A dynamic, developmental systems approach to emotional self-regulation in the still-face paradigm reveals effects of preterm birth

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Abstract

Emotional self-regulation involves different systems (such as motor, attentional and cognitive) interacting in time to influence emotional behaviour and physiology. We investigated differences in emotional self-regulation during the still-face paradigm in 111 9-month-old infants (61 term; 50 preterm, <33 weeks of gestation), in the amount of emotional self-regulatory behaviours, as well as the micro-level (obtained using recurrence quantification analysis) and macro-level behavioural dynamics (differences under repeated stress). Preterm birth was associated with fewer repetitive movements, and lower gestational age increased this effect. Unlike that of term-born infants, the behaviour of preterm-born infants changed under repeated stress, leading to fewer object-oriented attentional distraction strategies, fewer repetitive movements, and greater oral-tactile self-comforting strategies. No differences in micro-level behavioural dynamics, or socially-oriented regulatory behaviours were found. Prematurity results in greater regulatory "brakes" on emotional expression with repetitive movements, and emotional self-regulatory capacities may be more vulnerable to the nature of environmental stress.

Keywords: emotion regulation; self-regulation; still-face paradigm; recurrence quantification analysis; emotional development; preterm birth

Statement of relevance

This study investigates an important early-developing ability linked to poorer socioemotional outcomes - emotional self-regulation. We use a combination of traditional methods in the behavioural sciences and novel cross-disciplinary methods from complexity science, and considered the interplay of developing systems on emotional physiology and behaviour. We investigated whether preterm birth affected patterns of emotional self-regulation, including in the context of a repeated stressor. By doing so, we revealed that more intense stress altered preterm-born infants' capacity to self-regulate distress, and preterm-born infants show a more inhibited emotional behavioural response that may be an early indicator of anxiety risk. We demonstrate the potential of multidisciplinary methods within a theoretical framework in developmental psychology, to provide fresh perspectives on an important public health question. Our findings go some way to explaining why preterm born individuals may experience more emotional difficulties than their term-born peers in childhood and adult life.

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Emotional self-regulation is the modulation of neurophysiological and behavioural states related to emotional experience and expression, using self-initiated strategies (Nigg, 2017). It enables individuals to cope with emotions, affecting socioemotional adjustment (Eisenberg et al., 2010) and problems with it are implicated in mental health difficulties (Cludius et al., 2020).

The ability to self-regulate emotions develops substantially within the first year of life (Kopp, 1982), integrating developing systems (Thompson, 2011). Emotional behaviours begin to involve motor object manipulation skills to distract from stress (Ekas et al., 2013; Kopp, 1989); demonstrate awareness of intersubjective relations (Stern, 2018; Trevarthen & Delafield-Butt, 2013); involve greater executive attentional and behavioural control (Rothbart & Derryberry, 1981) and later on, more complex cognitive reappraisal and reasoning (Sala et al., 2014). In sum, emotional regulation increasingly reflects attentional, behavioural and socio-cognitive processes.

The still-face paradigm provides a context in which to study infants' behavioural responses to a stressor in the laboratory (Tronick et al., 1987). In the paradigm, normal playful social interactions between caregiver and infant are disrupted experimentally when the caregiver is instructed to stop interacting, look away, and put on a neutral facial expression (Murray & Trevarthen, 1985). This typically leads to infant distress, and behaviours to regulate distress. Then the caregiver is instructed to respond again in a "reunion" phase and can contribute to regulating infants' emotions. It is a rich paradigm allowing investigation of emotions expressed, strategies used to cope with stress, and the caregiver's behaviour.

Coded behaviours observed during this paradigm have been used to infer whether emotion regulation is disrupted. We can observe whether negative emotions have been dealt with effectively (by looking at the amount of negative emotion expressed) and whether self-regulatory behaviours are used (amount and type of behaviours). These are complementary approaches, as emotion and its regulation are inherently intertwined and influence each other dynamically (Kappas, 2011), so neither on its own provides a complete picture of emotion regulation. However, dichotomising behaviours into those that reflect emotional expression, and those that reflect regulation is at odds with the same theoretical rationale. Additionally, characterising observed motor activity is difficult because the same movement can be an expression of affect (Chiodelli et al., 2021), but may also be a regulatory strategy (Ekas et al., 2013).

A developing systems approach can advance the study of infant emotion regulation (Thompson, 2011). In this view, emotional self-regulation is not a modular cognitive skill that infants gain, but the result of complex interactions between developing systems (Karmiloff-Smith, 2018; Whitall et al., 2020). It enables consideration of the range of strategies that infants use in response to distress, including not just early-occurring oral-tactile ("self-comforting") strategies, but attentional, motor stimulatory and social-seeking strategies that develop later (Atkinson et al., 2021; Ekas et al., 2013; Moore et al., 2001; Rothbart et al., 1992; Shapiro et al., 1998; Toda & Fogel, 1993). Behaviours are seen as the result of interacting processes involved in expressing or regulating emotions.

This study considers the behaviours elicited by the still-face paradigm from a developing systems approach, to investigate whether preterm birth affects emotional self-regulation. Preterm birth, birth before 37 weeks of gestation (World Health Organisation, 2018), is associated with greater rates of socioemotional difficulties relative to term-born peers (Allotey et al., 2018; Peralta-Carcelen et al., 2017). Early emotional difficulties are important to understand as they predict later problems and psychiatric outcomes (Arpi & Ferrari, 2013; Compas et al., 2017)

The evidence on emotional self-regulatory differences due to preterm birth is far from conclusive. Researchers have consistently reported an absence of differences between preterm-born and term-born infants in gaze aversion at two to six months old (Hsu & Jeng, 2008; Jean & Stack, 2012; Yaari et al., 2018). However, at three months old, fewer object-manipulation strategies were observed in preterm-born infants relative to term-peers, but no differences at six to nine months old. No differences in self-comforting behaviours, or social gaze and social-seeking behaviours were observed by six to nine months old, but the pattern of differences were contradictory earlier in infancy (Atkinson et al., 2021; Chiodelli et al., 2021; Jean & Stack, 2012; Montirosso, Borgatti, et al., 2010). Only one study has looked at the effect of preterm birth on motor activity when under distress in the still-face paradigm, and did not find an effect at three to four months old (Chiodelli et al., 2021).

Additionally, we sought to employ a time-based analysis of behaviour. We build on research previously identifying an effect of preterm birth on behavioural change between phases of the still-face paradigm (Chiodelli et al., 2021; Yaari et al., 2018), by investigating whether a repeated stressor (Haley & Stansbury, 2003), leading to more intense or prolonged stress, may affect emotional self-regulation. We conceptualised this as a macro-dynamic change. Additionally, we quantify micro-level behavioural dynamics using recurrence quantification analysis (RQA) (Marwan et al., 2007). RQA characterises recurrences to the same behavioural state in time to capture a systems' dynamic organisation (Webber & Zbilut, 1994, 2005), compatible with the view that nonlinear dynamic interactions between developing systems are the building blocks of emotional self-regulatory abilities. This builds on recent advances in quantifying temporal information in the still-face paradigm (De Graag et al., 2012; Montirosso, Riccardi, et al., 2010; Provenzi et al., 2015), and research suggesting that micro-level behavioural dynamics captured by entropy could indicate developmental risk (Bisi & Stagni, 2018; Goldberger et al., 2002).

To summarise, this study investigates the effect of preterm birth on emotional self-regulation, including (1) the amount of different types of emotional self-regulatory behaviours, (2) micro-level behavioural dynamics (i.e., second-to-second unfolding of behavioural patterns) and (3) macro-level behavioural dynamics (i.e., changes in amount of behaviours and micro-level behavioural dynamics due to a repeated stressor).

Method

Participants

The study sample was drawn from the Theirworld Edinburgh Birth Cohort Study, comprising caregiver-infant dyads of term-born (>37 weeks of gestation) and preterm-born infants (≤32 weeks of gestation age). Infants with overt parenchymal brain injuries were excluded. Caregiver-infant dyads were included if they participated in their 9-month (corrected age for preterm-born infants) follow-up appointment before March 2021. Ethical approval was obtained from the National Research Ethics Service (NRES), South East Scotland Research Ethics Committee, and NHS Lothian Research and Development Committee. Participants were recruited at the Simpson Centre for Reproductive Health and parents provided written informed consent (see Boardman et al., (2020) for full study protocol).

Infants were included in this analysis if they met the following criteria: (1) completing at least one still-face phase; (2) analysable video data (SF phases excluded from analysis if more than 15% obstruction of view leading to estimated or unscorable codes) (3) data representative of the still-face perturbation. To apply this last criterion, data from SF phases containing violations of still-face procedure were excluded; with violations defined as disruptive interruptions during the still-face phase, or when the caregiver continues to interact with the infant.

Procedure

Still-face paradigm

Infants and their caregivers took part in the extended modification of the still-face paradigm with five 2-minute phases (Haley & Stansbury, 2003), beginning with an initial play interaction and then alternating with still-face episodes, in an A-B-A-B-A structure (Figure 1; modified from Tronick et al., 1987). Parents sat face-to-face with the infant seated in a high chair and were instructed to play as they usually do with the infant, without toys. The experimenter was hidden behind a partition screen. At transitions between phases, parents were told to “switch” between normal play interactions, or adopting a still-face (i.e., stop responding or looking at the infant and holding a neutral expression). Parents were able to stop the experiment early if they or the infant were too distressed. The infant and caregiver’s facial expression and behaviour were video-recorded using two Panasonic HC-W580 video cameras, directed at each of their faces.

Figure 1. The still-face phases in the still-face paradigm

Episode 1: Play

Episode 2: SF1

Episode 3: R1

Episode 4: SF2

Episode 5: R2

There were some experimental variations in the still-face procedure, including caregiver participating in the interaction, early termination of experiment, presence of objects other than the infant chair (e.g., soother, toys, sensors), and interruptions by the experimenter. Apart from interruptions, experimental variations were not systematically related to one group or the other (see Supplemental Table 1). Phases which contained interruptions were assessed qualitatively and excluded if it constituted a violation of the still-face procedure (see

Supplemental Table 2). Of note, we did not exclude experimental variations due to objects. This was because we considered object-oriented behaviours to serve an emotion regulation function and were interested in infants' behavioural preferences, and the variations were not systematically different between groups, so were unlikely to confound the results. Excluding these infants would also severely reduce the sample size.

Observational coding of infant behaviour

An observational coding scheme was developed to identify behaviours based on their function. Guided by a review of the targets of emotion regulation (e.g. attentional systems and bodily expression) (Koole, 2009), self-regulatory behaviours were defined in five categories – oral-tactile self-comforting, attentional distraction via object manipulation, social interactive, motor stimulatory, and distancing. It integrates earlier coding schemes that have defined behaviours that infants use during the still-face paradigm. The definitions of each category of self-regulatory behaviours were made after considering the developmental importance of a range of behaviours considered in previous coding schemes. Importantly, the definition of object-oriented behaviours focus on the active manipulation of objects (not just attending to objects) as this supports the development of attention (Brandes-Aitken et al., 2019; Kochanska et al., 2000). We also included developmentally important tactile stimulatory and midline behaviours (e.g. foot-bracing) (Begum Ali et al., 2020; Bigsby et al., 1996) in our definition of self-comforting behaviours. This coding scheme captures emotional self-regulatory behaviours under the assumption that they occur in the context of emotional distress and are self-initiated, subject to modification by top-down activation or inhibitory processes.

Only data from the two still-face phases were analysed, as this is when the caregiver is unresponsive and infants' have to rely on their own abilities to regulate any distress. Behaviours were coded second-by-second using ELAN (Version 5.9) and Microsoft Excel

(Version 16, 2018) by YWC. A second coder, LJ-S, was trained by YWC to code the full range of behaviours. Training proceeded until 90% agreement and greater than 0.70 kappa was achieved. LJ-S then coded 10% of randomly selected videos (11 videos, 22 still-face phases), achieving a reliability score of 78.5% agreement and 0.70 mean kappa (Chua, 2022).

Chromatic auto-recurrence quantification analysis

Following observational coding, each 120s timeseries comprising infants' self-regulatory behaviours during a still-face phase (see Figure 2) was analysed for behavioural dynamics using Chromatic-RQA (Cox et al., 2016; Xu et al., 2020). RQA characterises dynamics of a time series using recurrences, which describe the revisiting of a previous state in time. Recurrences are plotted graphically in a recurrence plot (Figure 3). Measures can then be obtained to quantify the graphical patterns in a recurrence plot, including specific to recurrences of emotional self-regulatory (ER states) (Figure 4). Detailed procedures for conducting chromatic RQA, including details on specifying parameter settings, are provided in the supplemental material (Section 1.1).

Figure 2. Example of a categorical timeseries of behavioural response during the 120s of the first still-face phase (120 – 240s of the whole still-face paradigm)

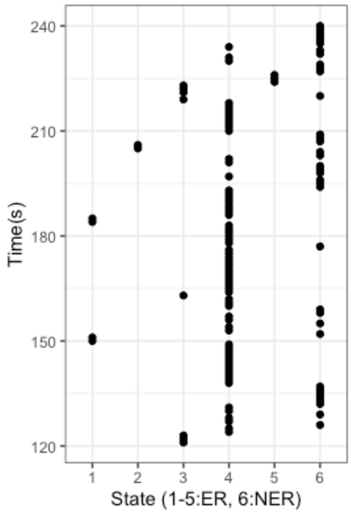
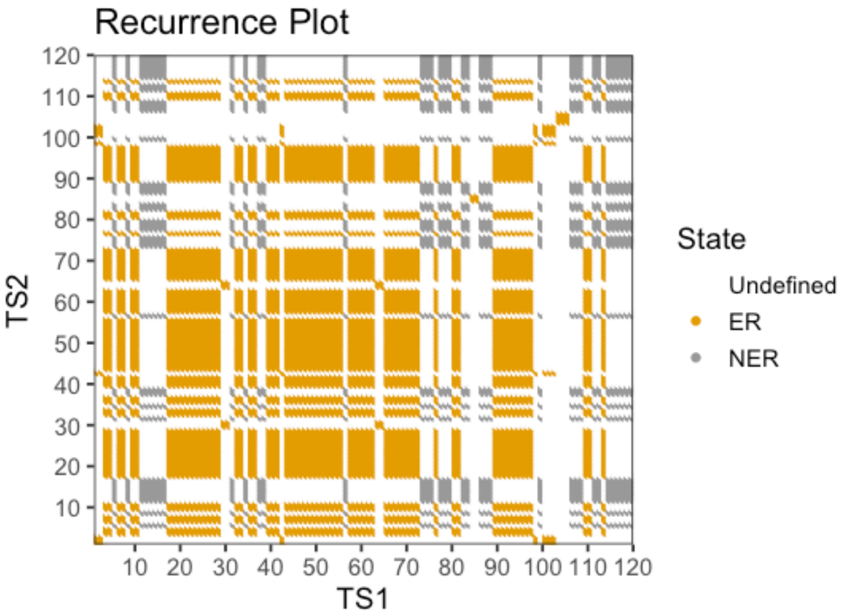


Figure 3. Simplified chromatic state space. States 1 to 5 correspond to ER states as defined in the video coding scheme (SC, SOC, OBJ, RME and DIST). State 6 corresponds to Non-ER

states (MOV: Undefined/Other movement). Recurrences of States 1 to 5 later in time were considered an ER recurrence (coded in Orange). Recurrences of State 6 were considered a non-ER recurrence (coded in Grey). White spaces represent undefined recurrences, not of interest to the present study.

	1	2	3	4	5	6
1	ER					
2		ER				
3			ER			
4				ER		
5					ER	
6						NER

Figure 4. Example of a recurrence plot. Orange dots represent recurrences of ER states, while grey dots represent recurrences of non-ER states.



Study design

A repeated-measures, between-subject design was used to examine the effect of preterm birth and the effecet of a repeated stressor on emotional self-regulation.

Exposure

Preterm birth was assessed using a binary measure of gestational age (preterm: <33 weeks gestational age; term-born controls >=37 weeks gestational age). The dose-response effect of preterm birth was assessed using gestational age in weeks. Birthweight Z-scores were used to assess the effect of fetal-growth restriction in both groups, which impacts emotional outcomes (Sacchi et al., 2021), and is often comorbid with preterm birth (Zeitlin et al., 2000).

Outcomes

Emotional self-regulation behavioural type. Proportion of time, out of 120s, spent in each observationally coded ER behavioural state (self-comforting, social interactive/monitor, object exploration/distraction, repetitive movement and distancing) were analysed. The total proportion of time spent in any of the 5 ER behavioural states was also analysed. Table 1 outlines the operational definitions of these behaviours and Figure 5 shows some examples.

Table 1. Operational definitions of the Function of Movement and Behaviour Phases video coding scheme

Behavioural state	Operational definition
1. Self-comforting (SC)	The function of infant's movement is to obtain oral or tactile stimulation. Infants is using own body to provide oral self-stimulation, exploring manipulating objects on self, or touching their own body, for 1s or longer. Examples: mouthing hand/objects, manipulating clothing, clasping hands, bracing feet or touching head. Note: Oral-behaviours related to soother use, was not coded
2. Object exploration/distraction (OBJ)	The function of infant's movement is to provide attentional distraction by exploring the perceptual properties of objects. Infant is reaching towards and/or using fine motor behaviours to move towards and/or manipulate objects not on self, for 1s or longer. Infants' gaze must be directed towards the object. Examples: playing with chair belt, exploring chair surface

3. Social interaction/monitor (SOC)	The function of infant's movement is to engage in or solicit social interaction. Infant is attending to the caregiver's face for 1s or longer, or using gestures or motor behaviours containing social interactive intention. Social interactive intention is defined as (a) infant-initiated arm movements, such as reaching, which must result in increased proximity or touch of any part of the caregiver, and (b) gestures or behaviours with social meaning. Examples: reaching towards caregiver, clapping, pointing
4. Repetitive movement (RME)	The function of infant's movement is to provide motor self-stimulation. Infant is using repetitive movements of the torso, arms or legs, defined by an identical pattern of flexion, extension, rotation, abduction, adduction or elevation in all possible directions, at least two times consecutively within a 3 second or smaller window. Examples: banging, leg kicking, body rocking, arm waving, clapping (clapping is assigned two behavioural functions)
5. Distancing (DIST)	The function of infant's movement is to increase their physical distance from the caregiver. Infant is trying to escape or get away from the caregiver by twisting, turning away from the caregiver, without engaging an object, for 1s or longer.
6. Other or no apparent emotional regulation behaviours (MOV)	The function of infant's movement for emotion regulation is not apparent. Infant is not moving or is engaging in motor activity that cannot be described by other emotion regulatory function.

Figure 5. Examples of ER behaviours

Emotional self-regulation microlevel behavioural dynamics. Measures of microlevel behavioural dynamics specific to ER behavioural states, obtained from Chromatic-RQA, were analysed. Here we provide both the mathematical definition and the contextual interpretation when applied to behaviours in the still-face paradigm. Recurrence rate (RR) is defined as the overall percentage of recurrent points in the recurrence plot (the extent that infants repeat a behaviour). Laminarity (LAM) is the percentage of recurrent points forming vertical lines in the recurrence plot (when behaviours occur, whether they tend to occur briefly, or for a substantial amount of time – defined as 3 seconds or longer in this study). Low laminarity means that the recurrence plot contains relatively more single recurrent points (or short periods of recurrence), than vertical lines (‘*laminar* states’) that indicate periods of stability. Trapping time (TT) is the average length of vertical lines, indexing the average time spent in a stable state (the average time that bouts of behaviours occur for). Entropy (ENTb) was the average amount of Shannon information in the rectangular block structures present in the RP (Leonardi, 2018), and represents the complexity in the temporal patterns in which ER behaviours occurred (whether infants use bouts of behaviours lasting specific lengths of time, or a mix of bouts of varying lengths). These measures capture the repetition of states, and the stability and flexibility of state shifts in the dynamic system. We would expect a well-regulated infant to show high recurrence rate (suggesting that behaviours that have occurred are useful for emotion regulation and hence are used again), laminarity (suggesting that these behaviours are stable and can persist for a sufficient length of time to have an effect on emotion), entropy (suggesting that behaviours are used in a flexible manner over time, rather than in the same patterns), and a moderate trapping time (behaviours persisting for stable periods of time, but do not persist for extensive periods which may suggest that the behaviour is not flexible to change).

Other variables. Proportion of time spent expressing negative affect was obtained as an additional descriptor of behavioural data, which had previously been observationally coded (reported in Ginnell et al., 2022) using the Infant and Caregiver Engagement Phases, revised Heidelberg version (Reck et al., 2009; Weinberg & Tronick, 1999).

Statistical analyses

All statistical analyses were performed in R (version 4.02), on RStudio (version 1.1). Pre-processing and analysis scripts are available on the Open Science Framework (see Open Practices Statement section)

Descriptive statistics

Median and IQR of all still-face negative affect and amount of emotional self-regulatory behaviours in SF1 and SF2 were obtained. Wilcoxon rank sum tests were run to describe the difference in negative affect between groups in SF1 and SF2, and difference between SF1 and SF2 in each group. Due to non-normality of all measures of interest but the total ER behavioural response (assessed using the Shapiro-Wilk test), non-parametric Spearman rank correlation coefficients were obtained to describe the relationship between negative affect with total ER behaviours, ER behavioural categories and ER behavioural dynamics, separately for SF1 and SF2.

Multivariate analyses

Linear mixed-effect models (*lme4* R package; Bates et al., 2015) were conducted with still-face phase and preterm birth (MODELS A), gestational age (MODELS B) or birthweight Z-score (MODELS C) as predictors of ER behaviours and behavioural dynamics, and preterm birth, gestational age and birthweight as predictors of total ER behaviours (MODELS D). Random intercepts were included to account for the correlated measurements in SF1 and SF2 within the same participant. Gestational age was centred at 33 weeks of gestation. As the effect of gestational age is potentially non-linear across preterm and full-term gestational ages, we further investigated gestational age and still-face phase as a predictor of emotion regulation separately in term (MODEL B1) and preterm (MODEL B2) groups. Gestational age and preterm birth were not considered in the same model, as the two predictors are not independent. To address our hypotheses, we tested for the significance of fixed effects of the exposure of interest (preterm birth, gestational age or birthweight), still-face phase (and interaction effect with the exposure where present). Details on model building and diagnostics are provided in the Supplemental material (Section 1.2).

Further analyses

Descriptive statistics showed that the overall behavioural response was highly correlated with all measures of behavioural dynamics. As such, we investigated the relationship between preterm birth, gestational age and birthweight Z-score on the total ER behaviours (MODEL D), which will indicate if findings related to dynamics are specific to the temporal structure of the behavioural response, and not simply the amount of ER behaviours used.

We further assessed whether measures of the micro-level dynamics obtained from RQA could describe meaningful processes involved in producing emotion regulation, and not just a result of random processes (see Supplemental material, Section 1.3). Surrogate analyses were conducted using *casnet* (R package Version 0.2.2) (Hasselman et al., 2022) and test the null-hypothesis that the temporal patterns of emotion regulation (described by RQA measures) were produced by a Gaussian process.

To examine the possibility that missing data in SF2 contributed to the effect of SF phase identified in MODELS B, we compared emotion regulation behaviours of infants with missing SF2 data and those who completed both SF1 and SF2. Wilcoxon rank-sum tests were run separately for preterm and term groups.

Post-hoc analyses

MODELS B identified different effects of SF phase in the preterm and term groups on behavioural type, suggesting that main effects estimated in MODELS A may be misleading if we did not include an interaction effect between SF phase and Group. Therefore, in post-hoc analyses we included the interaction effect in MODELS A, and conducted planned contrast analysis (Schad et al., 2020) to identify simple main effects of SF phase and preterm birth on amount of each behavioural type. As this was a novel exploratory approach to emotional self-regulation and the contrasts examined a priori hypotheses, we did not correct for multiple comparisons.

Power sensitivity analyses

Sample size was determined by the timeframe and resources feasible for 9-month follow-up data collection for this study. Power sensitivity analyses was conducted to guide interpretation of whether non-significant results could be false negatives (see Supplemental material, Section 1.4) (Lakens, 2022).

Open practices statement

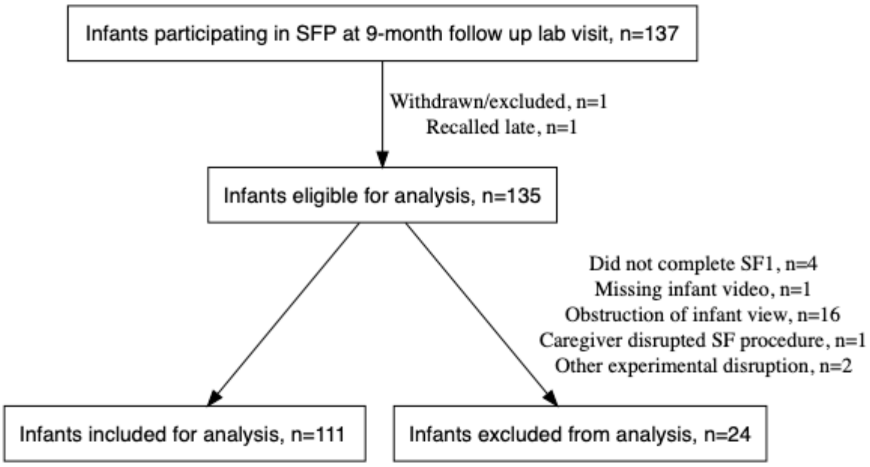
This study was not preregistered. The observational coding scheme is detailed in the Supplemental Material (Section 3). Data is available on request with the TEBC (www.tebc.ed.ac.uk). All scripts for pre-processing data, conducting RQA analysis and statistical analyses are openly available on https://osf.io/k2mvu/?view_only=03bd9ccc880a487a9bc84bc74bac92f5.

Results

Sample characteristics

137 infants took part in the still-face paradigm at the 9-month follow up visit. One infant withdrew from the study and one was recalled late. 24 infants (12 term, 12 preterm) were excluded due to non-analysable data or violations of the still-face procedure. A Chi-squared test did not reveal differences between term and preterm groups in the proportion followed up who were included or excluded from analysis ($\chi2(1)=1.83$, $p=0.176$). Figure 6 shows the inclusion and exclusion criteria applied to derive the analysis sample.

Figure 6. Flowchart showing definition of the analytic sample. Other experimental disruption includes experimental variations (different chair and experimenter not behind screen) that affected infants' behaviour in the still-face phase.



One hundred and eleven infants made up the analysis sample. Table 2 describes the sample characteristics of the analytic sample, grouped by term and preterm birth status. Sixty-one infants were born at term age (mean=39 weeks, SD=1, 51% male) and 50 infants were born before 33 weeks of gestation (mean=29 weeks, SD =2, 58% female). Six infants were part of three twin pairs. Infants were predominantly from White European ancestry and from higher socioeconomic backgrounds representative of Edinburgh, Scotland, based on the Scottish Index of Multiple Deprivation (SIMD), a measure of neighbourhood deprivation

(Ene et al., 2019). One hundred and one infants participated with their mother, nine with their father, and three with their grandmother. Nineteen infants (17.1%, 12 term and 7 preterm) completed only one still-face episode.

Table 2. Sample characteristics. Numbers and percentages are provided for categorical variables and means and standard deviation for continuous variables.

Infant characteristic	Term, N = 61[1]	Preterm, N = 50[1]
Age at visit (months)	9.03 (0.40)	8.96 (0.56)
Gestation (weeks)	39 (1)	29 (2)
Birthweight (g)	3,562 (461)	1,330 (381)
Birthweight Z-score	0.66 (0.98)	0.03 (0.82)
Sex		
Male	31 (51%)	29 (58%)
Female	30 (49%)	21 (42%)
Ethnicity		
Any White background	53 (91%)	46 (92%)
Any Mixed background	4 (6.9%)	3 (6.0%)
Any Asian background	1 (1.7%)	1 (2.0%)
SIMD (quintile)		
5	26 (43%)	14 (29%)
4	16 (27%)	14 (29%)
3	10 (17%)	6 (12%)
2	6 (10%)	10 (20%)

Infant characteristic	Term, N = 61[1]	Preterm, N = 50[1]
1	2 (3.3%)	5 (10%)
Singleton		
Singleton pregnancy	60 (98%)	36 (72%)
Multiple pregnancy	1 (1.6%)	14 (28%)
Height (cm)	72.6 (3.6)	71.4 (3.4)
Weight (kg)	9.24 (1.16)	8.64 (1.13)

Descriptive statistics

Table 3 shows infants' behavioural response during SF1 and SF2, expressed as proportion of time. The term group showed more negative affect compared to the preterm group in SF1 (W = 1786, p=0.013), but not in SF2 (W=1044, p=0.536). Both groups show an increase in negative affect from SF1 to SF2 (Term: W=1017, p=0.002; Preterm: W=465, p<0.001), in line with the effect of a repeated stressor. Distancing behaviours were rare, and as such we did not proceed in analysing this behavioural category.

Table 4 shows correlations between emotional self-regulatory behaviours and negative affect. All dynamic measures were highly correlated with total ER (see Table 5).

Table 3. Descriptive statistics of behaviours during the still-face phases

	SF1		SF2	
Characteristic	Term, N = 61[1]	Preterm, N = 50[1]	Term, N = 52[1]	Preterm, N = 43[1]
Negative affect[2]	0.16 (0.00, 0.39)	0.00 (0.00, 0.16)	0.58 (0.11, 0.75)	0.36 (0.06, 0.76)

	SF1		SF2	
Characteristic	Term, N = 61[1]	Preterm, N = 50[1]	Term, N = 52[1]	Preterm, N = 43[1]
Total ER	0.54 (0.44, 0.66)	0.56 (0.38, 0.67)	0.52 (0.42, 0.67)	0.54 (0.43, 0.67)
SC	0.15 (0.08, 0.30)	0.16 (0.07, 0.28)	0.17 (0.07, 0.31)	0.18 (0.09, 0.33)
SOC	0.05 (0.03, 0.12)	0.08 (0.03, 0.14)	0.05 (0.03, 0.10)	0.07 (0.05, 0.12)
OBJ	0.07 (0.01, 0.13)	0.10 (0.05, 0.22)	0.03 (0.00, 0.15)	0.07 (0.00, 0.14)
RME	0.24 (0.16, 0.36)	0.17 (0.07, 0.36)	0.21 (0.12, 0.36)	0.13 (0.08, 0.32)
DIST	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)

[1] Median (IQR)

[2] Four preterm-born infants (not included in Ginnell and colleagues' (2021) study) did not have data on negative affect.

Table 4. Spearman rank sum correlation coefficients between negative affect with ER behaviours, and with ER behavioural dynamics.

	Negative Affect	
	SF1, Rho	SF2, Rho
ER behavioural type		
Total ER	-0.01	-0.28***
SC	0.13	0.09
SOC	*0.16*$^{\#}$	0.00
OBJ	-0.41***	-0.40***
RME	-0.13	-0.24*

DIST	0.20^{*}	0.27^{*}
ER behavioural dynamics		
RR	0.01	-0.22^{*}
ENTb	-0.12	-0.24^{*}
LAM	-0.20^{*}	-0.24^{*}
TT	-0.14	-0.23^{*}

*# p<0.1   * p<0.05   ** p<0.01   *** p<0.001*

Table 5. Moderate and strong Spearman rank sum correlations between the Total ER response with each measure of behavioural dynamics in SF1 and SF2.

	Total ER	
	SF1, Rho	SF2, Rho
ER behavioural dynamics		
RR	0.924^{***}	0.904^{***}
ENTb	0.368^{***}	0.499^{***}
LAM	0.655^{***}	0.750^{***}
TT	0.416^{***}	0.536^{***}

**** p<0.001*

Main analyses

Figures 7 and 8 shows the results of MODELS A. Figure 9 shows the results of MODELS B. Tables 6 and 7 show the results of MODELS B in the preterm group. All other model results are presented in Supplemental Tables 3-8. In post-hoc analyses, interaction effects between preterm birth and SF phase were included in MODELS A of behavioural type, and simple main effects (effect of preterm birth at each level of SF phase and vice versa) obtained (see Table 8 and Supplemental Table 10). The confidence intervals may be wider than estimated as a result of violation of homogeneity of variance (Schielzeth et al., 2020) for OBJ, and RQA measures with the exception of ENTb (see Supplemental methods).

Figure 7. MODELS A – effect of preterm birth and still-face phase on behavioural type (including interaction effect) Marginal effects (i.e., effect of preterm birth or SF phase with

the other held constant) with standard errors, overlaid on violin plots and scatterplots of observed data.

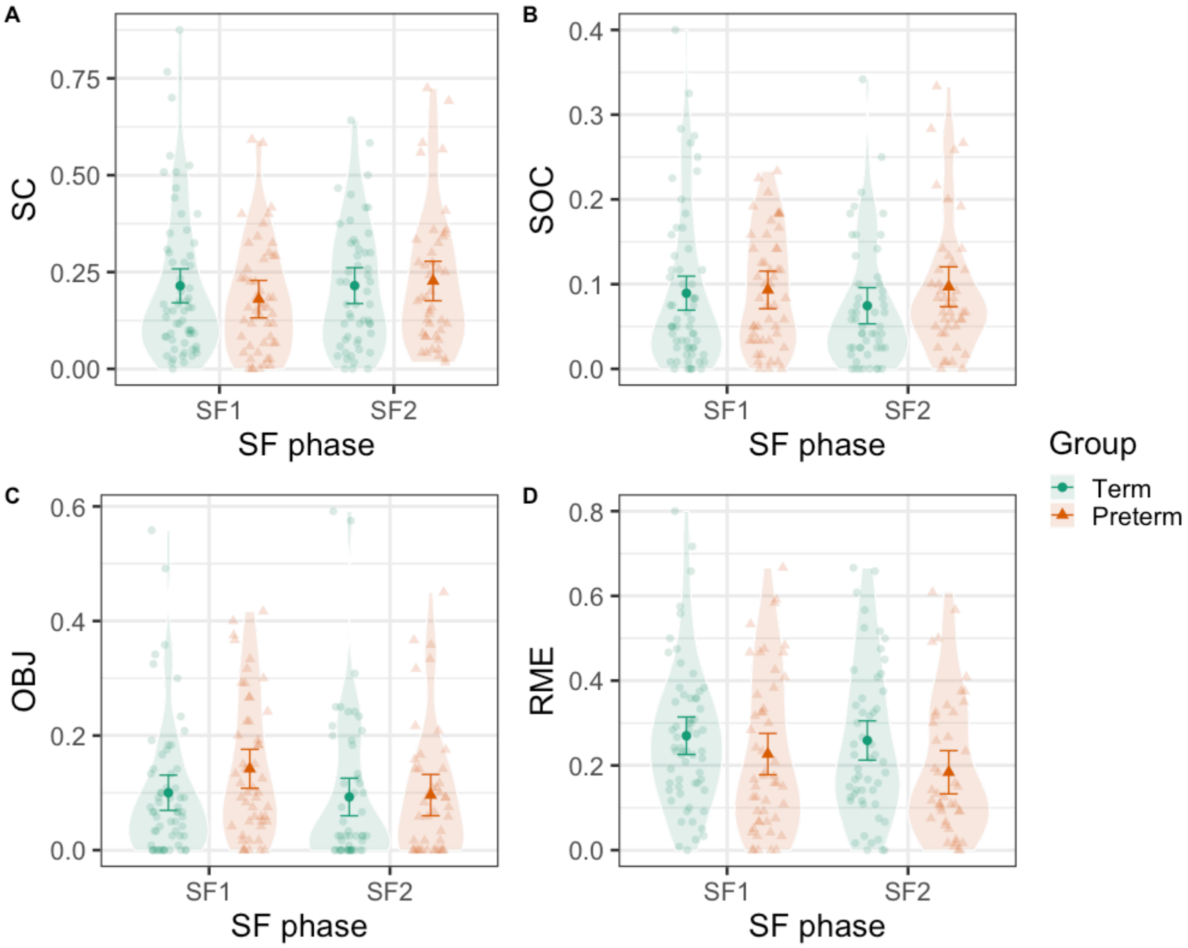


Figure 8. MODELS A – effect of preterm birth and still-face phase on behavioural dynamics (no interaction effect). Marginal effects (i.e., effect of preterm birth or SF phase with the other held constant) with standard errors, overlaid on violin plots and scatterplots of observed data.

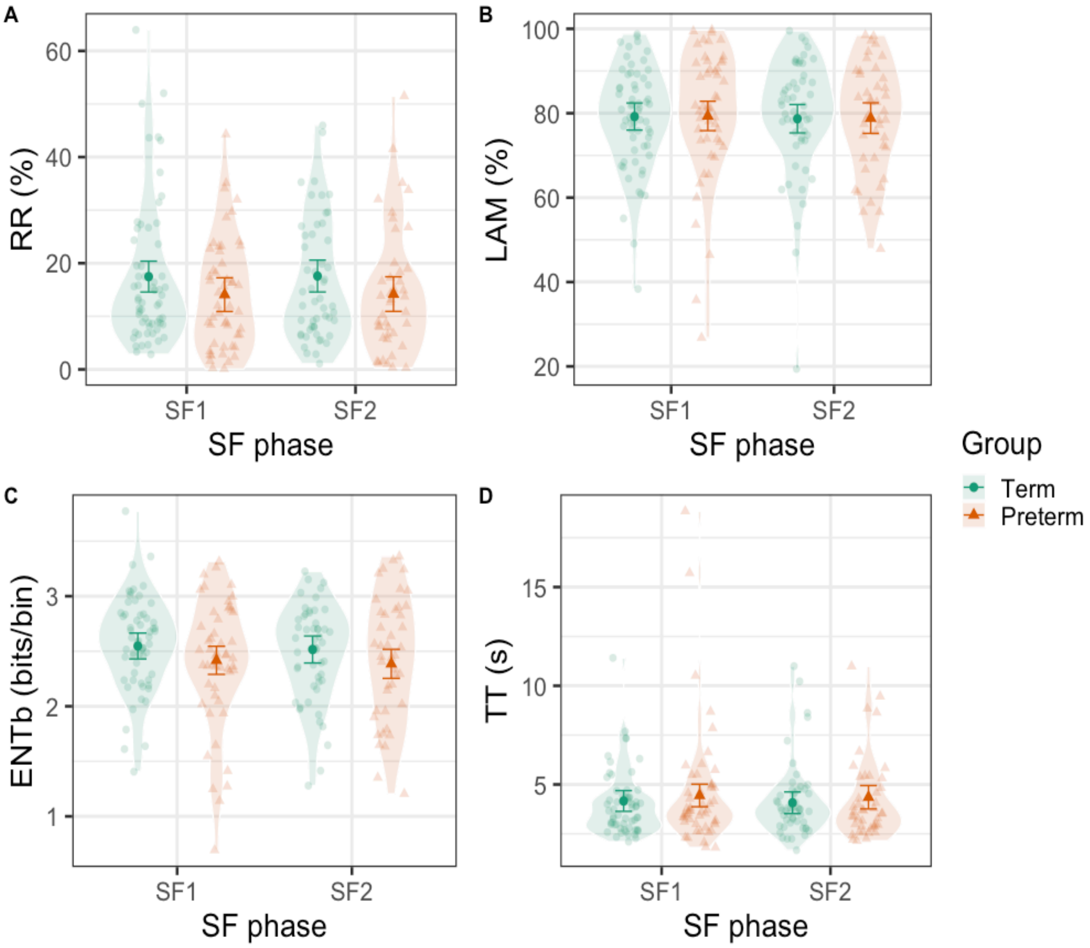


Figure 9. MODELS B, modelled for preterm and term group separately, marginal effects of gestational age and SF phase on ER behavioural type), overlaid on observed data.

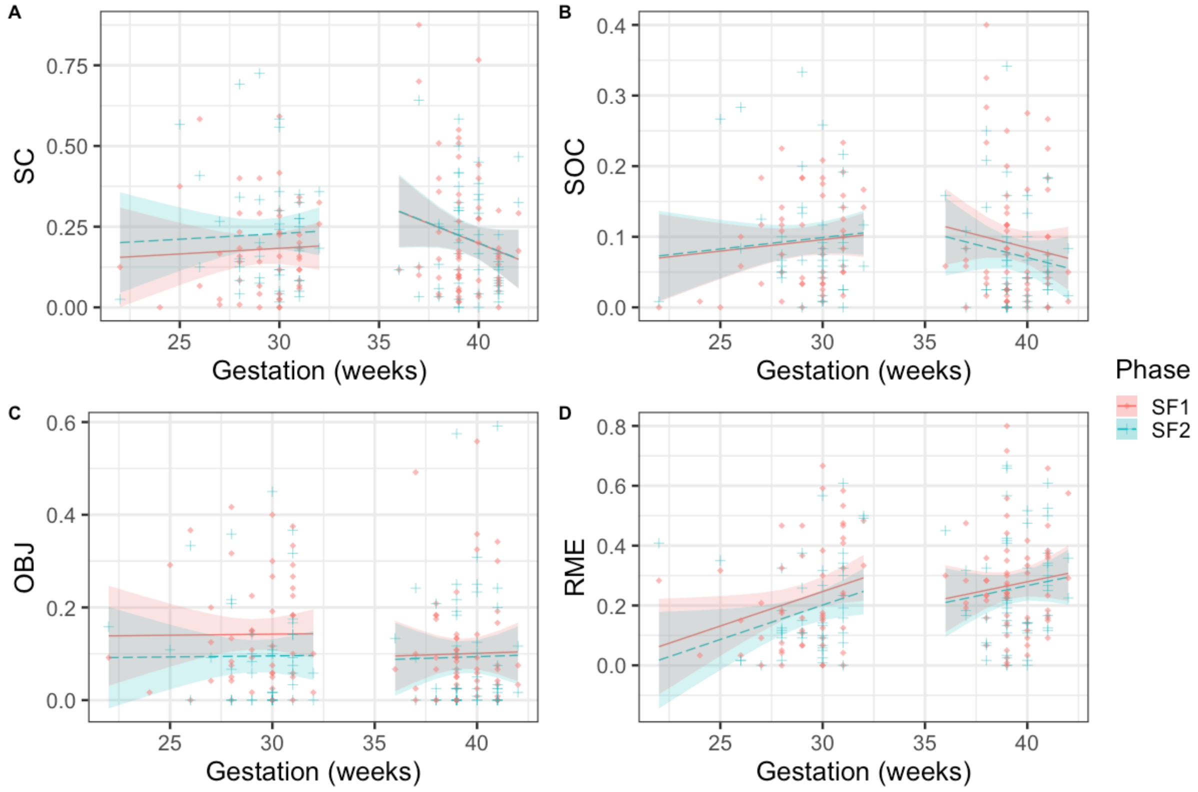


Table 6. MODELS B (preterm). Effects of gestational age and SF phase on ER behavioural type

	SC	SOC	OBJ	RME
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	0.155 (0.001 – 0.309)	0.070 * (0.008 – 0.132)	0.139 * (0.031 – 0.247)	0.062 (-0.097 – 0.222)
SF [Ref: SF1]	0.046 * (0.010 – 0.082)	0.003 (-0.022 – 0.028)	-0.047 ** (-0.080 – -0.013)	-0.045 * (-0.081 – -0.009)
Gestation [weeks]	0.004 (-0.017 – 0.024)	0.003 (-0.005 – 0.012)	0.000 (-0.014 – 0.015)	0.023 * (0.002 – 0.044)

Random effects				
σ^2	0.01	0.00	0.01	0.01
τ_{00}	0.02 ID	0.00 ID	0.01 ID	0.02 ID
ICC	0.72	0.34	0.53	0.73
Marginal R^2 / Conditional R^2	0.022 / 0.723	0.048 / 0.368	0.038 / 0.549	0.084 / 0.750

N=50, Observations=93

*# $p<0.1$ * $p<0.05$ ** $p<0.01$ *** $p<0.001$*

Table 7. MODELS B (preterm). Effects of gestational age and SF phase on ER behavioural dynamics

	RR	LAM	ENTb	TT
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	7.382 (-2.774 – 17.538)	68.199 *** (56.655 – 79.743)	1.534 *** (0.994 – 2.074)	3.773 ** (1.410 – 6.137)
SF2 [Ref: SF1]	-0.124 (-2.834 – 2.586)	-1.574 (-6.770 – 3.622)	0.007 (-0.166 – 0.179)	-0.495 (-1.316 – 0.326)
Gestation [weeks]	0.946 (-0.414 – 2.305)	1.625 * (0.101 – 3.149)	0.085 * (0.021 – 0.150)	0.118 (-0.196 – 0.433)
Random effects				
σ^2	78.03	110.17	0.13	1.80
τ_{00}	83.08 ID	60.41 ID	0.05 ID	1.30 ID
ICC	0.52	0.35	0.29	0.42

Marginal R^2 / Conditional R^2	0.003 / 0.517	0.022 / 0.368	0.015 / 0.2§97	0.009 / 0.426

N=50, Observations=93

\# $p<0.1$ * $p<0.05$ ** $p<0.01$ *** $p<0.001$

Table 8. Post-hoc analyses of simple main effects. Effect of SF phase and Preterm birth at each level of the other factor, on emotion regulation behavioural type

	SC Difference (SE)	SOC Difference (SE)	OBJ Difference (SE)	RME Difference (SE)
Contrasts of SF2 – SF1 [Ref] at level of preterm birth				
Term	0.00 (0.02)	-0.01 (0.01)	-0.01 (0.02)	-0.01 (0.02)
Preterm	0.05# (0.02)	0.00 (0.01)	-0.05* (0.02)	-0.04* (0.02)
Contrasts of Preterm – Term [Ref] at level of SF phase				
SF1	-0.03 (0.03)	0.00 (0.02)	0.04# (0.02)	-0.04 (0.03)
SF2	0.01 (0.03)	0.00 (0.02)	0.00 (0.02)	-0.08* (0.03)

\# $p_{adj}<0.1$, * $p_{adj}<0.05$, **$p_{adj}<0.01$, ***$p_{adj}<0.001$

Preterm birth leads to differences in macro-level behavioural dynamics (SF1 vs SF2) but not micro-level behavioural dynamics (RQA measures)

The SF phase effect on behavioural type was present in the preterm group only. The preterm group showed approximately 5% increase in SC (p=0.016), decrease in OBJ (p=0.009) and RME (p=0.019) from SF1 to SF2, independent of the effect of gestational age (MODELS B; see Table 6). Effects of SF phase were not detected in the term group (MODELS B; see Supplemental Tables 5 and 6). Post-hoc analyses of MODELS A also showed effects of SF phase in the preterm group only, with increases from SF1 to SF2 in SC (p= 0.054), decreases in OBJ (p= 0.017) and RME (p=0.049) (Table 8). No effect of SF phase on micro-level dynamics was found in either group.

Preterm birth and gestational age lead to differences in repetitive behaviours, but not in other behavioural type or in micro-level behavioural dynamics

Preterm birth and gestational age were associated with lower RME: there was lower RME in the preterm compared to the term group (MODELS A; Effect: -0.057, 95% CI -0.118 – 0.004, p=0.068) and lower gestational age was associated with lower RME (p=0.040) in the preterm group only (MODELS B; see Table 6 and 7). There were no associations of preterm birth or gestational age with other behavioural types or micro-level dynamics. In post-hoc analyses, strong evidence of group differences in RME was identified in SF2 (p=0.033) but not SF1 (p=0.196), attributable to the decrease in RME in SF2 for preterm-born but not term-born infants. There was some evidence of greater OBJ in the preterm group in SF1, but this was not present in SF2 (see Table 8). Gestational age was not associated with LAM and ENTb after removing the influence of extreme values (Effect on LAM: 1.31% 95% CI -0.25 – 2.88, p=0.105; Effect on ENTb: 0.06 bits/bin, 95% CI -0.01 – 0.12, p=0.087).

No evidence of birthweight Z-score effect on emotional self-regulation

Birthweight Z-score led to a non-significant increase in ENTb (Effect: 0.075, 95% CI -0.008 – 0.159, p=0.081) and no other effects (MODELS C; see Supplemental Table 7-8 and Supplemental Figures 5-6).

Further analyses

1. There was no evidence of effects of preterm birth or gestational age on total ER behaviours (MODELS D). See Supplemental Table 9 and Supplemental Figures 7-10.

2. Microlevel dynamics in ER behavioural data were not simply due to random Gaussian processes. The null hypothesis that the value of TT and LAM came from a Gaussian process was rejected in 100% of infants, for both SF1 and SF2. For ENTb, this was 97.5% for SF1, and 97.1% for SF2.

3. Missing data in SF2 due to early termination did not explain findings on behavioural dynamics (change between SF1 and SF2). Preterm-born infants who did not complete SF2 showed lower OBJ and RME in SF1 (see Table 9). This would result in greater average OBJ and RME in the SF2 sample if these missing data were the sole influence of the differences between SF1 and SF2. On the contrary, we found lower OBJ and RME in SF2 relative to SF1. It is therefore unlikely that missing data influenced these findings on behavioural dynamics.

Table 9. Behavioural type by infants who completed SF2 and infants whose experiment terminated early, without taking part in SF2, separately obtained for preterm and term groups. Median, IQR and p-values from Wilcoxon rank sum test testing the effect of early termination without SF2.

	Preterm			Term		
	SF2 available N = 43[1]	SF2 missing N = 7[1]	p-value[2]	SF2 available N = 49[1]	SF2 missing N = 12[1]	p-value[2]
SC	0.16 (0.07, 0.25)	0.16 (0.02, 0.30)	0.748	0.16 (0.08, 0.29)	0.15 (0.08, 0.40)	0.870
SOC	0.08 (0.03, 0.14)	0.13 (0.08, 0.18)	0.263	0.05 (0.03, 0.12)	0.07 (0.02, 0.13)	0.764
OBJ	0.13 (0.06, 0.25)	0.02 (0.01, 0.05)	0.004	0.07 (0.03, 0.13)	0.10 (0.00, 0.14)	0.763
RME	0.18 (0.11, 0.40)	0.07 (0.04, 0.09)	0.016	0.23 (0.15, 0.36)	0.25 (0.18, 0.29)	0.821

[1] *Median (IQR)*

[2] *Wilcoxon rank sum test*

Power sensitivity analyses

Results of power sensitivity simulation analyses are presented in Supplemental Table 11A and 11B. MODELS A for behavioural outcomes were not sensitive at 80% power to detect small interaction effects but were sensitive to main effects of preterm birth and SF phase as small as 1%. This suggests the non-significant interaction effects of preterm birth and SF phase were likely false negatives, as different effects of SF phase in each group (and vice-versa) were detected in contrasts analyses and in MODELS B.

Discussion

We approached emotional self-regulation from a dynamic and developmental systems lens, considering amounts of different emotional self-regulatory behaviours, and micro-level and macro-level behavioural dynamics. We provide novel evidence that compared to their term peers, preterm-born infants regulate emotions differently in response to prolonged, intense stress: term-born infants did not show self-regulatory behavioural changes, whereas preterm-born infants shifted from initially higher levels of attentional distraction (OBJ) and repetitive movements (RME) to greater oral-tactile self-comforting (SC). Preterm birth was associated with fewer repetitive movements, attributable to risks associated with a lower gestational age. There was no compelling evidence that preterm birth disrupted micro-level behavioural dynamics.

To correct for prematurity, preterm-born infants were followed up at older chronological ages. Repetitive movements in emotional contexts may decrease after 1 year of age (Rothbart et al., 1992). Nevertheless, timing of developmental follow-up is unlikely to explain the association of lower gestational age on greater repetitive movements – in this sample, motor skills was not associated with repetitive movements, and in fact higher daily living skills was associated with fewer repetitive movement (Chua, 2022).

Our findings are consistent with previous works showing that preterm-birth does not affect emotional self-regulation in the domains of attentional behaviours and oral-tactile self-comforting around the age of six to nine months old (see Introduction). However, differences in the latter behaviours may be present in younger infants (Chiodelli et al., 2021; Fuertes et al., 2022; Provenzi et al., 2017). Differences in dyadic, socially-oriented strategies identified in older infants (Evrard et al., 2011) are also important to understand further as these increase only after the first year of life, and are predicted by greater self-comforting at 6 months (Atkinson et al., 2021).

Insights on emotional self-regulation in preterm birth

While attentional distraction and oral-tactile self-soothing are effective in lowering negative affect (Ekas et al., 2013; Gennis et al., 2022; Stifter & Braungart, 1995), the former requires effortful control (Stifter & Braungart, 1995) which is protective for emotional development in preterm birth (Burnson et al., 2013; Eisenberg et al., 2009; Witt et al., 2014). Indeed, greater attentional strategies correlated with lower negative affect in SF1, and greater sustained attention is associated with lower fear (Langerock et al., 2013). However, effortful strategies may tax cognitive resources (Muraven & Baumeister, 2000; Oeri & Roebers, 2020) and implicate behavioural regulation (Caporaso & Marcovitch, 2021). Our findings show that more persistent and intense environmental stress influences effortful control capacity in preterm-born infants, similar to findings that preterm-born infants show decreasing attention alongside increasing (less-effortful) self-comforting strategies over time (Langerock et al., 2013). Consideration of environmental factors may be needed in understanding the emotional development of preterm-born infants, over whether emotional capacities are disrupted.

Our group has previously identified a dampened affective behavioural response despite high cortisol stress in preterm-born infants, suggesting an apparent decoupling of physiological arousal and its behavioural manifestation (Ginnell et al., 2022). The finding on repetitive behaviours, thought to indicate physiological arousal (Feldman, 2009) and carry emotional expression (Chiodelli et al., 2021), contributes another piece to the puzzle. However, motor activity is not a siloed process of emotional expression - research on the behavioural manifestation of negative reactive temperament highlights the involvement of regulatory mechanisms. Negatively reactive infants use more motor activity when faced with novel or fearful stimuli. This changes to inhibited, withdrawn behaviour by childhood (Pérez-Edgar & Guyer, 2014) due to behavioural inhibition, a reactive, involuntary aspect of emotion regulation (Eisenberg et al., 2013; Hendry et al., 2022). Rather than a simple biobehavioural decoupling, automatic self-regulatory mechanisms, may similarly be at play to dampen emotional expression with repetitive movements. Behavioural inhibition is a reliable early risk factor for anxiety (Pérez-Edgar & Guyer, 2014) and preterm-born infants are at risk of anxiety (Fitzallen et al., 2021). High stress reactivity coupled with high behavioural regulation, producing a dampened affective *and* behavioural emotional expression, may reflect an early identifiable biobehavioural profile for anxiety in preterm birth.

In essence, executive attention and behavioural inhibition, traditionally considered in the cognitive domain, are implicated in the emotional self-regulatory behaviour of preterm-born infants. This echoes evidence of an infant preterm phenotype, characterised by consistent differences in domain-general cognitive processes, attributable to diffuse white matter injury (Back & Miller, 2014; Boardman et al., 2010; Dean et al., 2021). Promoting upstream pathways in the Neonatal Intensive Care Unit that shape early brain development, such as improving nutrition and preventing infections, may be critical for improving developmental outcomes.

Strengths, limitations and future directions

Future research can consider particular aspects of emotional self-regulation as outcome measures. Mechanistic and intervention research on preterm birth can focus on the differences here.

More research is needed on emotion regulation in more vulnerable subgroups within the preterm population. One study identified that extreme prematurity influenced oral-tactile self-comforting, attentional and socially-oriented emotional self-regulatory strategies (Maclean et al., 2009), warranting further investigation as our sample had relatively few extremely preterm infants. Social deprivation can worsen the effect of preterm birth (Boardman & Counsell, 2020) and affect brain development including in the cohort studied here (Mckinnon et al., 2023), though this was outside the scope of our study.

Our preliminary findings are grounded in in the theory of complex dynamical systems, but examining micro-level behavioural dynamics is a recent and novel approach. Dynamic measures of infant affect map onto a single factor (Sravish et al., 2013); similarly our RQA measures of emotional self-regulation correlated with negative affect and with each other. While further validation work is needed to draw implications, micro-level dynamical approaches provide the means to empirically test other theories in emotional regulation and developmental psychology. For example, behavioural reciprocity is an important developmental basis for social understanding (McGowan & Delafield-Butt, 2022) and RQA can examine the cross-system dynamics of dyadic regulation (Lira-Palma et al., 2018; Main et al., 2016).

Conclusions

A dynamic, developmental systems approach can advance the empirical study of emotional self-regulation. Preterm birth resulted in greater regulatory “brakes” on emotional expression with repetitive movements and the emotional self-regulatory behaviours of preterm-born infants was susceptible to a repeated stressor, leading to fewer attentional strategies, fewer repetitive movements and greater self-comforting at 9 months old. Preterm birth did not affect socially-oriented behaviours or micro-level behavioural dynamics.

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Author contributions

Conceptualisation: YWC (lead), JDB; Conceptualisation – TEBC: SFW, JPB; Methodology – behavioural coding: YWC (lead), LJS (coding scheme validation), Methodology – RQA: YWC (lead), RC; Methodology – Still-face paradigm: SFW, LG; Methodology – TEBC: SFW, JPB; Software: YWC; Formal analysis: YWC; Investigation – TEBC: VL, LG, SO, YWC; Data Curation: YWC, LG (negative affect data); Visualisation: YWC; Project administration – TEBC: JH, SFW, JPB; Writing – Original Draft: YWC; Writing – Review & Editing: YWC, LJS, LG, VL, RC, JPB, SFW, JDB; Supervision: JDB; Funding acquisition: YWC, JDB; Funding acquisition – TEBC: SFW, JPB

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Supplemental material

Contents

1. Supplemental methods

1.1. Chromatic auto-RQA

In auto-RQA, the timeseries is compared against itself and a recurrence plot is produced by plotting all the times (on the x-axis) where the system's state matches itself at another time (on the y-axis), or vice versa. This produces repeating patterns of different lengths along the diagonal, horizontal and vertical lines (Webber & Zbilut, 2005). Chromatic RQA is a modification of the RQA algorithm to distinguish different types of recurrent states of interest to the researcher (Xu et al., 2020) and involves colour-coding of each recurrence in the RP according to a chromatic state space (Figure 3).

Categorical behavioural timeseries show a characteristic pattern in the recurrence plot, checkerboard-like patterns formed of rectangular structures (Leonardi, 2018). Therefore, the measures selected for this study were related to the vertical structures in the recurrence plot (or, equivalently, horizontal structures, as the recurrence plot is symmetric when a timeseries is plotted against itself).

Auto-RQA depends on a reconstruction of the state space by embedding a time-delayed replica of the original timeseries against itself, if continuous data is used. With categorical data, the state space is already defined by the pre-defined categories; therefore, reconstructing the state space is not necessary. In this case, the behavioural states that were observationally coded defines the behavioural states infants visit during distress. The free parameters normally required by RQA algorithms, delay d and embedding dimension m, take the value of 1, indicating that the original unembedded timeseries were used.

The final parameter, radius r normally specifies how close to points are in the state space to be counted as a recurrence. Chromatic RQA, is a modification of the RQA algorithm to distinguish different types of recurrent states of interest to the researcher (Xu et al., 2020). Recurrence was defined as a match of the exact category of self-regulatory behaviour later (Figure 5-3). As infants may show two behaviours concurrently, partial match of either one of the behaviours at another point in time was considered a recurrence. This is represented in the full chromatic state space in Supplemental Figure 10. Following colour-coding of each recurrence in the RP, measures relating to different types of recurrence could then be computed separately. This enabled us to obtain dynamics specific to recurrences of emotional self-regulatory (ER) behavioural states.

1.2. Model building and diagnostics

Correlated data from twins were initially accounted for by considering twins as clustered within a family. Due to low percentage of twin pairs relative to the total number of clusters (N=3, 2.7%), this model with two random effects did not converge. Models were run subsequently assuming each infant's data was independent (Sauzet et al., 2013). Interaction effects between prematurity and still-face phase were included in models only if it reached statistical significance at the 95% confidence level, following a step-down strategy (Zuur et al., 2009). Influence diagnostics and regression assumptions of normality and homogeneity of variance were checked (see Supplemental Material).

Cook's distance, obtained using *influence.ME* (R package Version 0.9-9) was used to examine the sensitivity of model estimates when omitting one or more influential data points. No interaction effects between gestational age and still-face phase were identified following influence diagnostics (see Supplemental figures 1 and 2). Regression assumptions of normality and homogeneity of variance were checked respectively, by visually inspecting q-q plots and plots of residuals against fitted values. The variance of residuals appears to be smaller when LAM was high, and larger only at the largest values of RR and TT, indicating greater noise in using observational coding in identifying these extreme values. OBJ appeared to show a slight fanning out pattern of residuals (see Supplemental methods and Supplemental Figures 9-13). As mixed-effect models are robust to violations including homogeneity of residual variance, we did not apply a transformation as this would affect the interpretability of the model (Schielzeth et al., 2020).

The variance was smaller only when the proportion of ER behaviours was very low. Majority of residuals fall on the line, roughly within the expected distribution of a normally distributed sample. Relatively few deviations were observed and only at the ends of the distribution (2-3 SD) suggesting that some of the distributions were slightly skewed. Where present, a linear trend in residuals suggests that the effect estimate of preterm birth, gestational age or birthweight may be biased (i.e., a linear effect was modelled when there is none) - however we include this in our models as they are used to test the hypothesis of prematurity on emotion regulation. Crucially, no assumptions were violated in Model B for RME, where we identified an effect of gestational age on RME. (see Supplemental Figures 9-13).

1.3. Surrogate analyses

Surrogate analysis is approached via "constrained realisation". In other words, surrogate timeseries were generated from the original data in a way that matches the sampling distribution, other than the characteristic being tested (Theiler et al., 1992). Random shuffling of the original data produces timeseries of the same total behavioural response and recurrence rate, but destroys the temporal order within the original timeseries. 100 surrogate timeseries were generated and chr-RQA applied to each timeseries. This generates an approximation of the distribution of values expected from a Gaussian process. The null hypothesis that the value of each behavioural dynamics from the original timeseries came from a Gaussian process was then tested using the *casnet* package, presently available in its development version; Hasselman et al., 2022). *Casnet* obtains the rank order probability for the true value (obtained from the original timeseries). A confidence level is applied to determine if the null hypothesis should be rejected, for example at a 0.01 alpha significance level indicates that the original data led to a value more extreme than the end of the surrogate distribution. As three hypothesis tests were conducted for each timeseries (for TT, ENTb and LAM), Bonferroni correction was applied for three tests at the 0.05 alpha level, leading to rejection of the null hypothesis at alpha<0.017.

1.4. Power sensitivity analyses

We used the R package *simr* (version 1.0.5) (Green & MacLeod., 2016) to simulate the power for a range of unstandardized interaction and main effect sizes, and identified the smallest effect sizes that our sample had close to 80% power to detect. Data from Yaari and colleagues (2018) guided our selection of the range of unstandardised effect sizes (1-10%) for power simulations of behavioural outcomes.

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2. Supplemental Tables

Supplemental Table 1. Experimental variations of the still-face paradigm. Experimental characteristics of the still-face procedure were tabulated by group, and chi squared tests were run to provide an indicator of whether experimental inconsistencies may be important for group differences.

Still-face experiment characteristics	**Term, N = 61**[1]	**Preterm, N = 50**[1]	**p-value**[2]
Caregiver			0.262
Mother	57 (93%)	42 (84%)	
Father	3 (4.9%)	6 (12%)	
Grandmother	1 (1.6%)	2 (4.0%)	
Partial camera obstruction of infant view	10 (16%)	14 (28%)	0.139
Early termination of experiment	12 (20%)	7 (14%)	0.430
Toy present	6 (9.8%)	3 (6.0%)	0.688
Soother present	2 (3.3%)	5 (10%)	0.510
Interruption	**0 (0%)**	**5 (10%)**	**0.017**
Experimental protocol			0.688
Latest protocol (New infant chair, with experimenter behind screen)	57 (93%)	48 (96%)	
Old protocol (different chair or experimenter not behind screen)	4 (6.6%)	2 (4.0%)	
Sensors present	11 (18%)	12 (24%)	0.440

Still-face experiment characteristics	**Term, N = 61**[1]	**Preterm, N = 50**[1]	**p-value**[2]

[1]n (%) [2]Pearsons Chi-squared test

Supplemental Table 2. Details of interruption during SFP

Reasons for interruption	**Phases included/excluded**
Researcher interrupts briefly in SF1 to check if mum wants to stop	Not excluded as SF procedure not disrupted
Mum and experimenter discuss stopping in SF2	SF2 excluded, considered a SF violation due to significant disruption during the episode
Mum clarifies with experimenter about SF procedure in first approximately 10s of SF1	Not excluded as SF procedure not disrupted subsequently
Mum and researcher discuss stopping ~20s before end of R2	Not excluded as SF episodes not affected
Mum' phone rang around 30s before end of SF2	SF2 excluded, disruption of SF procedure and early termination of the episode

Supplemental Table 3. MODELS A – effect of prematurity on ER behavioural type

	SC	SOC	OBJ	RME
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	0.205 *** (0.163 – 0.247)	0.086 *** (0.067 – 0.105)	0.108 *** (0.079 – 0.137)	0.276 *** (0.234 – 0.319)
SF2 [Ref: SF1]	0.021 (-0.011 – 0.053)	-0.006 (-0.022 – 0.010)	-0.025# (-0.050 – 0.001)	-0.025# (-0.054 – 0.003)
Preterm [Ref: Term]	-0.014 (-0.073 – 0.045)	0.012 (-0.014 – 0.038)	0.025 (-0.015 – 0.065)	-0.057 (-0.118 – 0.004)
Random effects				
σ^2	0.01	0.00	0.01	0.01
τ_{00}	0.02 $_{\text{ID}}$	0.00 $_{\text{ID}}$	0.01 $_{\text{ID}}$	0.02 $_{\text{ID}}$
ICC	0.57	0.48	0.45	0.66
Marginal R^2 / Conditional R^2	0.005 / 0.576	0.007 / 0.488	0.020 / 0.457	0.031 / 0.673

N=111, Observations=206
*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Supplemental Table 4. MODELS A – effect of prematurity on ER dynamics

	RR	LAM	ENTb	TT
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	17.483 *** (14.580 – 20.386)	79.207 *** (75.999 – 82.415)	2.547 *** (2.430 – 2.665)	4.164 *** (3.639 – 4.690)
SF2 [Ref: SF1]	0.101 (-2.097 – 2.299)	-0.515 (-3.738 – 2.708)	-0.032 (-0.141 – 0.078)	-0.091 (-0.563 – 0.382)
Preterm [Ref: Term]	-3.394 (-7.471 – 0.683)	0.142 (-4.119 – 4.403)	-0.130 (-0.289 – 0.029)	0.280 (-0.438 – 0.997)
Random effects				
σ^2	61.63	135.37	0.16	2.88
τ_{00}	84.48 $_{\text{ID}}$	55.58 $_{\text{ID}}$	0.09 $_{\text{ID}}$	2.09 $_{\text{ID}}$
ICC	0.58	0.29	0.38	0.42
Marginal R^2 / Conditional R^2	0.019 / 0.586	0.000 / 0.291	0.018 / 0.391	0.004 / 0.423

N=111, Observations=206

*# $p<0.1$ * $p<0.05$ ** $p<0.01$ *** $p<0.001$*

Supplemental Table 5. MODELS B (term) – effect of birthweight Z-score on ER behavioural type in term-born infants

	SC	SOC	OBJ	RME
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	0.272 *** (0.189 – 0.355)	0.107 *** (0.066 – 0.147)	0.097 ** (0.039 – 0.154)	0.237 *** (0.152 – 0.321)
SF [Ref: SF1]	0.001 (-0.049 – 0.051)	-0.014 (-0.034 – 0.006)	-0.007 (-0.044 – 0.029)	-0.013 (-0.055 – 0.030)
Gestation [weeks]	-0.025 (-0.055 – 0.005)	-0.007 (-0.022 – 0.007)	0.001 (-0.019 – 0.022)	0.014 (-0.017 – 0.045)
Random effects				
σ^2	0.02	0.00	0.01	0.01
τ_{00}	0.01 $_{\text{ID}}$	0.00 $_{\text{ID}}$	0.01 $_{\text{ID}}$	0.02 $_{\text{ID}}$
ICC	0.45	0.61	0.40	0.59
Marginal R^2 / Conditional R^2	0.032 / 0.463	0.021 / 0.621	0.001 / 0.401	0.012 / 0.598

N=61, Observations=113

*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Supplemental Table 6. MODELS B (term) – effect of birthweight Z-score on ER behavioural dynamics in term-born infants

	RR	**LAM**	**ENTb**	**TT**
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	18.686 *** (12.664 – 24.709)	75.344 *** (69.368 – 81.320)	2.499 *** (2.307 – 2.691)	3.804 *** (2.986 – 4.622)
SF [Ref: SF1]	0.101 (-3.237 – 3.440)	0.171 (-3.772 – 4.114)	-0.078 (-0.213 – 0.057)	0.222 (-0.283 – 0.726)
Gestation [weeks]	-0.529 (-2.709 – 1.652)	1.489 (-0.642 – 3.621)	0.029 (-0.039 – 0.097)	0.093 (-0.201 – 0.387)
Random effects				
σ^2	78.03	110.17	0.13	1.80
τ_{00}	83.08 $_{ID}$	60.41 $_{ID}$	0.05 $_{ID}$	1.30 $_{ID}$
ICC	0.52	0.35	0.29	0.42
Marginal R^2 / Conditional R^2	0.003 / 0.517	0.022 / 0.368	0.015 / 0.297	0.009 / 0.426

N=61, Observations=113
*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Supplemental Table 7. MODELS C – effect of birthweight Z-score on ER behavioural type

	SC	SOC	OBJ	RME
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	0.198 *** (0.163 – 0.233)	0.094 *** (0.078 – 0.110)	0.125 *** (0.100 – 0.149)	0.243 *** (0.208 – 0.279)
SF [Ref: SF1]	0.023 (-0.009 – 0.055)	-0.007 (-0.023 – 0.010)	-0.026# (-0.051 – -0.000)	-0.027# (-0.056 – 0.002)
Birthweight Z-score	0.004 (-0.027 – 0.035)	-0.006 (-0.020 – 0.008)	-0.015 (-0.036 – 0.006)	0.018 (-0.014 – 0.051)
Random effects				
σ^2	0.01	0.00	0.01	0.01
τ_{00}	0.02 $_{ID}$	0.00 $_{ID}$	0.01 $_{ID}$	0.02 $_{ID}$
ICC	0.57	0.48	0.45	0.67
Marginal R^2 / Conditional R^2	0.005 / 0.575	0.007 / 0.483	0.023 / 0.460	0.015 / 0.674

N=111, Observations=206
*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Supplemental Table 8. MODELS C – effect of birthweight Z-score on ER behavioural dynamics

	RR	**LAM**	**ENTb**	**TT**
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	15.649 *** (13.224 – 18.075)	78.744 *** (76.046 – 81.441)	2.462 *** (2.363 – 2.561)	4.209 *** (3.768 – 4.650)
SF2 [Ref: SF1]	0.033 (-2.189 – 2.256)	-0.421 (-3.670 – 2.828)	-0.032 (-0.143 – 0.078)	-0.086 (-0.561 – 0.389)
Birthweight Z-score	0.969 (-1.202 – 3.141)	1.716 (-0.508 – 3.939)	0.075# (-0.008 – 0.159)	0.253 (-0.125 – 0.632)
Random effects				
σ^2	62.34	136.35	0.16	2.88
τ_{00}	86.57 ID	51.47 ID	0.09 ID	2.08 ID
ICC	0.58	0.27	0.37	0.42
Marginal R^2 / Conditional R^2	0.006 / 0.584	0.014 / 0.284	0.021 / 0.386	0.012 / 0.426

N=111, Observations=206

*# p<0.1 * p<0.05 ** p<0.01 *** p<0.001*

Supplemental Table 9. MODELS D – effect of preterm birth, gestational age and birthweight Z-score on Total ER behaviours

	Total ER	Total ER	Total ER (Term)	Total ER (Preterm)
Fixed effects	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**	**Beta (95% CI)**
(Intercept)	0.567 *** (0.522 – 0.612)	0.549 *** (0.512 – 0.586)	0.579 *** (0.501 – 0.657)	0.291 ** (0.093 – 0.490)
SF [Ref: SF1]	-0.018 (-0.052 – 0.015)	-0.018 (-0.052 – 0.015)	-0.020 (-0.067 – 0.027)	-0.022 (-0.068 – 0.023)
Preterm [Ref: Term]	-0.037 (-0.100 – 0.026)			
Birthweight Z-score		0.009 (-0.022 – 0.041)		
Gestation [weeks]			-0.005 (-0.033 – 0.023)	0.024# (-0.001 – 0.050)
Random effects				
σ^2	0.01	0.01	0.02	0.01
τ_{00}	0.02 $_{ID}$	0.02 $_{ID}$	0.01 $_{ID}$	0.03 $_{ID}$
ICC	0.59	0.59	0.44	0.70
Marginal R^2 / Conditional R^2	0.012 / 0.592	0.004 / 0.588	0.006 / 0.439	0.058 / 0.720
N, Observations	111 $_{ID}$, 206	111 $_{ID}$, 206	61 $_{ID}$, 113	50$_{ID}$, 93

# *p<0.1* * *p<0.05* ** *p<0.01* *** *p<0.001*

Supplemental Table 10. Post-hoc analyses of fixed-effects. Type III ANOVA tables showing fixed effects with Satterthwaite method for modelling type of emotion regulation behaviour

Fixed effects	**SS**	**MS**	**NumDF**	**DenDF**	**F**	**p**
SC						
Preterm	0.00	0.00	1	106.00	0.14	0.706
SF	0.03	0.03	1	95.80	2.13	0.148
Preterm x SF	0.03	0.03	1	95.80	2.06	0.155
SOC						
Preterm	0.00	0.00	1	106.42	0.97	0.326
SF	0.00	0.00	1	97.68	0.46	0.498
Preterm x SF	0.00	0.00	1	97.68	1.31	0.255
OBJ						
Preterm	0.01	0.01	1	112.95	1.25	0.266
SF	0.03	0.03	1	104.77	4.31	0.040*
Preterm x SF	0.02	0.02	1	104.77	2.26	0.136
RME						
Preterm	0.04	0.04	1	108.58	3.68	0.058$^{\#}$
SF	0.04	0.04	1	96.96	3.45	0.066$^{\#}$
Preterm x SF	0.01	0.01	1	96.96	1.20	0.277

$^{\#}p_{adj}<0.1$, $^{*}p_{adj}<0.05$, $^{**}p_{adj}<0.01$, $^{***}p_{adj}<0.001$

Supplemental Table 11A. Results of power sensitivity analysis (behavioural outcomes). MODELS A were sensitive to an unstandardized interaction effect size of 7-10%, although simpler models (MODELS B) examining the preterm and term group separately and contrasts analyses suggest a 5% interaction effect (difference in the effect of SF phase in the term, vs preterm group). When considering main effects of SF phase and Preterm birth, MODELS A were sensitive to effects smaller than 1% for behavioural measures suggesting that non-significant results are unlikely to be false negatives.

			Effect size detectable with approximately 80% Power			
Model	Sample size	Model term	SC	SOC	OBJ	RME
A	N=111, observations=206	Preterm x SF	0.10	0.04-0.05	0.07	0.08
A	N=111, observations=206	Preterm	<0.01	<0.01	<0.01	<0.01
A	N=111, observations=206	SF	<0.01	<0.01	<0.01	<0.01
B1 (term)	N=61, observations=113	SF	0.07	0.03	0.05-0.06	0.06
B2 (preterm)	N=50, observations=93	SF	0.06	0.04	0.05	0.06
B1 (term)	N=61, observations=113	GA	0.05	0.02-0.025	0.03	0.05
B2 (preterm)	N=50, observations=93	GA	0.03	0.01-0.015	0.02-0.025	0.03
C	N=111, observations=206	Birthweight Z-score	0.04	0.02	0.03	0.05

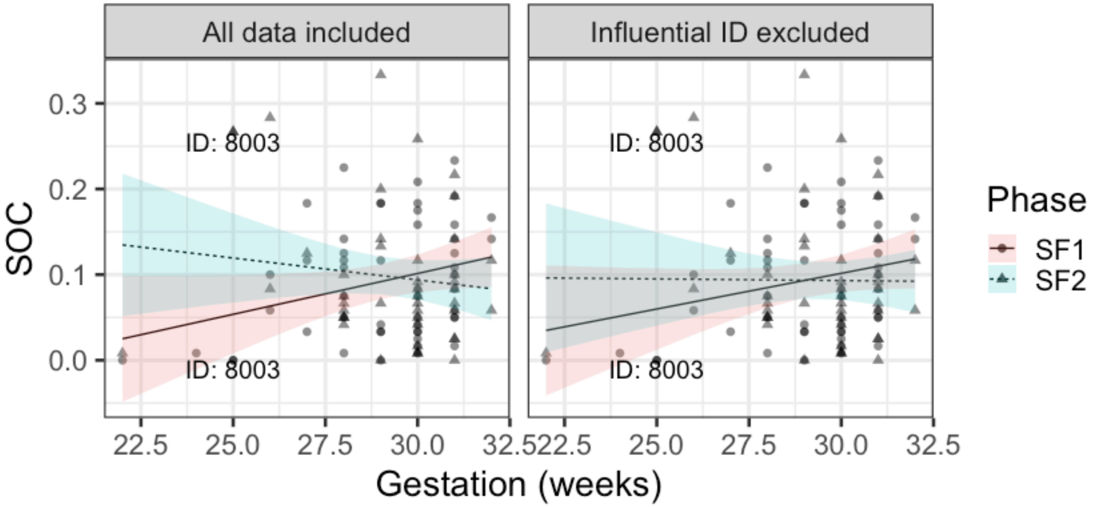
Supplemental Table 11B. Results of power sensitivity analysis (micro-level dynamic outcomes). RR and LAM were sensitive to unstandardized effect sizes of <1%, but were only sensitive to larger interaction effects . While models were only sensitive to effects of 1-4 bits/bin for ENTb and 0.5s - 2.5s for TT, it is unclear if being able to detect any smaller differences would be clinically meaningful.

			Effect size detectable with approximately 80% Power			
Model	Sample size	Model term	RR (%)	LAM (%)	ENTb (bits/bin)	TT (s)
A	N=111, observations=206	Preterm x SF	10.0	6.0	>4.0	>5.0
A	N=111, observations=206	Preterm	<1	<1	4.0	2.5
A	N=111, observations=206	SF	<1	<1	1.0 - 2.0	0.5
B1 (term)	N=61, observations=113	SF	7.0	5.0	>4.0	5.0
B2 (preterm)	N=50, observations=93	SF	6.0	4.0	>4.0	4.0
B1 (term)	N=61, observations=113	GA	3.6	3.5	>2.0	>2.5
B2 (preterm)	N=50, observations=93	GA	2.0	2.0	2.0	2.0
C	N=111, observations=206	Birthweight Z-score	3.0	3.0	3.0	3.0

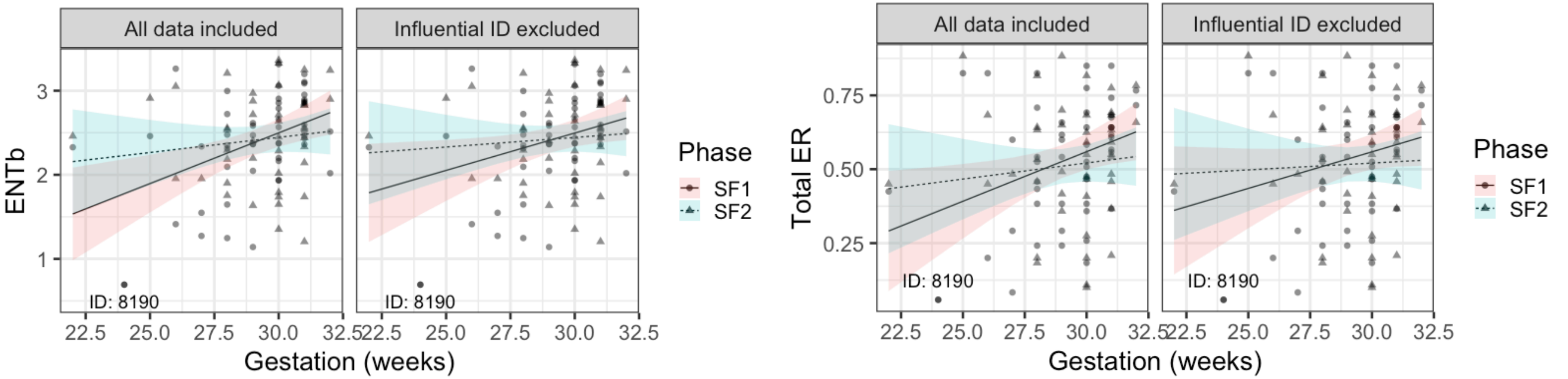
Supplemental Table 12. Full chromatic state space. State 1-5 corresponds to ER behavioural categories defined in the observational coding scheme. States 12, 13, 14 etc corresponds to concurrent behaviours, for example state 1 and 2 (or 1 and 3, or 1 and 4) within the same second. A recurrence is considered as long as another behavioural state in time matches at least one of the behaviours.

TS2 TS1	1	2	3	4	5	6	12	13	14	15	23	24	25	34	35	45	123	124	125	134	135	145	234	235	345
1	ER						ER	ER	ER	ER							ER	ER	ER	ER	ER	ER			
2		ER					ER				ER	ER	ER				ER	ER	ER				ER	ER	
3			ER					ER			ER			ER	ER		ER			ER	ER		ER	ER	ER
4				ER					ER			ER		ER		ER		ER		ER		ER	ER		ER
5					ER					ER			ER		ER	ER			ER		ER	ER		ER	ER
6						NER																			
12	ER	ER					ER	ER	ER	ER	ER	ER	ER				ER	ER	ER	ER	ER	ER	ER	ER	
13	ER		ER				ER	ER	ER	ER	ER			ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER
14	ER			ER			ER	ER	ER	ER		ER		ER		ER	ER	ER	ER	ER	ER	ER	ER		ER
15	ER				ER		ER	ER	ER	ER			ER		ER	ER	ER	ER	ER	ER	ER	ER		ER	ER
23		ER	ER				ER	ER			ER	ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER
24		ER		ER			ER		ER		ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER
25		ER			ER		ER			ER	ER	ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER
34			ER	ER				ER	ER		ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER
35			ER		ER			ER		ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER
45				ER	ER				ER	ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER
123	ER	ER	ER				ER	ER	ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER
124	ER	ER		ER			ER	ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
125	ER	ER			ER		ER	ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
134	ER		ER	ER			ER	ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
135	ER		ER		ER		ER	ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
145	ER			ER	ER		ER	ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
234		ER	ER	ER			ER	ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
235		ER	ER		ER		ER	ER		ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
345			ER	ER	ER			ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER

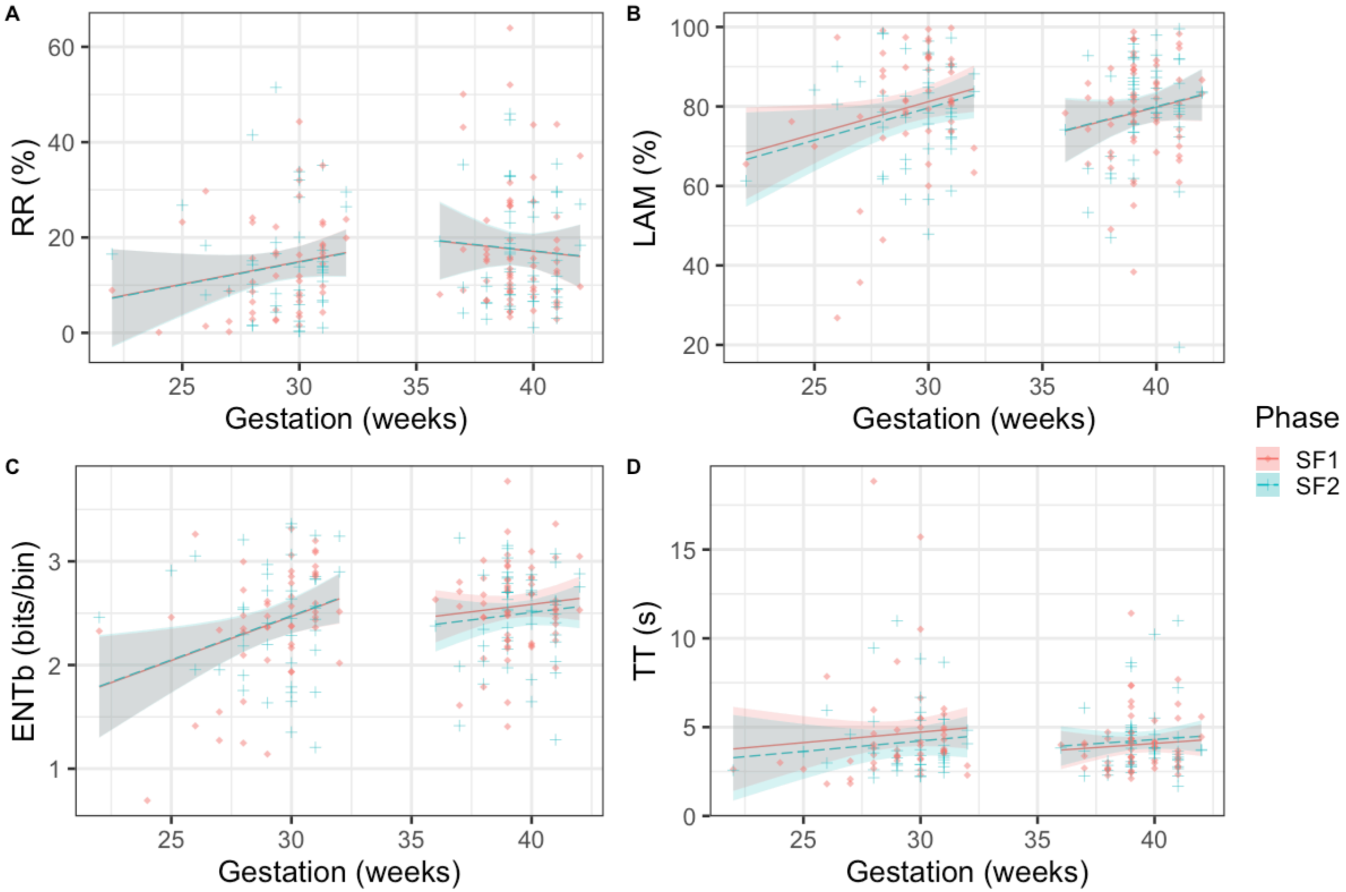
Supplemental Figure 1. Model building – analysis of influence (Interaction effect Gestational age x SF phase on SOC). Influence of a single participant (ID: 8003) on the size of the interaction term. Removing this participant with low GA who showed a large change in SOC from SF1 to SF2 removes evidence of an interaction effect from -0.015 (-0.027 – 0.002, p=0.025) to -0.009 (-0.021 – 0.004, p=0.169).



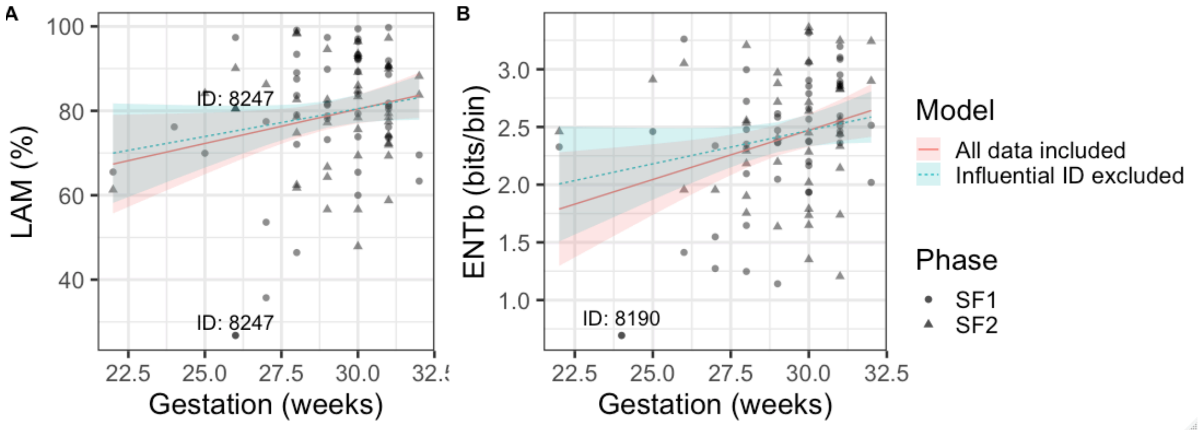
Supplemental Figure 2. Model building – analysis of influence (Interaction effect Gestational age x SF phase on ENTb and Total ER) Influence of a single participant (ID: 8190) with very low GA, very low ENTb / Total ER in SF1 and missing data in SF2 drives the interaction effect in the model. For model on ENTb, the interaction effect reduced from -0.08 (95% CI -0.17 – 0.00, p=0.067) to -0.07 (95% CI -0.15 – 0.02, p=0.153). For model on Total ER, the interaction effect reduced from -0.023 (95% CI -0.046 – 0.001, p=0.062) to -0.020 (95% CI -0.043 – 0.003, p=0.098)



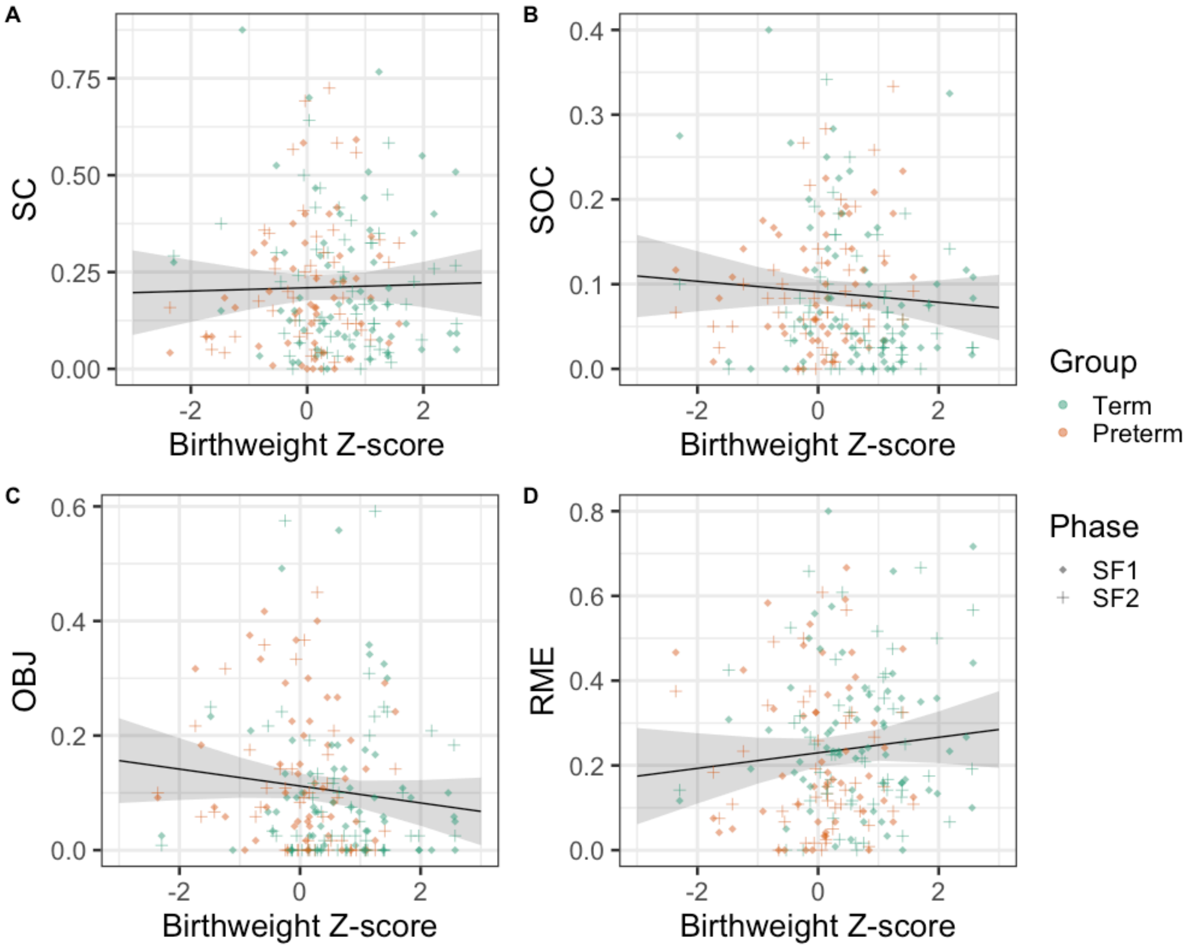
Supplemental Figure 3. MODELS B – effect of gestational age on behavioural dynamics modelled for preterm and term group separately. Marginal effects with standard errors overlaid on observed data



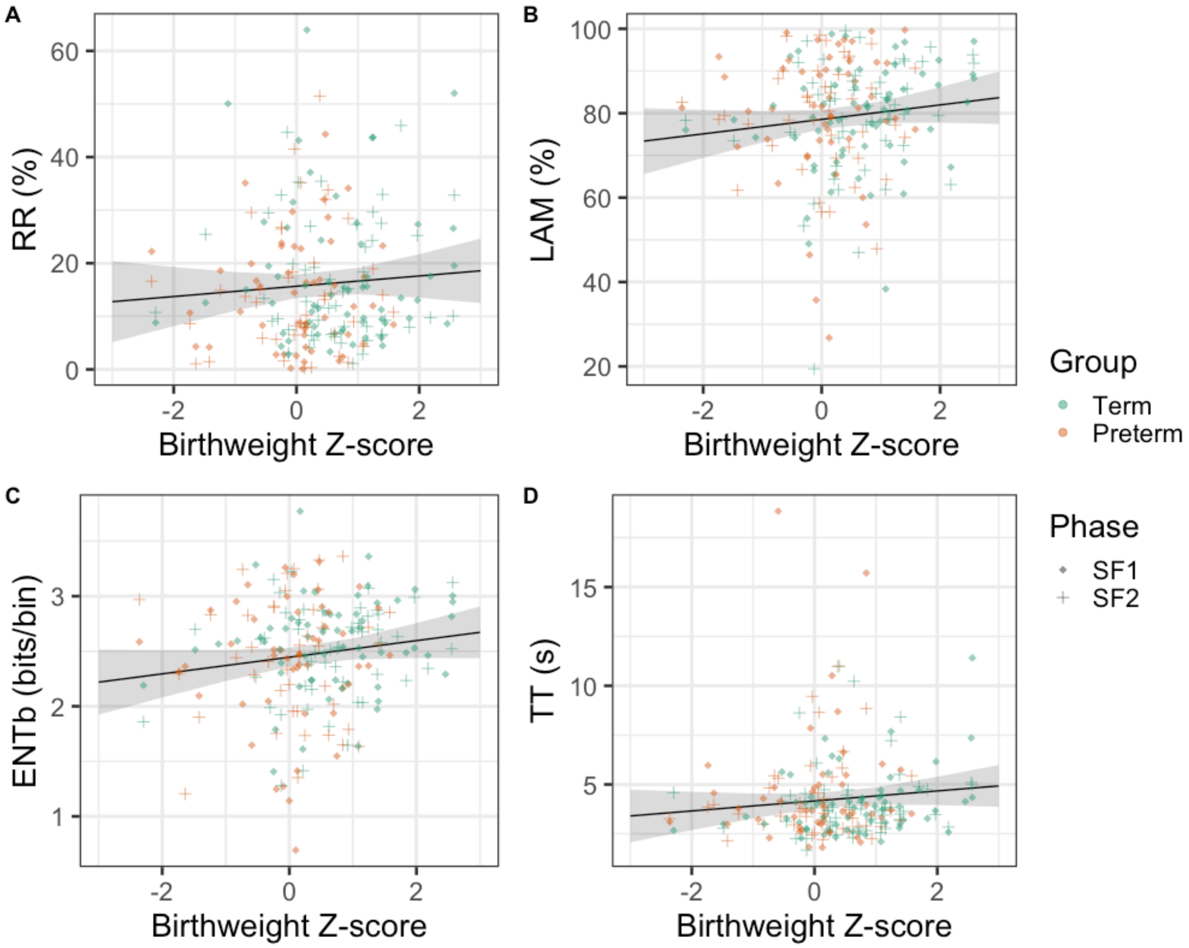
Supplemental Figure 4. Marginal effect of gestational age on Laminarity (left) and Entropy (right) with influence diagnostics, overlaid on observed data


A
100
80
60
40
LAM (%)
ID: 8247
ID: 8247
22.5
25.0
27.5
30.0
32.
Gestation (weeks)
B
3.0
2.5
2.0
1.5
1.0
ENTb (bits/bin)
ID: 8190
22.5
25.0
27.5
30.0
32.5
Gestation (weeks)
Model
All data included
Influential ID excluded
Phase
SF1
SF2

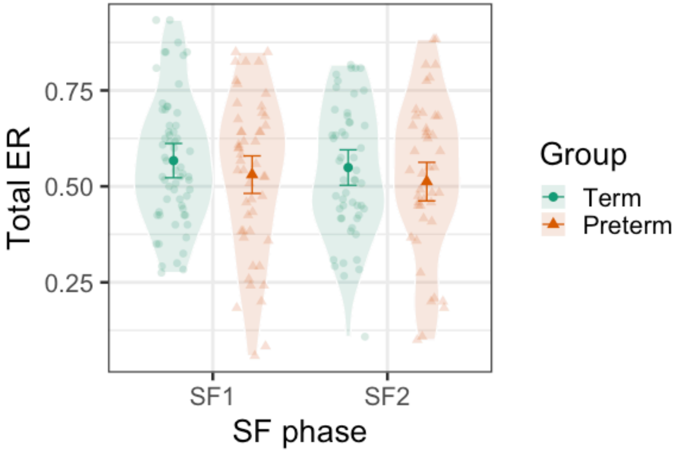
Supplemental Figure 5. MODELS C – effect of birthweight Z-score on ER behavioural type. Marginal effects with standard errors overlaid over observed data.



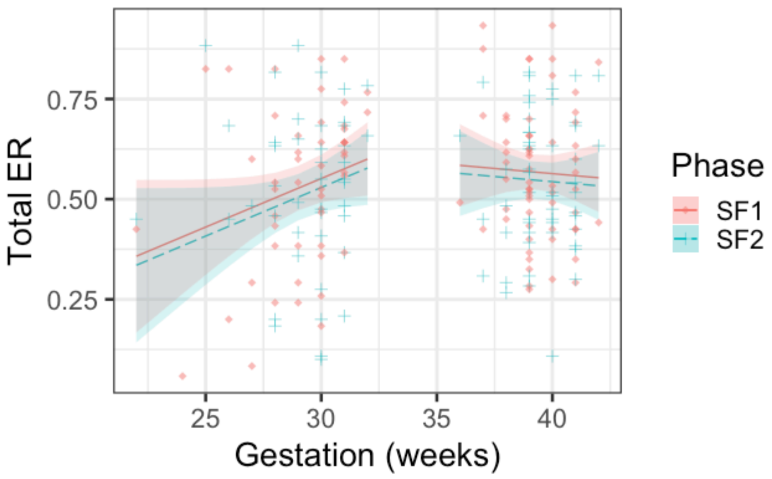
Supplemental Figure 6. MODELS C – effect of birthweight Z-score on ER behavioural dynamics. Marginal effects with standard errors overlaid over observed data.



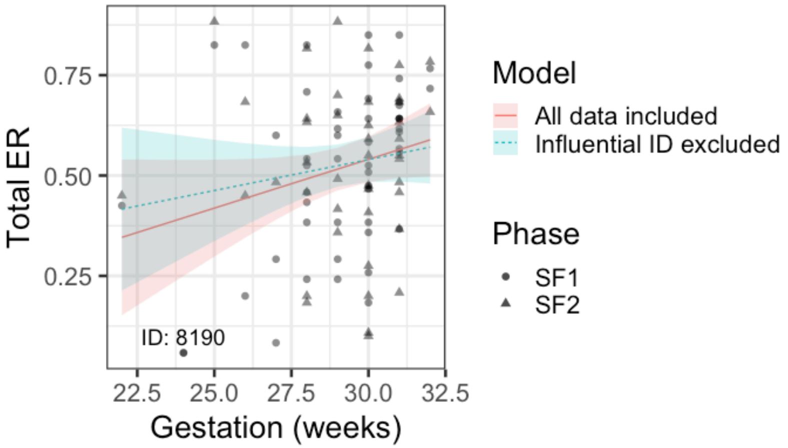
Supplemental Figure 7. MODELS D – effect of preterm birth on Total ER behaviours. Marginal effects with standard errors overlaid over observed data including violin plot.



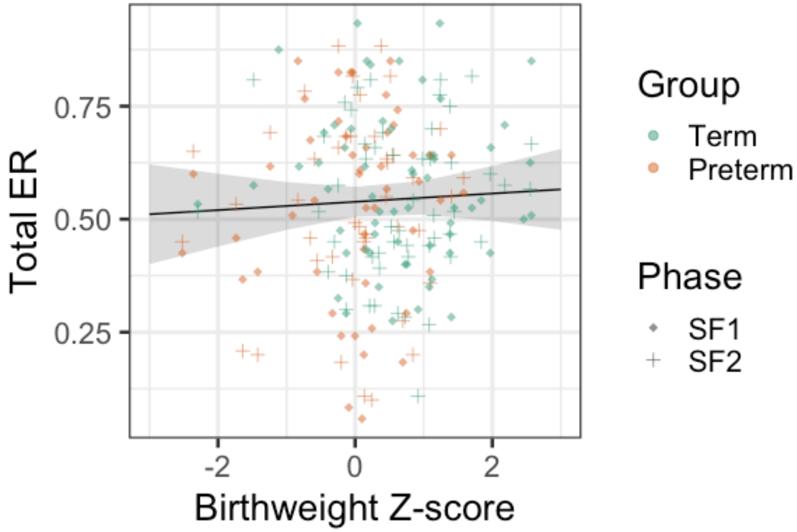
Supplemental Figure 8. MODELS D – effect of gestational age on Total ER behaviours. Marginal effects with standard errors overlaid over observed data.



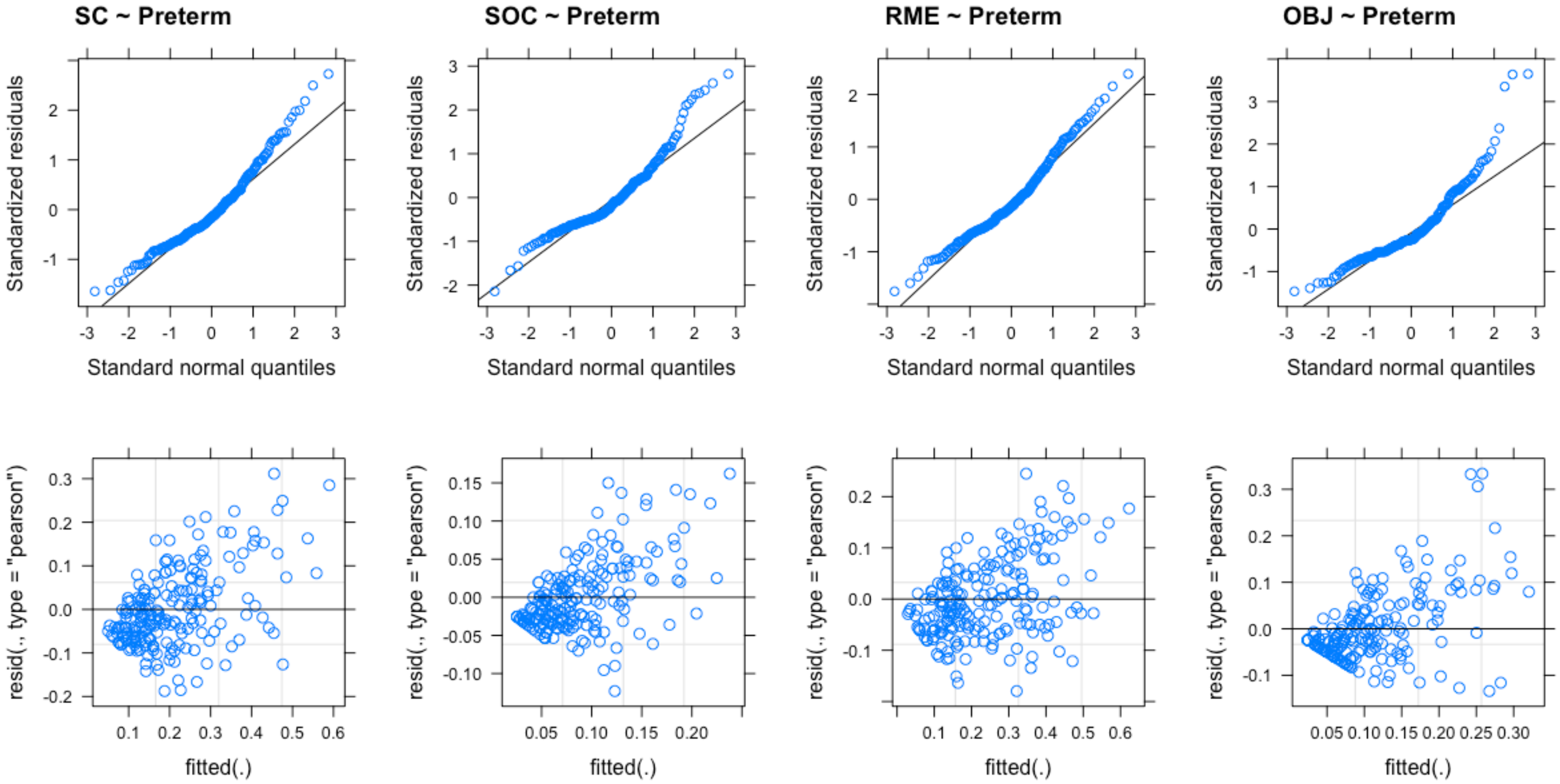
Supplemental Figure 9. Marginal effect of gestational age on Total ER with influence diagnostics, overlaid on observed data



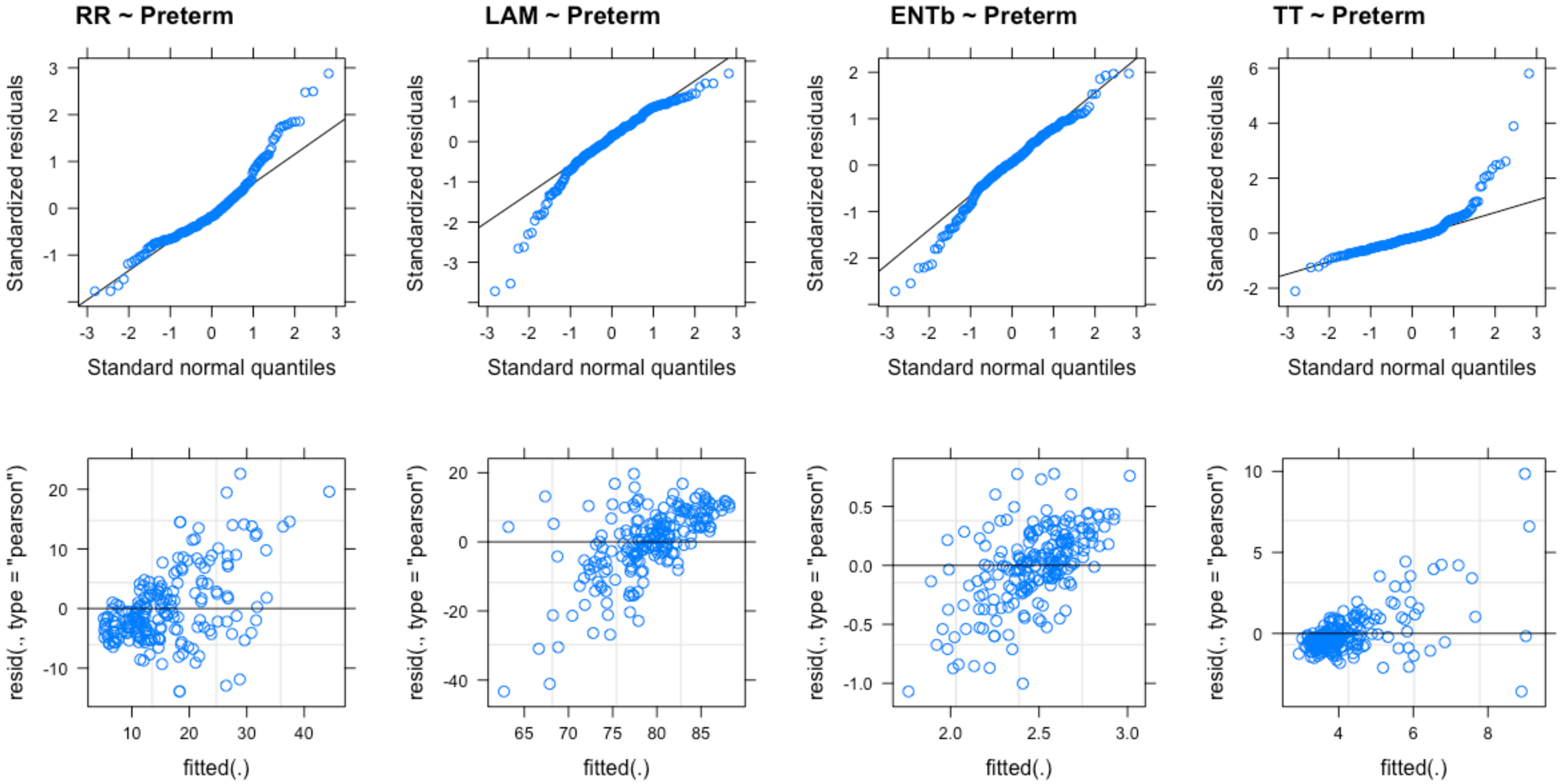
Supplemental Figure 10. MODELS D – effect of birthweight Z-score on Total ER behaviours. Marginal effects with standard errors overlaid over observed data.



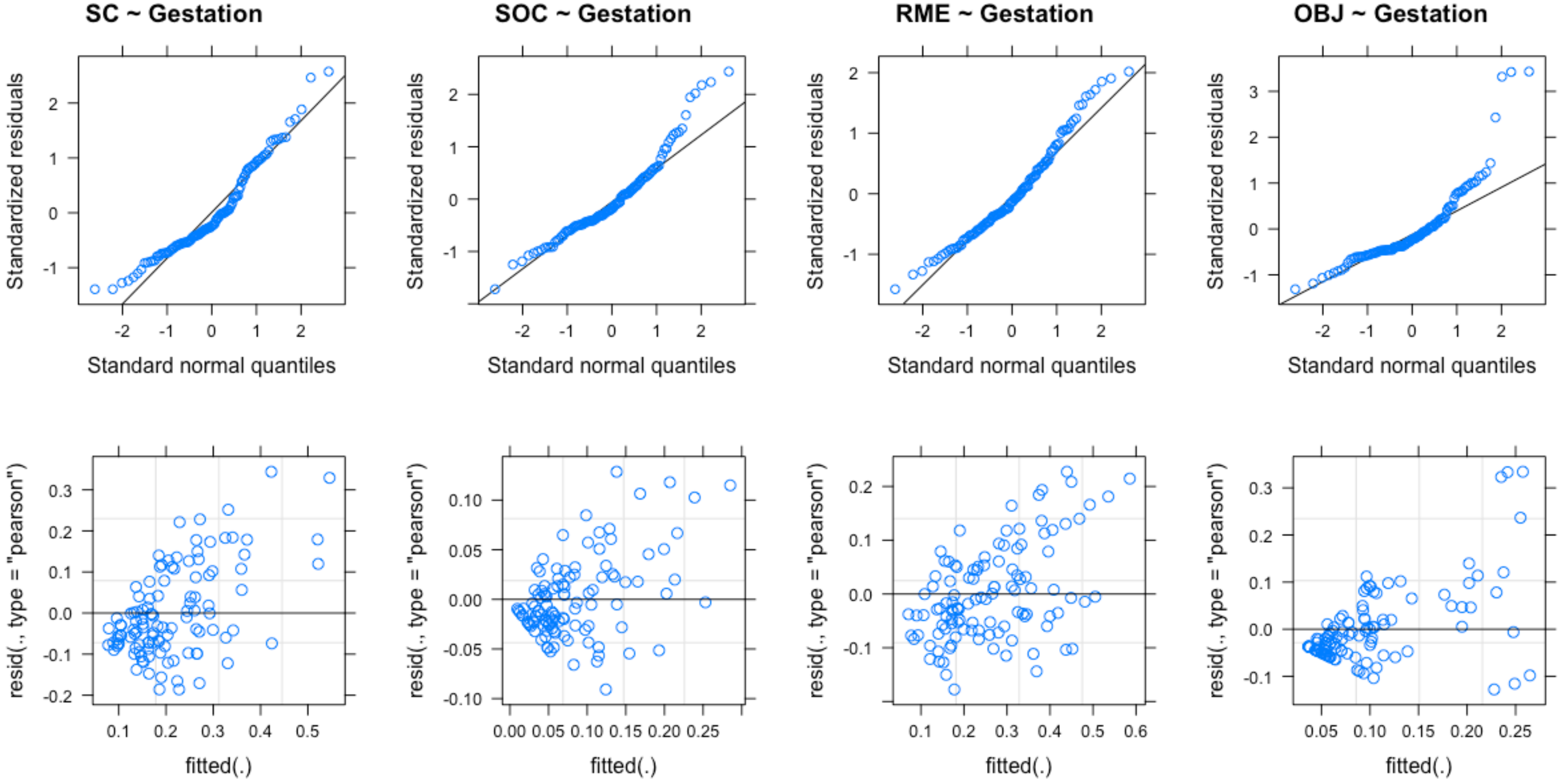
Supplemental Figure 9A. Model A diagnostic plots for behavioural type (top: normal q-q plots, bottom: residuals vs fitted)



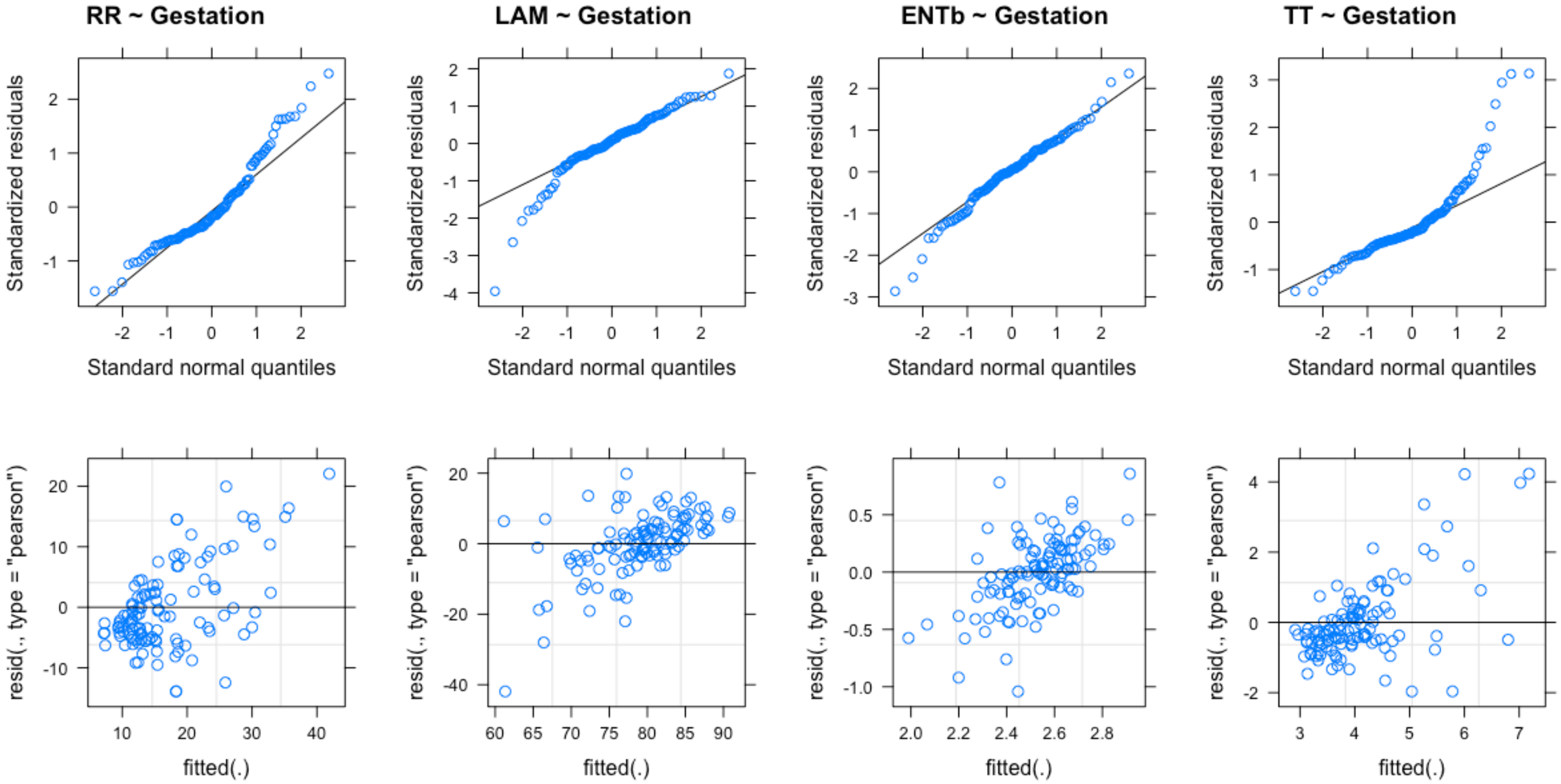
Supplemental Figure 9B. Model A diagnostic plots for behavioural dynamics (top: normal q-q plots, bottom: residuals vs fitted)



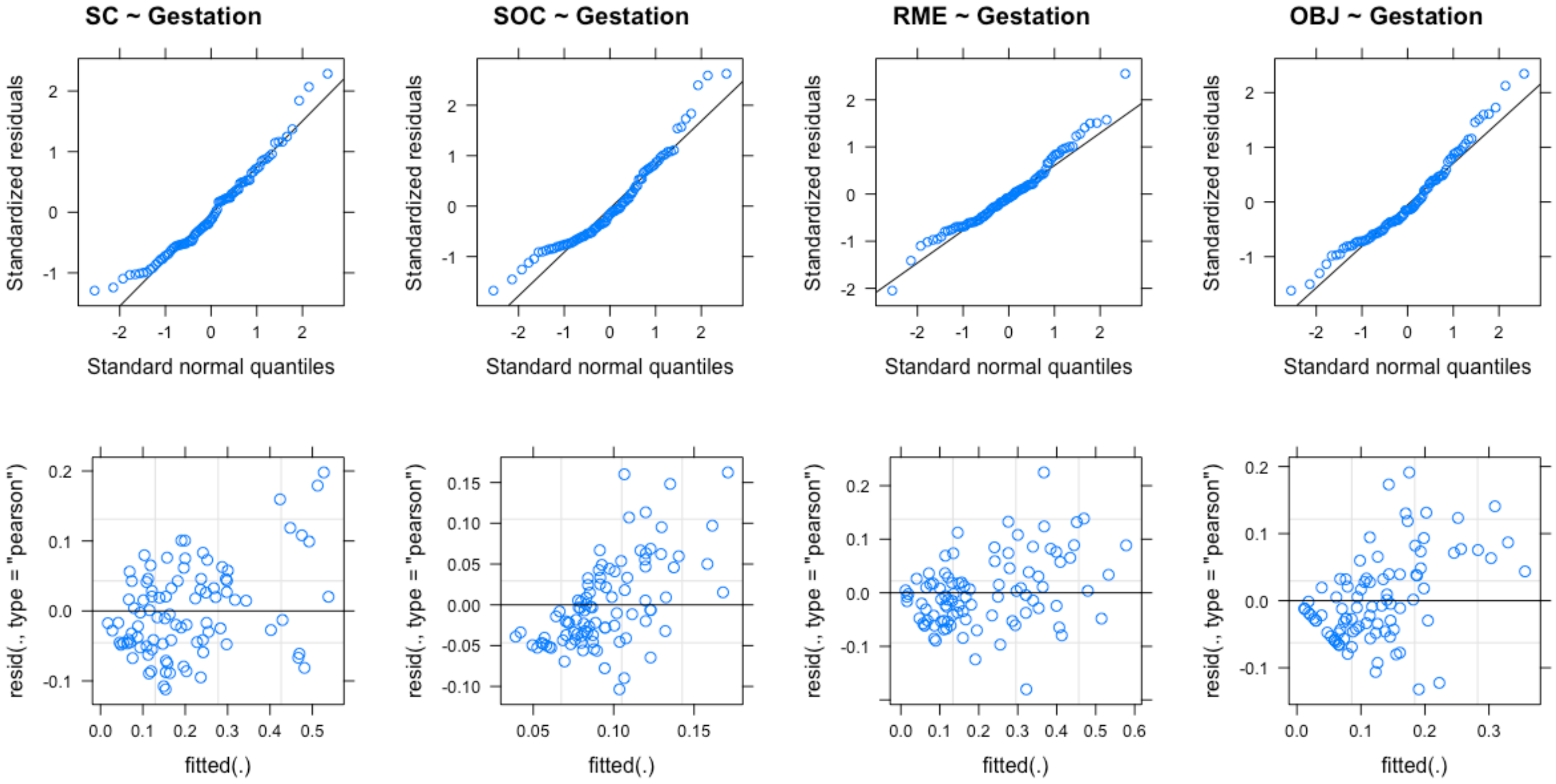
Supplemental Figure 10A. Model B (Term group) diagnostic plots for behavioural type (top: normal q-q plots, bottom: residuals vs fitted)



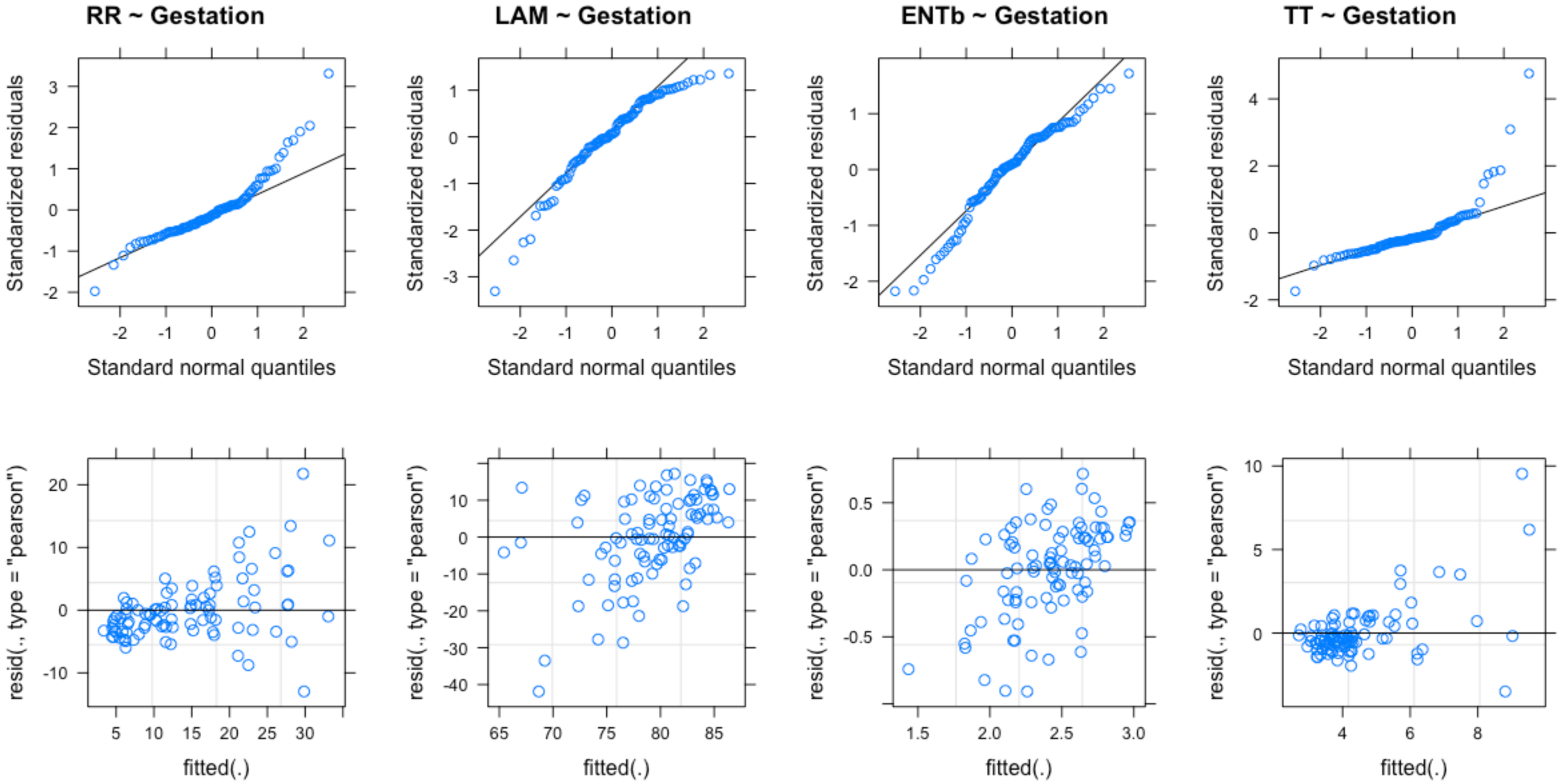
Supplemental Figure 10B. Model B (Term group) diagnostic plots for behavioural dynamics (top: normal q-q plots, bottom: residuals vs fitted)



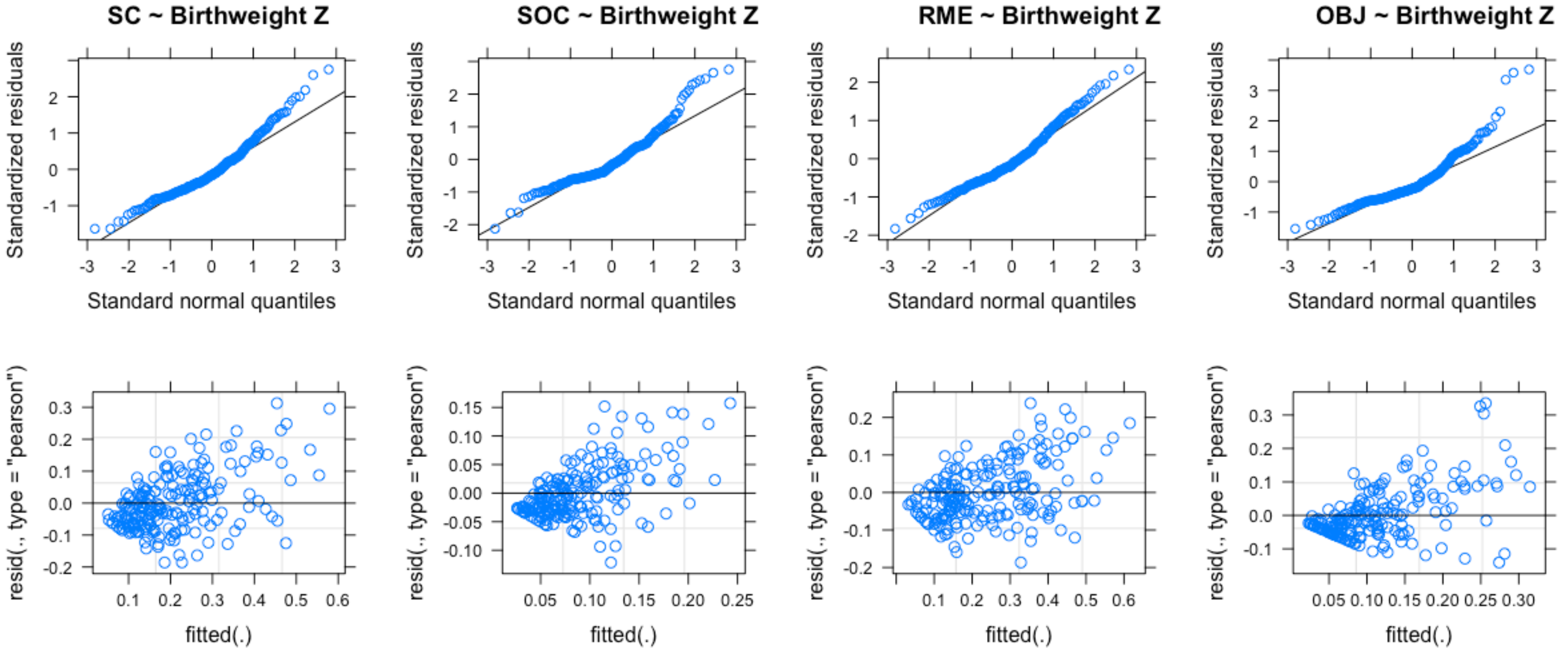
Supplemental Figure 11A. Model B (Preterm group) diagnostic plots for behavioural type (top: normal q-q plots, bottom: residuals vs fitted)



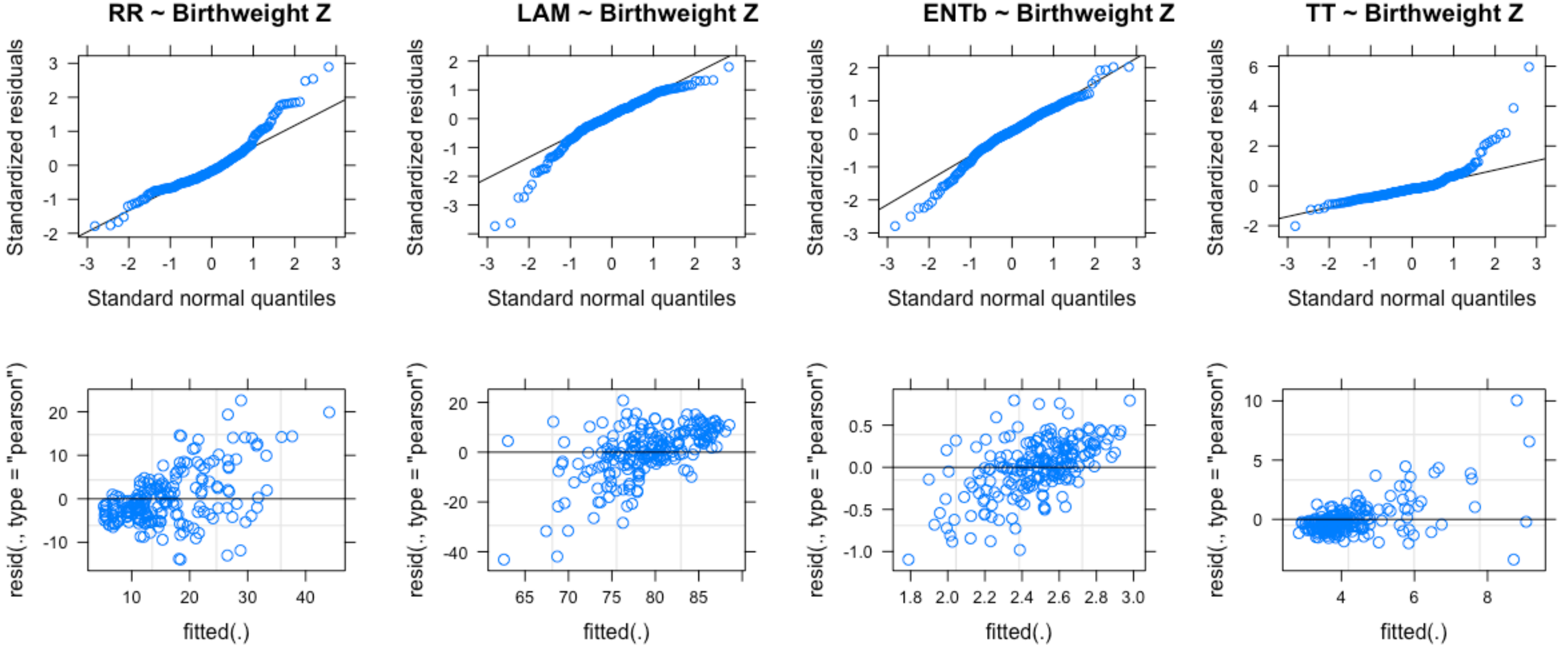
Supplemental Figure 11B. Model B (Preterm group) diagnostic plots for behavioural dynaics (top: normal q-q plots, bottom: residuals vs fitted)



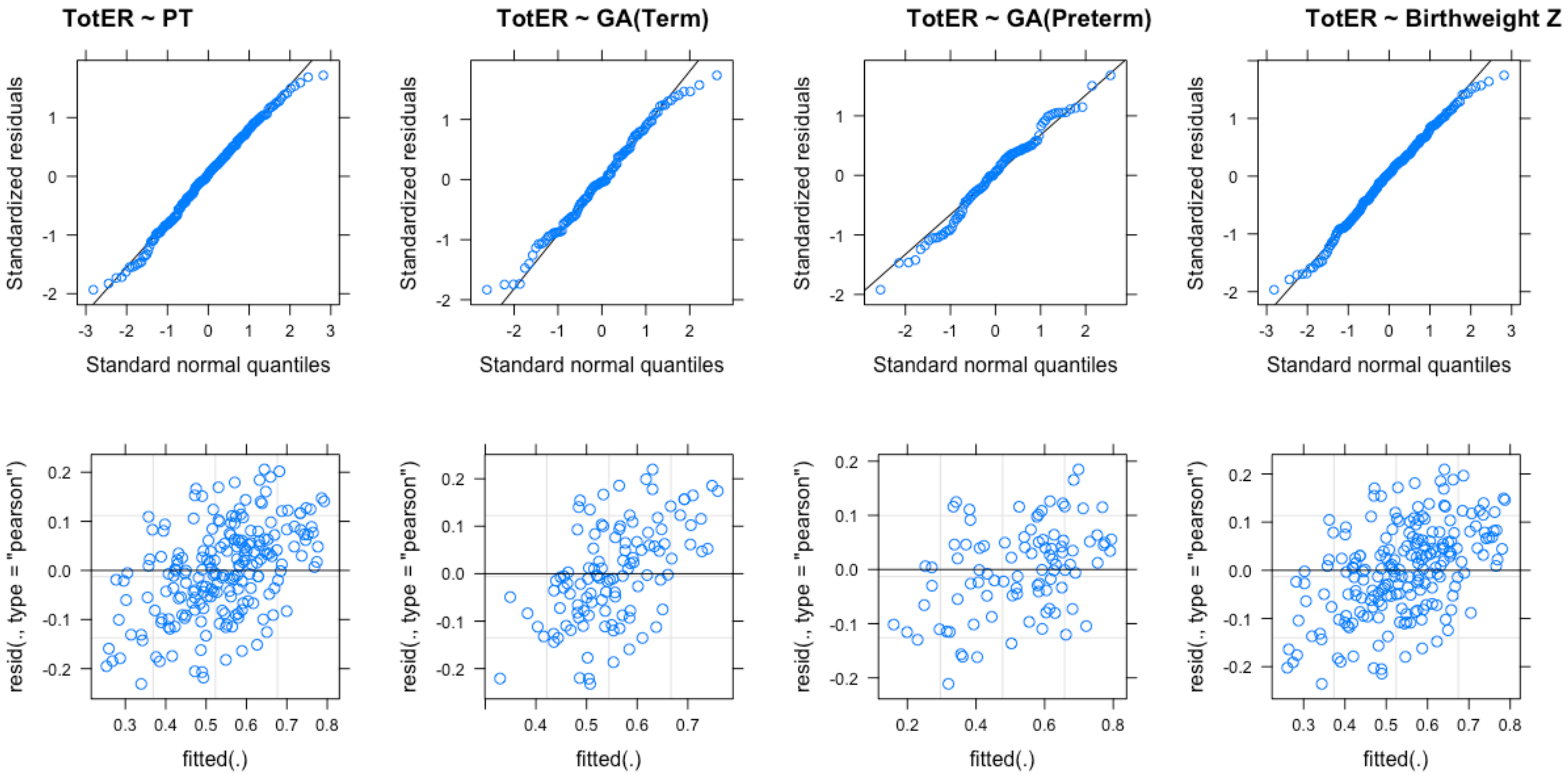
Supplemental Figure 12A. Model C diagnostic plots for behavioural type (top: normal q-q plots, bottom: residuals vs fitted)



Supplemental Figure 12B. Model C diagnostic plots for behavioural dynamics (top: normal q-q plots, bottom: residuals vs fitted)



Supplemental Figure 13. Model D diagnostic plots (top: normal q-q plots, bottom: residuals vs fitted)



3. Behavioural coding scheme

Infant Function of Movement and Behaviour Phases
Video coding scheme

A. Introduction

This coding scheme comprehensively capture the range of movement and behaviours used by infants to self-regulate emotions during the stressful still-face interaction. The codes are characterised by the intention of infant movement and behaviours, such as regulatory, reactive, stimulatory, social and attentional functions. The scheme is developed with reference to earlier video coding schemes characterising infant self-regulation behaviours and research substantiating the function of infant behaviours during the still-face interaction.

Code each 1 second period for infant self-regulation state. If there is a transition between movements during the 1s period, code the new behavioural state that the movement describes using information in the next period. Use the concurrent behaviour code only if two behaviours occur concurrently. For periods where infant movements do not meet criteria for any of the regulatory motor behavioural states, use Mmov for other movement and Mna for absence of movement.

This video scheme was developed with a secondary aim to accompany the codes for Infant Engagement Phases in the Infant Caregiver Engagement Phases (ICEP), which would additionally capture the affective dimension of infant emotional regulation. This video scheme was developed mainly for use in the still-face phases but also includes codes to specify periods in play and reunion phases where the caregiver can move the infant, as this means the infants may use less self-regulation strategies.

References

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B. Operational definitions

1. **(Msc) Self-comforting behaviours.** The function of infant's movement is to obtain oral or tactile stimulation. This includes when infant is using their own body to provide oral self-stimulation (infant mouths on a part of a body, or initiates oral contact with objects), infant is exploring or manipulating objects on self (eg clothing), or touching parts of their own body (eg, touching head, clasping hands, or bracing feet), for 1s or longer

2. **(Mobj) Object exploration/distraction.** The function of infant's movement is to provide attentional distraction by exploring the perceptual properties of objects. This includes reaching and fine motor behaviours which enables infant to manipulate or move to objects not on self, while infants' gaze is directed towards the object, for 1s or longer

3. **(Msoc) Social interactive/monitor behaviours.** The function of infant's movement is to engage in or solicit social interaction. This includes gestures or motor behaviours containing social interactive intention. Social interactive intention is defined by: infant-initiated arm movements, such as reaching, which result in increased proximity or touch of any part of the caregiver, and gestures or behaviours with social meaning, such as pointing or clapping. See note on clapping. Social monitor is defined as instances where the infant attends to the caregiver's face for 1s or longer.

4. **(Mrme) Repetitive motor behaviours**. The function of infant's movement is to provide motor self-stimulation. This includes repetitive movements of the torso, arms or legs (such as banging, leg kicking, body rocking, arm waving, clapping – see note on clapping), defined by an identical pattern of flexion, extension, rotation, abduction, adduction or elevation in all possible directions, at least two times consecutively within a 3 second or smaller window.

5. **(Mdis) Distancing behaviours.** The function of infant's movement is to increase their physical distance from the caregiver. This includes when infant tries to escape or get away from the caregiver by twisting, turning away from the caregiver, without engaging an object, for 1s or longer

6. **(Mmov/Mna) Other spontaneous or no movement.** The function of infant's movement for emotion regulation is not apparent. This includes all instances of motor activity that cannot be described by other emotion regulatory function or if Infant is not moving.

7. **(Musc) Unscorable.** Camera angle obscured infant movement

C. Additional coding guidelines

Concurrent behaviours. Infant is engaging in more than one type of motor behaviour concurrently. If infant shifts between behavioural states in the period, code the most recent state achieved at the end of the period. Do not code Mmov/Mna as a concurrent behaviour.

Sensors. Code Msc.t **i**f infant is touching sensor clothing. Code Mobj if infant is pulling or tugging at sensor clothing, or removes sensors and starts manipulating sensors/clothing.

Repetitive movements involving objects. Code Mobj.rme if infant repeatedly touches an object (at least twice within a 3s window) with gaze directed towards the object. Code Mrme.obj if infant repeats an identical movement that involves an object, without gaze directed towards the object (eg. banging chair)

Clapping. Code as Msoc_Mrme.armB

Msc. Msc.o for instances where infant uses oral self-comforting, Msc.ml for instances where infant two hands or feet are touching, and Msc.t if infant is touching objects on self or parts of their own body. Code Msc.ml even if hands or feet are lightly touching and not clearly or forcefully clasped, for 1s or longer. Code Msc.t only if infant is actively exploring the area touched, ie do not code if infant arm is not moving with hand resting on leg or accidental touches, for example if infants' hands touch while manipulating objects or if infant is repetitively kicking and feet brushes past each other. Code concurrent Msc and Mrme states, for example, in the event of repeated 1s or longer periods of clasping or touching

Mobj. Code Mobj from the period where movement begins and is continuous with the final period where the movement contacts an object. Stop coding Mobj if infant touch remains on an object but gaze is no longer on the object. If view of infant hands is partially obscured by infant chair and it is unclear (for example, if infant is manipulating an object or touching clothing), use adjacent periods if possible, where view is unobscured, to determine the correct code.

Msoc. Code Msoc.att if infant is attending to the caregiver's face. Do not assume social interactive intent unless it meets the definition described. For example, if infant is holding their arm wide and caregiver responds by holding the infant, or if infant is expressing fussiness in response to caregivers' attention, or looking at caregiver while making repetitive movements. If infant moves to touch caregiver and touch remains on caregiver, continue coding Msoc only if infant is actively moving the effector or has attention directed at the touch. Code Msoc.c for periods where caregiver is moving the infant, in addition to, if any, other motor behavioural states are shown by the infant.

Unscorable periods. For analyses where some extent of missing data can be tolerated**,** optionally code Mmov.usc for periods where camera obscures infant movement fully or partially such that it is not possible to determine the function of motor behaviour.

D. Composite scores

Repetitive motor behaviours composite. In a separate code, for periods involving repetitive movements, indicate if movement involved head, torso, and/or bilateral or unilateral arms or legs.

Table 1. Composite scores.

Composite score	Definition
Repetitive motor behaviours regulation composite	Sum of all periods containing Mrme, Mrme.obj, Mobj.rme Breakdown by head, torso, bilateral/unilateral arms and legs
Object-oriented regulation composite	Sum of all periods containing Mobj, Mrme.obj, Mobj.rme
Self-comforting regulation composite	Sum of all periods containing Msc.o, Msc.ml, Msc.t
Social regulation composite	Sum of all periods containing Msoc, Msoc.att
ER composite	Sum of all periods containing Mrme, Mobj, Msc and Mdis codes

E. Violations

Coding violations. Coding violations are incurred when it is not possible to code according to the scheme, such as if parts of the infant's body are obscured due to camera view, if infant turns away from camera, or caregiver obstructs camera view. To minimise the impact of violations on identification of infant self-regulatory behaviours, periods where there is not enough information to assign a code due to the obstruction are coded as absence of behaviour, along with an 'unscorable' label (this is equivalent to imputation of missing values). Code as normal if there is sufficient information to assign a code in the event of partial obstruction. Indicate 'estimated' in the event of partial obstruction and the code was estimated, such as due to information from adjacent periods or information from audio. Indicate estimated for absence of behaviour only if information from adjacent periods or audio indicate the possibility of an ER behaviour, but do not do so sufficiently. Exclude from timeseries analysis if more than 15% of the phase contained unscorable periods. Exclude from still-face analysis if 25% or more of the phase contained unscorable periods.

Still-face violations. Violations of the still-face paradigm are incurred when the still-face procedure is not maintained. This could be due to early termination, interruptions during the still-face, when caregiver does not follow the procedure (touches infant during still-face, does not maintain a still-face), when there are objects introduced to the still-face such as soothers and props, which are not usually considered as part of the setting. Sensors are considered part of the infants' clothing and as an object if infant removes the clothing or the sensor or is distracted by it.

Caregiver moves infant. When caregiver moves the infant during play and reunion phases, infant self-regulatory behaviours may be lower. This is not a violation of the still-face procedure, but potentially implicates the extent of self-regulatory behaviours used by the infant when the caregiver is available.

F. Glossary

Table 2. Glossary of codes and appending codes.

Infant function of motor behaviour	Appending codes
1. (Msc) Self-comforting behaviours	Msc.o, Msc.ml, Msc.t
2. (Mobj) Object exploration	Mobj.rme
3. (Msoc) Social interactive behaviours	Msoc.att, Msoc.c
4. (Mrme) Repetitive motor behaviours	Mrme.obj
5. (Mdis) Distancing behaviours	
6. (Mmov) Other spontaneous or no movement	Mmov.usc
Concurrent codes (Code with underscore between codes or multiple behavioural streams)	eg. Mobj_Msc