads and illustrated the results with scatterplots. It is important to note that our small sample size limits the interpretability of these results, and they should be interpreted cautiously (Bonett & Wright, 2000; Knudson & Lindsey, 2014).

3 | RESULTS

Descriptive statistics are presented in Table 1. SU mothers showed mild anxiety symptoms, mostly had upper secondary education (81.5%), were unemployed (44.4%), single or divorced (59.2%), and had received psychiatric (81.5%) or substance use treatment (81.5%) by children's age of 24 months. Substance use during pregnancy was common, and 44.4% of mothers still reported psychological dependency and 29.6% physical dependency on substances at T2. Most children of the SU mothers had received physio- or speech therapy (63%) by 24 months of age and many had been referred to specialized hospital treatment (37%). Child protection services were heavily involved with these families starting from pregnancy.

NU mothers had mostly higher education (76%), were often employed (76%) and lived in a cohabitation or marriage (96%). Some mothers (26.1%) had received psychiatric treatment by children's age of 24 months. NU mothers did not have any substance use during pregnancy or children's lifetime, but some mothers (12%) had used prescribed medication, for example, paracetamol, during pregnancy. Some children of the NU mothers had received physio- or speech therapy (32%) and specialized hospital treatment (28%). Child protection services were not involved with any of these families.

Children of SU mothers had average cognitive and language development at 24 months and average nonverbal development at 48 months. Their verbal development was low average at 48 months. In comparison, children of NU mothers had average development across all measures at 24 and 48 months. (Table 2).

In line with previous studies (e.g. Davis et al., 2019; Holmberg et al., 2022), entropy rate was not associated with the number of the transitions (pooled $r = 0.17$, 95% CI [-0.12, 0.43]) indicating that they are separate constructs.

3.1 | Unpredictability of maternal sensory signals between SU and NU groups

We found only a small group effect on the unpredictability of maternal sensory signals—quantified as entropy rate (Table 2). In other words, unpredictable maternal sensory signals were of similar magnitude between SU and NU mothers (Figure 2). Moreover, the entropy rate of the SU group (0.71) and of the NU group (0.65) were approximately the same size compared with previous studies (0.72/0.77, Davis et al., 2017; 0.82/0.88, Davis et al., 2019; 0.87/0.79, Holmberg et al., 2022). The results did not substantially change when evaluated with each imputed dataset (Figure S7).

3.2 | Frequency and duration of maternal sensory signals between SU and NU groups

We found only small group effects between SU and NU mother–child dyads in the frequency and the duration of maternal sensory signals (Table 2). That is, SU mothers showed similar frequency and duration in their auditory, visual and tactile signals compared with NU mothers (Figure 3). The results did not substantially change when evaluated with the imputed datasets (Figure S8).

TABLE 1 Descriptive characteristics of substance-using and non-using groups.

Variable	Substance-using ($n = 27$)		Non-using ($n = 25$)	
Mother characteristics	*M* (*SD*)	*N*	*M* (*SD*)	*N*
Age (years) at delivery	27.4 (5.7)	27	31.9 (3.2)	24
BDI at T2	12.3 (9.2)	27	6.0 (8.2)	24
BAI at T2	12.5 (13.1)	27	5.6 (6.4)	24
AUDIT at T2	6.5 (7.4)	25	2.1 (1.4)	24
	n (%)	*N*	*n* (%)	*N*
Education at T2				
Primary school	4 (14.8)	26	0 (0)	23
Upper secondary	22 (81.5)		4 (16)	
Higher level	0 (0)		19 (76)	
Work status at T2				
Student	7 (25.9)	26	1 (4)	24
Employed	2 (7.4)		19 (76)	
Unemployed	12 (44.4)		2 (8)	
Other, for example, maternity leave	5 (18.5)		2 (8)	
Family type at T2				
Single	9 (33.3)	26	0 (0)	24
Cohabitation/marriage	10 (37)		24 (96)	
Divorced/separated	7 (25.9)		0 (0)	
Psychiatric treatment by T2	22 (81.5)	27	6 (26.1)	23
Substance use treatment by T2	22 (81.5)	27	0 (0)	23
Opioid replacement therapy by T2	7 (25.9)	25	0 (0)	23
Substance use during pregnancy[a]				
Alcohol	4 (14.8)	27	0 (0)	23
Tobacco	4 (51.9)		0 (0)	
Cannabinoids	4 (14.8)		0 (0)	
Stimulants	1 (3.7)		0 (0)	
Opioids	9 (33.3)		0 (0)	
Medication use during pregnancy[b]	16 (59.3)	27	3 (12)	23
Psychological dependency on substances at T2				
Not at all	12 (44.4)	24	23 (92)	23
Mild, moderate, severe, extreme, don't know	12 (44.4)		0 (0)	
Physical dependency on substances at T2				
Not at all	16 (59.3)	24	23 (92)	23
Mild, moderate, severe, extreme, don't know	8 (29.6)		0 (0)	
Child characteristics	*M* (*SD*)	*N*	*M* (*SD*)	*N*
Gestational age at birth	38.6 (2.6)	27	39.5 (1.1)	24
Birth weight (g)	3186.1 (632.9)	27	3494.0 (459.8)	24
	n (%)	*N*	*n* (%)	*N*
Sex (female)	11 (40.7)	27	12 (48)	25
Medical treatment of withdrawal symptoms	4 (14.8)	26	0 (0)	24

(Continues)

TABLE 1 (Continued)

Variable	Substance-using ($n = 27$)		Non-using ($n = 25$)	
Physiotherapy and/or speech therapy by T2	17 (63)	24	8 (32)	25
Specialized hospital treatment (e.g. child psychiatry or neurology) by T2	10 (37)	25	7 (28)	25
Child protection referral during pregnancy	18 (66.7)	27	0 (0)	25
Child protection services at T2				
Currently	14 (51.9)	27	0 (0)	25
Previously	9 (33.3)		0 (0)	
Never	4 (14.8)		25 (100)	

Note: Some information is missing, and percentages are counted based on the total group size. BDI scores range from 0 to 63 and scores below 14 indicate none to minimal depression. BAI scores range from 0 to 63 and scores from 0 to 7 indicate minimal anxiety, scores from 8 to 15 mild anxiety. AUDIT scores range from 0 to 40 and scores from 0 to 7 indicate low-risk consumption.
Abbreviations: AUDIT, the Alcohol Use Disorders Identification Test; BAI, Beck Anxiety Inventory; BDI, Beck Depression Inventory; T1, pregnancy and children's first 2 years of life; T2, children 24 months of age.
[a]Polysubstance use was common and many mothers in the substance-using group used more than one substance.
[b]Refers to all registry-based medication use, for example, benzodiazepines, oxanest and paracetamol.

TABLE 2 Means, standard deviations and effect sizes of the analysis variables in substance-using and non-using groups.

	Substance-using ($n = 27$)		Non-using ($n = 25$)		Effect size	
Variable	*M*	*SD*	*M*	*SD*	Hedges' *g*	95% CI
Bayley-III cognitive	95.96	9.46	108.00	14.95	−0.96	−1.53, −0.38
Bayley-III language	93.71	12.62	102.41	14.93	−0.62	−1.18, −0.06
WPPSI-III VIQ	84.48	19.56	100.20	19.30	−0.80	−1.36, −0.23
WPPSI-III PIQ	96.45	11.64	103.22	18.40	−0.44	−0.99, 0.11
Entropy rate	0.71	0.12	0.65	0.15	0.44	−0.11, 0.99
Frequency of auditory signals	164.92	40.71	168.24	40.29	−0.08	−0.62, 0.46
Frequency of visual signals	32.26	8.04	28.10	9.82	0.46	−0.09, 1.01
Frequency of tactile signals	6.23	6.53	6.42	8.76	−0.02	−0.57, 0.52
Duration of auditory signals	1.14	0.08	1.13	0.05	0.15	−0.40, 0.69
Duration of visual signals	6.52	3.01	5.70	3.15	0.26	−0.28, 0.81
Duration of tactile signals	1.31	1.90	1.32	1.88	−0.01	−0.55, 0.54

Note: Values are pooled estimates after multiple imputation. Bayley (Bayley Scales of Infant and Toddler Development, third edition) and WPPSI (Wechsler Preschool and Primary Scale of Intelligence, third edition) scores are standardized with $M = 100$, $SD = 15$. Scores between 90 and 110 indicate average, scores between 80 and 89 indicate low average. Entropy rate ranges between 0 and 2.807 with higher values indicating more unpredictable pattern of maternal sensory signals. Duration of sensory signals is the mean duration in seconds.
Abbreviations: PIQ, performance intelligence quotient; VIQ, verbal intelligence quotient.

3.3 | Unpredictability of maternal sensory signals and Children's cognitive development

We found large negative effects between entropy rate and children's cognitive development at 24 months of age (pooled Pearson's correlation coefficients for cognitive development, $r = -0.38$, 95% CI [−0.60, −0.11] and for

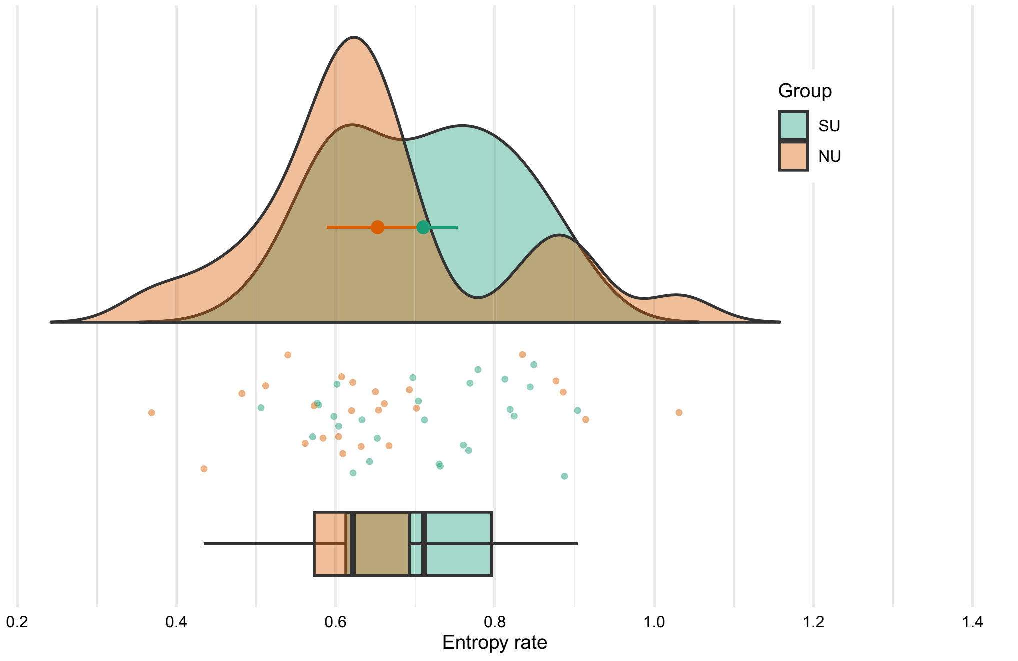

FIGURE 2 Unpredictability of maternal sensory signals (entropy rate) in substance-using and non-using groups. Higher scores indicate more unpredictable patterns of sensory signals. Data distributions are illustrated as the 'clouds' and raw data as the 'rain'. The point and line in the centre of each cloud represents its mean and 95% confidence interval. Box plot on the bottom shows the range of values (whiskers), 25% and 75% quartiles (box), and a median (line dividing the box). Averaged data of multiple imputation is used in the figure. NU, non-using group; SU, substance-using group.

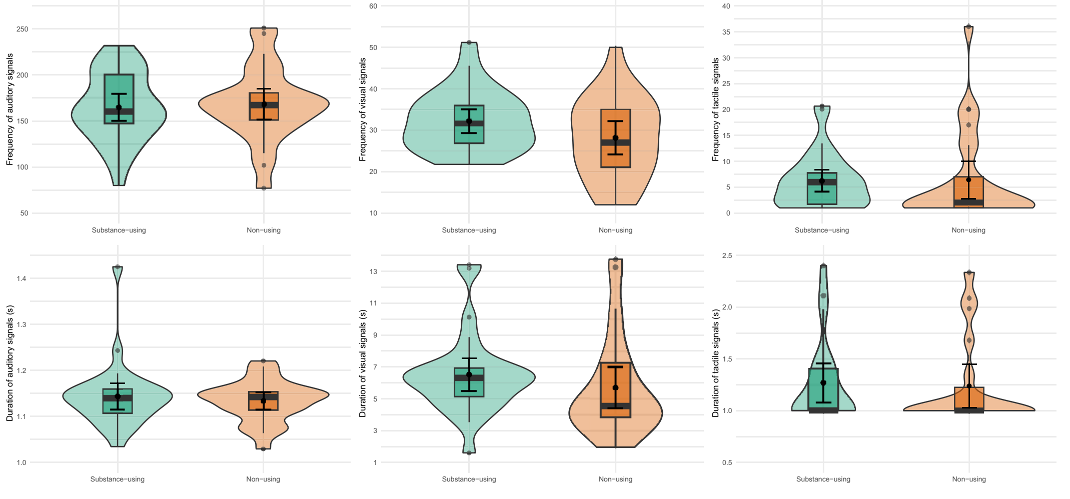

FIGURE 3 Frequency (on the top) and duration (on the bottom) of maternal sensory signals in substance-using and non-using groups. Violin plots show the density of points at different values. Box plots show the range of values (whiskers), 25% and 75% quartiles (box), and a median (line dividing the box). Black dots show the mean and error bars show the 95% confidence interval. The duration of tactile signals ranges from 0 to 9.48, but there are only few values above 2.5, and for clarity, the extreme values are omitted in the figure. Averaged data of multiple imputation are used in the figure.

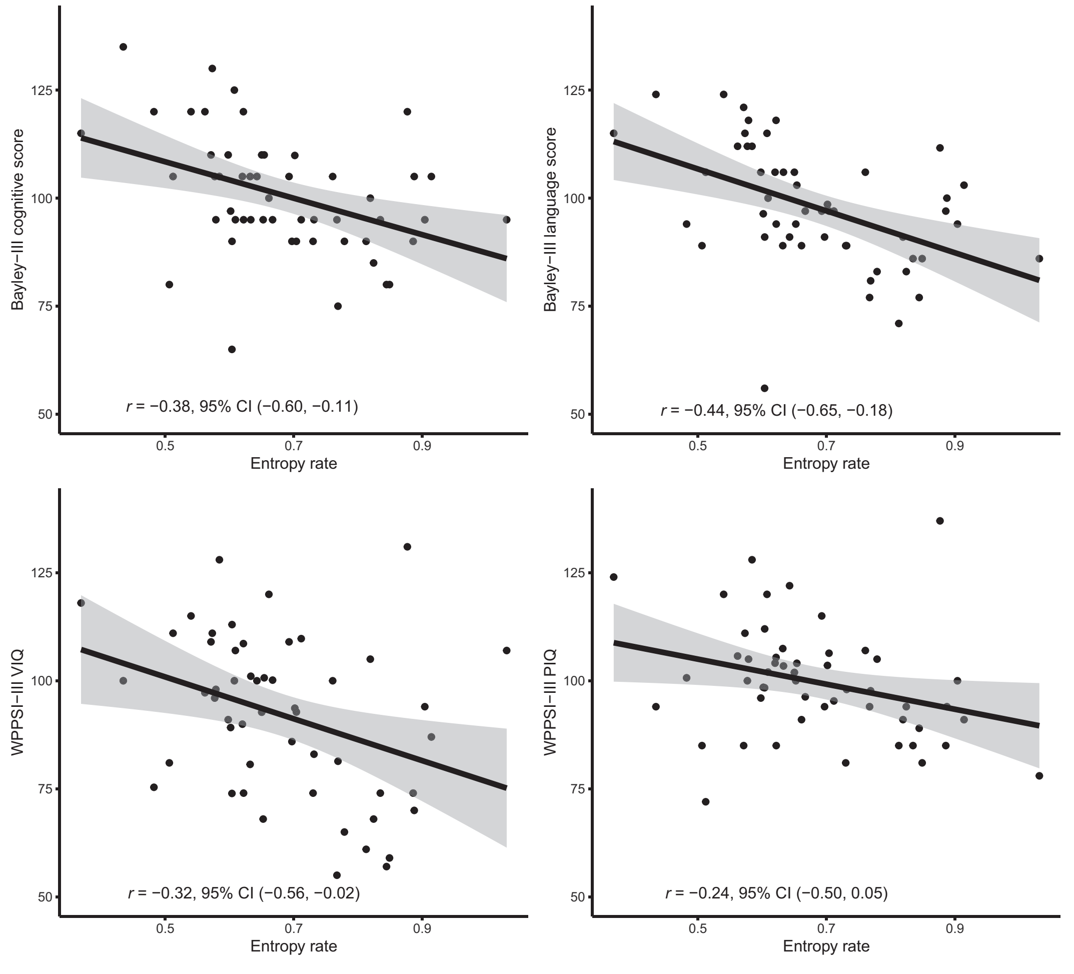

FIGURE 4 Associations between the unpredictability of maternal sensory signals (entropy rate) and children's cognitive development at 24 months of age (Bayley-III cognitive and language scores on the top), and at 48 months of age (WPPSI-III VIQ and WPPSI-III PIQ on the bottom) with 95% confidence interval. Higher scores of entropy rate indicate more unpredictable pattern of maternal sensory signals. Cognitive scores are standardized with $M = 100$ and $SD = 15$, higher scores indicating better cognitive performance. Averaged data of multiple imputation are used in the figure, but correlation coefficients are pooled. Bayley-III, Bayley Scales of Infant and Toddler Development—Third edition; PIQ = performance intelligence quotient; VIQ, verbal intelligence quotient; WPPSI-III, Wechsler Preschool and Primary Scale of Intelligence—Third edition.

language development, $r = -0.44$, 95% CI [−0.65, −0.18]). Children whose mothers showed more unpredictable patterns of sensory signals performed poorer in both cognitive and language tests at 24 months (Figure 4).

At 48 months, we also found a large negative effect between the unpredictability of maternal sensory signals and children's verbal reasoning (pooled $r = -0.32$, 95% CI [−0.56, −0.02]). The effect size was medium concerning children's nonverbal reasoning (pooled $r = -0.24$, 95% CI [−0.50, 0.05]). Thus, children whose mothers showed more unpredictable patterns of sensory signals at children's age of 24 months performed poorer in verbal and non-verbal reasoning tests at 48 months, although results were more uncertain regarding nonverbal tests (Figure 4). The associations remained in the same direction when assessed separately with 40 imputed datasets (Figure S9).

Supplementary analyses yielded similar findings when accounting for the influence of maternal substance use. First, effect sizes between unpredictable maternal sensory signals and children's cognitive development ranged from medium (cognitive development at 24 months and verbal reasoning at 48 months) to large negative (language development at 24 months) when maternal substance use was controlled (Table S4). Association of unpredictable maternal sensory signals with children's nonverbal reasoning at 48 months showed a small negative effect. Thus, the effects between unpredictable maternal sensory signals and children's language development at 24 and 48 months remained in the same magnitude, and the effects between unpredictable maternal sensory signals and children's cognitive development at 24 months and nonverbal development at 48 months diminished when controlling for maternal substance use.

Second, when we evaluated the associations of unpredictable maternal sensory signals and children's cognitive development separately for SU and NU groups, all effects remained negative. However, effect sizes varied from small to large with no clear pattern which group showed larger effects than the other (Table S4, Figure S10). Altogether, the results of supplementary analyses indicate that the relation between higher unpredictable maternal sensory signals and poorer child cognitive development was not clearly affected by maternal substance use.

4 | DISCUSSION

Maternal substance use and unpredictable patterns of their sensory signals are potential risk factors for child neurocognitive development. However, no previous studies have examined their mutual associations and role for child development. In this exploratory study, we assessed the unpredictability, frequency and duration of maternal sensory signals in SU and NU mothers, and the association of unpredictable sensory signals and children's cognitive development. We found that the unpredictability, frequency and duration of maternal sensory signals were of similar magnitude between SU and NU mothers at children's age of 24 months. Nevertheless, we found robust links between unpredictable maternal sensory signals and children's poorer cognitive development at 24 months that persisted, although weakened, to 48 months. When controlling for maternal substance use or evaluating the links separately for SU and NU mothers, the links remained negative varying from small to large in effect size.

We found similar sensory signal unpredictability between SU and NU mothers and identified rates of similar size compared with previous studies (Davis et al., 2017, 2019). The result could indicate that substance use may not be associated with unpredictable maternal sensory signals. Equally, a relation may exist, but our study was not able to identify it due to a small sample size that could detect only medium to large effects or the heterogeneity of SU mothers. Interestingly, our study groups differed in several characteristics (e.g. maternal substance use, socioeconomic status and child psychomotor development) that could have inflicted differences in the unpredictability of sensory signals. There is evidence that maternal mental health and environmental factors, such as income, are associated with unpredictability (Davis et al., 2019; Holmberg et al., 2020). It is plausible that unpredictable parental signals are a pathway by which these characteristics influence developmental outcomes. Future work could further consider how different maternal characteristics are associated with the unpredictability of maternal sensory signals and the mechanisms underlying our findings.

Our study was the first to assess the frequency and duration of maternal sensory signals among SU mothers. Despite previous literature suggesting reduced sensory signals among depressed mothers (Lam-Cassettari & Kohlhoff, 2020; Mantis et al., 2019), we found similar frequency and duration of auditory, visual and tactile signals between SU and NU mothers. These findings provide a basis for following studies that should discern potential fine-grained interaction characteristics distinguishing high- and low-risk mothers.

Last, we observed robust links between higher maternal sensory signal unpredictability and children's poorer cognitive development at 24 months. The links persisted but weakened to 48 months. These findings build on prior studies showing that unpredictability in early caregiving environment is associated with children's cognitive and language development (Davis et al., 2017, 2022; Howland et al., 2021) and that unpredictable patterns of maternal sensory signals may be a form of adversity that impairs children's neurobiological development (Granger et al., 2021; Noroña-Zhou et al., 2020). Although we were unable to assess the moderation of maternal substance use due to sample size, we found that links remained negative, although varied in magnitude, when controlling for maternal substance use or evaluating separately in SU and NU mothers. This suggests that maternal substance use may not affect the association between sensory signal unpredictability and child cognitive development. Future larger sample high-risk studies should replicate our findings to explore whether and how caregiver risks may moderate the association between unpredictable maternal sensory signals and child development.

4.1 | Strengths and limitations

The strength of our study was that we used a novel measure of a fine-grained interaction among high-risk mothers for the first time. Thus, we opened a new research avenue among this high-risk group where mothers and children are especially vulnerable to developmental risks. Clinically, understanding dyadic interaction is important as it is often the core target in interventions for families with maternal substance use (Suchman & DeCoste, 2018). However, the clinical applications of studying maternal sensory signals remain to be uncovered. Another strength was that we measured children's cognitive development longitudinally at two time points (at 24 and 48 months).

The main limitation of our study was the small sample size that allowed us to detect only medium to large effects between the groups. Nevertheless, as the first study of maternal sensory signals among high-risk mothers, we give a starting point for future research. Based on our results, we recommend researchers to collect samples that can detect even small effects ($g = 0.20$) between study groups. Another limitation was that maternal substance use at T2 was very heterogenous and registry information was not available. Substance use was thus evaluated with a self-report, which is prone to bias. Also, not having information concerning maternal substance use at T3 is a limitation. However, heterogeneity is characteristic of SU samples, and as the registry information revealed extensive substance use during pregnancy, the chronic nature of substance use disorders implies that similar patterns were likely to carry on when children were older. On the contrary, most mothers had received extensive psychiatric and substance use treatment, which could have promoted their recovery. This could partially explain the similarities in sensory signals between the groups. It would also have been ideal if all coders had been blind to maternal group status. However, the method used is not very sensitive to subjective evaluations, and blind coders had good agreement with the non-blind coder. Finally, variations in assessment locations (home vs. lab) may have affected our results, although evidence from other methods of parent–child interaction suggest otherwise (Biringen et al., 2014).

5 | CONCLUSION

In the current study we found support for the previous literature and identified robust links between mothers' unpredictable sensory signals and children's poorer cognitive development. This suggests that unpredictability in maternal sensory signals is a potentially vital aspect of caregiving that can shape children's development. However, our study highlights the need for additional research on how maternal substance use and other risk factors are associated with maternal sensory signals and how this contributes to child development. Our study provides a starting point for these investigations.

AUTHOR CONTRIBUTIONS

Noora Hyysalo: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; software; visualization; writing – original draft; writing – review and editing. **Minna Sorsa:** Conceptualization; supervision; writing – review and editing. **Eeva Holmberg:** Resources; writing – review and editing. **Riikka Korja:** Resources; writing – review and editing. **Elysia Poggi Davis:** Writing – review and editing. **Eveliina Mykkänen:** Validation. **Marjo Flykt:** Conceptualization; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

None.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The analysis code is available on Open Science Framework at https://osf.io/mwerc/. The data are not publicly available due to ethical restrictions.

ETHICS STATEMENT

This study obtained an ethical approval from Pirkanmaa Hospital District Ethics Committee.

ORCID

Noora Hyysalo https://orcid.org/0000-0003-4391-8527
Minna Sorsa https://orcid.org/0000-0003-1988-0362
Eeva Holmberg https://orcid.org/0000-0003-0046-3155
Riikka Korja https://orcid.org/0000-0002-6833-1565
Elysia Poggi Davis https://orcid.org/0000-0001-6345-9271
Eveliina Mykkänen https://orcid.org/0009-0002-2209-1444
Marjo Flykt https://orcid.org/0000-0003-0874-4357

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