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CHILD DEVELOPMENT

EMPIRICAL ARTICLE

A dynamic systems account of parental self-regulation processes in the context of challenging child behavior

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Abstract

To advance the understanding of how parental self-regulation contributes to their role in supporting children's development, this study proposes a model of the dynamic processes involved in parental self-regulation. Based on time-series data from 157 mothers and their 30- to 60-month-old children (49.7% female; 96% White; data collected June 2017–December 2019 in central Pennsylvania, U.S.) during a challenging wait task, the model was tested by examining the temporal relations among challenging child behavior, maternal physiology, and maternal responsiveness. Results were consistent with the hypothesized dynamic negative feedback processes and revealed their associations with the overall quality of parenting behaviors and experiences. Findings elucidate how parents adapt to competing external (attending to child) and internal (restoring parents' equilibrium) demands during parenting challenges.

During early childhood, children typically show a decline in negative emotions and behavior problems (Cole et al., 2011; Kerr et al., 2007), which is critical for school readiness and further psychosocial adjustment (Raver, 2002). Parental responsiveness—attending and tailoring behavior to children's interests and needs—is thought to contribute to the decline by constructing an accepting and supportive environment where children are more willing to internalize appropriate coping strategies and rules of conduct (Bernier et al., 2010; Kochanska & Murray, 2000). However, situations in which children's self-regulation is challenged are often challenging for parents as well, especially when they need to manage multiple tasks and conflicting demands (e.g., working from home while attending to a young child; Crnic & Low, 2002; Kwon et al., 2013). Thus, how parents self-regulate in challenging parenting situations and manage to, or fail to, act in a responsive way to their children is receiving increasing attention in developmental research (Hajal & Paley, 2020).

Studies of parental self-regulation and related constructs (e.g., emotion regulation) often conceptualize them as trait-like abilities, measured through questionnaires or computer tasks unrelated to parenting. However, this approach does not address the actual processes of self-regulation in the challenging moments of parenting, which are critical for identifying the timings and mechanisms to target for promoting parenting competence. To address this, researchers have called for utilizing the rich information embedded in time-series data, that is, the moment-to-moment dynamics of parents' responses in parenting contexts, to understand their regulatory processes (Morris et al., 2018; Teti & Cole, 2011). However, there has not been a conceptual account of dynamic parental self-regulation to help integrate the empirical efforts. Taking a dynamic systems approach, this paper proposes and tests a model that defines parental

Abbreviations: ANS, autonomic nervous system; ECG, electrocardiography; FDA, functional data analysis; IBI, inter-beat interval; ICC, intraclass correlation coefficient; ODE, ordinary differential equation; PDH, Parenting Daily Hassles scale; RSA, respiratory sinus arrhythmia.

self-regulation as a set of processes unfolding in the challenging moments of parenting, allowing parents to balance both external (responding to children's needs) and internal (restoring parents' own equilibrium) demands.

A dynamic systems approach to the study of parental self-regulation

Recent conceptual work defines self-regulation as engaging higher-order cognitive processes to alter prepotent emotional and behavioral reactions (Cole et al., 2019; Nigg, 2017). However, the actual processes of regulation are hard to measure directly. Parents may invoke a diverse set of cognitive processes to manage their emotions and behaviors (e.g., re-prioritizing goals, shifting attention). Those processes are largely internalized and not always conscious, and may vary across individuals, contexts, and moments. It is difficult to assess them through self-report and observation or examine how they influence emotions and behaviors. What can be measured, however, is the moment-to-moment changes in behavioral and emotional indicators. Taking a dynamic systems approach, we argue that these temporal dynamics are the key to extracting patterns of regularity that reflect underlying regulatory processes.

A dynamic system refers to a collection of elements that interact constantly to support the system's functioning as a whole (Kelso, 1995). How these elements evolve over time is organized by a set of rules governing both the intrinsic dynamics of individual elements and how they coordinate with each other. Thus, a dynamic systems approach includes conceptual and mathematical accounts of time-structured intra-individual variability and the underlying *dynamic processes*—the organizing rules reflected in patterns of regularity (Ram & Gerstorf, 2009). For instance, an individual can be considered a complex system, with billions of basic elements (e.g., neurons, muscles) coordinating constantly to serve various functions (e.g., speaking, walking; Kelso, 1995; Vallacher et al., 2002).

In the study of parental self-regulation, the elements of interest are not individual neurons or muscles, but functional sub-systems relevant to the demands in parenting contexts. Here, we focus on two important demands parents often need to balance when challenged by children's behavior—responding to children's needs and restoring parents' internal equilibrium. In considering how a parent's functioning, conceptualized as a dynamic system, adapts to both external and internal demands, we examine two elements: (1) parasympathetically mediated physiological activity (measured by respiratory sinus arrhythmia; RSA), which is functionally associated with the maintenance of homeostatic body functioning and the preparation for action in challenging situations, and (2) the level of responsiveness in child-directed behavior. We propose that how these elements evolve and interact with each other in challenging parenting situations reflects the core *dynamic processes* of parental self-regulation.

The dynamic processes of parental self-regulation

Taking a systems view, challenging child behaviors (i.e., interfering with parents' tasks or conflicting with parents' expectations) constitute external sources of perturbation to the equilibrium of the system. Several conceptual accounts of self-regulatory systems—systems that form organized responses and restore equilibrium after being perturbed—suggest that how system elements evolve and interact over time is typically characterized by negative feedback processes (Carver & Scheier, 2008; Gross, 2015; Hollenstein, 2015; Lewis, 2000). Accordingly, we hypothesize that the dynamic processes underlying functioning *parental self-regulation*—enabling parents to show responsiveness to their children and restore internal equilibrium after being perturbed by children's behavior—unfold as summarized in Figure 1.

Briefly, the model proposes that children's behavior that is challenging for parents perturb the system away from internal equilibrium, indexed by an increase in parents' physiological arousal. Ideally, the perturbation gives rise to more responsive parenting behavior as parents manage to acknowledge and tailor their behavior to meet children's needs despite being challenged. Responsive parenting behavior should, in turn, facilitate the restoration of parents' internal equilibrium by modifying children's behavior (external sources of perturbation) and through self-regulatory feedback processes. Other types of dynamic processes are usually also involved in a system's functioning (e.g., governing the elements' intrinsic dynamics). However, we focus the introduction on the following dynamic processes reflecting how the system is perturbed and how its elements interact to adapt to internal and external demands.

Perturbation as a function of child behavior

Perturbation, by definition, disturbs the equilibrium of a system. It indicates a shift in circumstances and/or goals, motivating individuals to react and adapt to challenges (e.g., emotions can be considered as perturbations from a functionalist perspective; Frijda, 1986). Here, we are interested in parents' experience of *perturbation as a function of child behavior*. Among adults, perturbations are not always displayed or expressed. Therefore, one approach to capture how the parental system is perturbed is to measure physiological reactivity, indexed by changes in autonomic nervous system (ANS) activity. ANS measures can be collected continuously and unobtrusively during parenting, providing access to

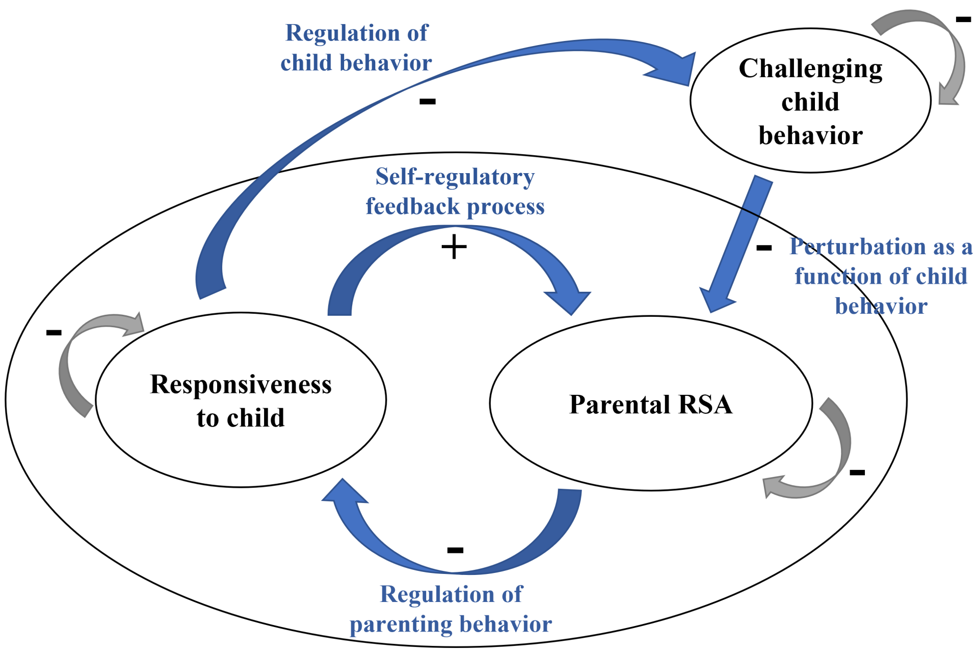

FIGURE 1 The hypothesized dynamic processes involved in parental self-regulation.

the rapid and often unconscious process of how parents react to and prepare to engage with the circumstance. ANS comprises the sympathetic and the parasympathetic branches. The sympathetic branch typically reacts to intensive challenge and threat to meet defensive needs, whereas the parasympathetic branch inhibits arousal to maintain homeostatic body functioning and can quickly withdraw and reinstate the inhibition, allowing increases in arousal in response to mild to moderate challenges and timely recoveries (Porges, 2007). Therefore, parents' parasympathetic reactivity may be a particularly relevant index of perturbation when facing child-related challenges.

When challenged by children's behavior, parents should evidence a withdrawal of parasympathetic control, resulting in an increase in arousal, reflecting a perturbation to internal equilibrium has occurred. Parasympathetic activity is commonly quantified as RSA, an index of heart rate variability as a function of respiration (higher RSA indicates greater parasympathetic activity; Berntson et al., 1993). Although parasympathetic input to cardiac rhythm occurs on a millisecond timescale (Somsen et al., 2004), previous research often calculated average RSA across 30 s or longer. Therefore, although several studies found that parental RSA was lower than resting baselines when children were distressed or disruptive (Augustine & Leerkes, 2019; Lorber & O'Leary, 2005), the average RSA reactivity may reflect a mixture of initial perturbations and ensuing regulatory effects. To capture momentary changes in parental RSA, we adopt a moving-window technique that has been validated in recent research to obtain estimates of second-by-second dynamic changes in RSA (Gates et al., 2015; Ravindran et al., 2021).

The regulation of parenting behavior

Once perturbed from equilibrium, the mobilization of physiological resources prepares individuals to act in response (Keltner & Gross, 1999). When children's behavior perturbates parents' equilibrium, whether and how parents choose to act results in variations in parental responsiveness. Compared to more prepotent reactions such as lashing out at the child or disengaging, acknowledging and tailoring behaviors to the child's interests and needs require higher-order executive processes (Deater-Deckard et al., 2012; Harris et al., 2021). Parents must monitor and interpret children's behavior to understand their needs, search for potential ways to respond, evaluate potential consequences of specific responses, and inhibit prepotent reactions to take on alternative behaviors. Thus, if perturbation gives rise to more responsive parenting behavior, it can be inferred that some executive processes are involved to support the action, a process we label as the *regulation of parenting behavior*.

Although no research has examined moment-to-moment dynamics, a recent study provided evidence for inferring parental self-regulation from the relation between emotions and parenting behaviors. Hajal et al. (2019) examined how intra-individual variations in mothers' subjective emotions across occasions (sampled throughout several days) predicted momentary motivation to engage or disengage with their infants, as well as actual engagement or disengagement. They found that on occasions when mothers reported greater irritation or discouragement than personal averages (which can be considered as perturbations from equilibrium), they reported a greater extent of not wanting to engage, but their actual engagement behaviors were comparable to other occasions. Here, we hypothesize that when parents are regulating their reactions in a challenging parenting situation, they would take on parenting behaviors that reflect higher levels of responsiveness when perturbed from internal equilibrium—a child-centered way to respond to parenting challenges.

The restoration of equilibrium

In addition to responding to children's needs, parents need to restore their internal equilibrium after being perturbed. This may be achieved through regulating the external source of perturbation (children's challenging behavior) and directly regulating the internal reactivity. First, although little evidence is available on the momentary effects of parental responsiveness on child behavior, responsive parenting behaviors should soothe the child and help the child adopt coping strategies endorsed by the parent (Bernier et al., 2010; Kochanska & Murray, 2000). Thus, higher levels of parental responsiveness should reduce challenging child behavior (i.e., *regulation of child behavior*) and, in turn, dissipate the perturbation. Second, even if children's challenging behavior persists, it is not optimal for parents to experience sustained arousal. As parents take actions to cope with the parenting challenge, their internal states should move back toward equilibrium, indicating the *self-regulatory feedback process*. A variety of parenting behaviors may serve the function of restoring parents' equilibrium, ranging from providing support and addressing children's needs to harshly shutting down children's bids. However, as a functioning parental system needs to balance external and internal demands, the restoration of equilibrium should be facilitated by addressing the parenting challenge in a child-centered way. That is, higher levels of parental responsiveness should lead to a recovery from perturbation (i.e., increases in RSA) through regulating the child and self-regulatory feedback process (Figure 1).

Inter-individual differences in the dynamic processes of parental self-regulation

Examining the dynamic processes of parental self-regulation may further our understanding of proximal mechanisms underlying inter-individual differences in parenting behaviors and experiences. For instance, parents who are generally less responsive to their children may differ from others in multiple dynamic processes. Their equilibrium may not be perturbed when children demonstrate behaviors that other parents find challenging, thus missing the opportunity to address children's needs. This is consistent with evidence showing blunted cardiac responses to contextual demands among less sensitive or emotionally available parents (Joosen et al., 2013; Zhang et al., 2017). Lower responsiveness may also indicate less likelihood of being responsive and greater likelihood of disengaging or acting harshly when parents are perturbed (i.e., less regulation of parenting behavior). This may explain inter-individual differences in how much parents reduce supportiveness or increase harshness in reaction to young children's negative behaviors (Deater-Deckard et al., 2010; Ravindran et al., 2018).

Additionally, parenting experiences, including negative emotions and the accumulation of minor stresses during parenting tasks (i.e., parenting hassles), also have important implications for parent and child well-being (Crnic & Low, 2002; Rueger et al., 2011). Examining dynamic parental self-regulation may offer insights into the mechanisms underlying negative parenting experiences. Parents who are perturbed to a greater extent (e.g., greater decreases in RSA) by children's behavior may experience more negative emotions and parenting hassles. Meanwhile, whether parents efficiently restore internal equilibrium after being perturbed may also determine whether negative feelings accumulate. For instance, parents who report more negative parenting experiences often have lower self-efficacy (Crnic & Ross, 2017). They may lack confidence in their ability to resolve parenting challenges, and/or that their children's behaviors are hard to manage. As a result, even when they manage to be responsive to their children, these parents may not recover timely from perturbations, resulting in less optimal parenting experiences. Therefore, we examine whether dynamic parental self-regulation processes are associated with the overall quality of parenting behaviors and experiences.

The current study

This study presents a dynamic systems account of parental self-regulation processes. We test the model with time-series data of maternal physiology and behaviors during a challenging parenting task (the wait task) in a community sample of mothers and young children. During the task, children had to wait to open an appealing gift while mothers completed work in the same room. In this context, we operationalized and assessed maternal responsiveness as behaviors (including speech, vocalization, and other observable indicators) that convey genuine interest in and concern about the child, and/or attempts to help or support the child, versus attempts to disengage with and/or shut down the child. Based on second-by-second measures of challenging child behavior, maternal RSA, and maternal responsiveness, we conducted confirmatory analyses to test the following hypotheses generated from the conceptual model:

The first set of hypotheses examines whether the observed temporal relations are consistent with the intra-individual dynamic processes which is shown in Figure 1. We hypothesize that challenging child behavior is associated with momentary decreases in maternal

RSA (Hypothesis 1a; perturbation as a function of child behavior), and lower maternal RSA is associated with momentary increases in maternal responsiveness (Hypothesis 1b; regulation of parenting behavior). In turn, higher levels of maternal responsiveness are associated with momentary decreases in challenging child behavior (Hypothesis 1c; regulation of child behavior) and momentary increases in maternal RSA (Hypothesis 1d; self-regulatory feedback process). Beyond these cross-variable associations, the model articulates intrinsic tendency for stability maintenance where each process seeks to return to an equilibrium set point. Given the task design (i.e., mothers completed questionnaires and told their children to wait), focusing on questionnaires is considered as the set point for maternal behavior, and task-average RSA is defined as the set point for maternal RSA. In parallel, we expect child behavior to show a tendency to return to non-challenging states (e.g., playing alone), which is likely weak as young children have limited ability to self-regulate (Cole et al., 2017).

The second set of hypotheses examines whether inter-individual differences in the four dynamic processes (Hypotheses 1a to 1d) are associated with the overall quality of parenting behaviors and experiences. We hypothesize that mothers who demonstrate lower task-average responsiveness will evidence both less perturbation due to children's challenging behavior, indexed by smaller decreases in RSA, and less regulation of parenting behavior, indexed by smaller increases in parental responsiveness when RSA was lower (Hypothesis 2a). For Hypothesis 2b, we test whether mothers who report more negative emotions during the task and higher levels of parenting hassles in everyday life show greater perturbation by child behavior, lower efficiency in regulating child behavior (i.e., smaller decreases in challenging child behavior when maternal responsiveness is higher), and/or a weaker self-regulatory feedback process (i.e., smaller increases in maternal RSA when maternal responsiveness is higher).

METHODS

Participants

This study used data drawn from the Development of Self-Regulation Dynamics Project, a cross-sectional study of age differences in young children's self-regulation. Families were recruited from central Pennsylvania through letters distributed in a university participant pool, flyers posted at schools and public places frequented by families (e.g., groceries), and community events (e.g., art festivals). Interested families were screened for eligibility on (1) child age (i.e., 30–60 months), (2) no report of developmental delays or health concerns that interfere with providing valid data (e.g., cognitive limitations, deafness); (3) the family speaks English well enough to complete study procedures; and (4) at least one caregiver is the child's legal guardian. Both parents (mother and father in most cases) were invited to participate. Data collection took place between June 2017 and December 2019. The current study used data from a task completed by children and mothers (the wait task). The final sample included 157 children (49.7% female) between 30 and 60 months of age (M_{age} = 45.08 months, SD = 8.17 months) and their mothers (all biological mothers; M_{age} = 35.19 years, SD = 5.10 years). The children were identified by their mothers as White (95.6%), Asian (2.6%), Black (1.3%), and Native American (0.6%). The sample had an average annual income of $89,875 ($SD$ = $50,303) with a wide range (10th and 90th percentiles were $35,000 and $150,000). Most mothers were married (89.6%), had attained a bachelor's degree or above (78.2%), and were working full time (53.5%) or part time (23.6) at the time of the visit.

Procedures

Research assistants contacted enrolled families to collect demographic information and schedule a 4-h laboratory visit. Before the visit, parents were asked to complete a packet of questionnaires using an online platform (Qualtrics). Upon arrival at the laboratory, the family was met by a research assistant who explained study purposes and procedures. The parent(s) then signed consent forms. Research assistants measured each family member's height and weight and applied electrodes connected to the ambulatory device that recorded physiological signals (Mindware Technologies LTD.). The child and the parent(s) participated in a series of tasks, sometimes alone and sometimes in pairs (mother–child or father–child). The parent(s) completed more questionnaires during the visit. At the end of the visit, the parents were debriefed, the electrodes were removed, the child received the earned rewards, and the family received compensation. Study procedures were approved by the Institutional Review Board of Pennsylvania State University (Study ID: STUDY00005112).

Mothers and children were videorecorded during the 9-min wait task (Cole et al., 2011; Vaughn et al., 1984). At the start of the task, the child and the mother were seated at separate tables in the same room. The child was provided with a boring and broken toy, and the mother was given questionnaires to fill out. The research assistant then placed a gift wrapped in shiny metallic paper on the child's table and told the child there was a surprise inside. The mother received written instructions: "before you start working, and right after the research assistant leaves the room, tell the child to wait to open the gift until you finish your work," and was instructed to act as they normally would when the mother must finish some work and the child need to wait. The research assistant placed a 3-min sand timer on the mother's table and left the room. This task included three segments (3 min each); after each of the first two segments, the research assistant entered the room, said to the parent "Oh, you need more time," and reset the timer before leaving again.

Measures

Challenging child behavior

The degree to which children's behavior would challenge a typical adult was rated during the wait task using a scale adapted from work by Lorber and O'Leary (2005). We adopted their operational definitions of negative child behavior in a similar task (e.g., bids for parent's attention, violating task rules, expressing negative emotions) but converted the system from binary decisions (whether a behavior is present) to an ordinal rating of how challenging children's behavior is (see S1 in Supporting Information). Child behavior was rated independently of maternal behavior. Using the Datavyu software (Datavyu Team, 2014), trained research assistants rated children's behavior second-by-second based on videotapes using a 5-point scale (from 0 "Not at all challenging" to 4 "Highly challenging"). Each family's video was rated independently by a research assistant, and 32 randomly selected families (20% of the sample) were double-coded to check inter-rater consistency. The intraclass correlation coefficient (ICC) across all double-coded videos was .83 (ICC 2 is selected to assess raters' absolute agreement during each second; Shrout & Fleiss, 1979). For double-coded cases that did not achieve an ICC greater than .70 (2 of 32 cases), the two raters consensus coded the final ratings included for analysis. Observational data were available for all but one family whose audio was lost by device malfunction. The second-by-second ratings were later averaged to create an index of inter-individual differences in child challengingness. Of a possible range of 0–4 (0 = no challenging behaviors at any second, 4 = highly challenging throughout task), the average score ranged from 0 to 2.46 ($M = 0.59$, $SD = 0.47$). All but one of child showed some challenging behaviors during the task (see S2 in Supporting Information for examples of the dynamics in challenging child behaviors, which indicate substantial intra-individual variability).

Maternal RSA

Mothers' second-by-second RSA was measured during the wait task. Electrocardiography (ECG) data were collected using Mindware Technologies ambulatory devices and BioLab software (version 3.1; Mindware Technologies LTD.) from three disposable cardiac electrodes placed over participants' distal right collar bone, lower left rib, and lower right rib (sampling frequency = 500 Hz). ECG data were imported into Mindware's HRV software (version 3.1.5), which identified R peaks algorithmically and produced inter-beat interval (IBI) series. All the ECG data were visually inspected and manually cleaned by trained research assistants. Mothers' respiration rate was estimated through impedance cardiography collected through four additional electrodes, which was used to ensure that respiration rate remained within the targeted frequency band for calculating adult RSA.

The cleaned IBI series was output from Mindware HRV and into R (R Core Team, 2020). Second-by-second RSA was estimated using the *RHRV* package (Martínez et al., 2017). The input IBI series was first filtered for outliers based on a possible range of IBI (300–2000 ms) and the algorithm of the FilterNIHR function. Outliers were removed while a separate variable tracked accumulated time to ensure the alignment between the IBI series and the actual flow of time. Based on the filtered IBI data, a series of equidistant IBI values were generated at a sampling frequency of 4 Hz through cubic spline interpolation. The interpolation generated imputed IBI values for portions of missing data; however, we removed the interpolated values for missing portions ≥10 s to maintain the precision of imputation. Second-by-second RSA estimates were calculated for the entire visit using overlapping 30-s windows that each moved forward 1 s through the interpolated, equidistant IBI series. The IBI series within each window was subject to a Hamming window function that up-weights the center of the window, and a short-time Fourier transform was applied to obtain an estimate of the power spectrum for the 15th second of the window. Second-by-second RSA was then computed as the natural log of power within the adult respiration frequency band (0.12–0.40 Hz; Berntson et al., 2007). This approach requires 30 s of continuous data to generate each RSA estimate. As the recording of ECG data was initiated before task started, estimates were available across the entire task. When there is a segment of missing data in the IBI series, the RSA values would be missing from 15 s before the segment until 15 s after the segment. Across all mothers, approximately 1.5% of second-by-second RSA values during this task were missing.

In addition to the second-by-second estimates, the average RSA across each 30-s epoch of the task was also computed using the same technique described above, but with nonoverlapping 30-s windows that moved through the equidistant IBI series. The average RSA across the task for each mother was then calculated by averaging the 30-s RSA values to indicate inter-individual differences in maternal RSA.

Maternal responsiveness

Maternal responsiveness was rated on an ordinal rating scale of the extent to which mothers' behaviors reflected attempts to acknowledge and address the child's needs versus to dismiss or avoid attending to the child (see S3 in Supporting Information). Using Datavyu, trained research assistants watched the videorecord and rated mothers' behavior second-by-second on a 7-point scale ranging from −3 to 3. The upper half of the scale (1, 2, or 3) was used when the mother displayed attentiveness to, initiation of interaction, and/or response to the child that reflected different levels of interest in or concern about the child and/or efforts to acknowledge and support the child's interests and needs. The lower half of the scale (−1, −2, or −3) was used when the mother's behavior explicitly conveyed disinterest in the child's states and/or that they did not want to interact or provide any help. The midpoint of the scale (0) was used when the mother did not show observable indicators of either attending to the child or dismissing the child, for example, mother worked on questionnaires without showing any attention, speech, or behavior toward the child. Thus, higher ratings indicate higher levels of responsiveness reflected in parents' behaviors at a given moment, whereas negative ratings represent not just a lack of responsiveness, but active dismissiveness or invalidation of children's needs (e.g., "Don't bother me!"). Ratings were based on mothers' body orientation, verbalizations, vocalizations, facial expressions, and/or gestures. Note that although second-by-second ratings were obtained, each second was not judged in isolation. Rather, research assistants viewed the ongoing stream of behavioral instances and then assigned corresponding ratings to the seconds involved (see S3 in the Supporting Information for details). The same approach was applied to the rating of challenging child behaviors.

Each case was rated independently by a trained research assistant, and 31 randomly selected videos (20% of the sample) were double-coded. The ICC across all double-coded videos was .82, and consensus ratings were obtained for 4 of the 31 double-coded videotapes that had ICCs below .70. All mothers showed at least some behaviors that received non-zero ratings. Most mothers (89%) were highly responsive to their children (i.e., receiving a 3) at some point while their lowest scores during the interaction ranged from −3 to 0, showing substantial within-person dynamic changes. The second-by-second ratings were also averaged across the task for each mother to represent the overall degree of responsiveness. Of a possible range of −3 to 3, the average score ranged from −0.10 to 1.83 ($M = 0.39$, $SD = 0.31$).

Maternal subjective experience of negative emotions

Mothers completed questionnaires during the wait task, including one in which they reported their emotions about how the child was handling the wait. Mothers rated the extent to which they felt each of 8 positive and 12 negative emotions on an 11-point Likert scale from 0 "not at all" to 10 "strongly." An average score across the 12 negative emotions (i.e., impatient, annoyed, irritated, angry, nervous, tense, anxious, scared, bored, disappointed, discouraged, sad) was calculated to represent each mother's subjective experience of negative emotions (possible range = 0–10). There was a good internal consistency across the items (Cronbach's $\alpha = .88$). On average, mothers reported feeling relatively low levels of negative emotions ($M = 1.30$, $SD = 1.25$) and used only the lower half of the scale (Range = 0–5.33).

Parenting hassles

During the visit, mothers completed the 20-item Parenting Daily Hassles scale (PDH; Crnic & Booth, 1991). Each item describes a minor event related to the caring of young children that occurs routinely in life (e.g., "Being nagged, whined at, complained to," "The need to keep a constant eye on where the kids are and what they are doing"). Respondents indicate how often each event occurs (i.e., frequency score, rated on a Likert Scale of 1 "rarely" to 4 "constantly") and how much of a hassle the event has been for them over the past 6 months (i.e., intensity score, rated on a Likert Scale of 1 "low" to 5 "high"). Both the frequency scale and the intensity scale of PDH have shown good internal consistency in previous studies and have been associated with lower satisfaction about parenting experiences and feelings of fatigue (Crnic & Greenberg, 1990; White et al., 2009). Here, the 20 intensity items were averaged to indicate mothers' experience of hassles related to parenting challenges (Cronbach's $\alpha = .87$ in this sample). The average score ranged from 1.20 to 4.15 ($M = 2.34$, $SD = 0.58$; possible range = 1–5).

Data preparation and analysis

Before testing hypotheses, we examined correlations among the summarized measures. Then, ordinary differential equation (ODE) modeling, which has been applied to study dynamic system functioning and self-regulatory processes (Cole et al., 2017; Steele & Ferrer, 2011), was used to model the temporal dynamics of variables hypothesized in Figure 1. ODE treats time as a continuous variable; compared to discrete-time modeling that imposes equally split time intervals, continuous-time modeling assumes that the underlying process is continuous (even if it is observed at regular intervals). Therefore, continuous-time modeling can better account for the timing of changes and is more appropriate for modeling processes that do not unfold on a unified time course (de Haan-Rietdijk et al., 2017). A two-step approach (Chow, 2019) was adopted. Using functional data analysis (FDA; Ramsay & Silverman, 2005), we first obtained the smoothed time-series estimates and derivatives of challenging child behavior, maternal RSA, and maternal responsiveness. FDA was completed using the 'getdx()' function in the *dynr* R package (version 0.1.15-1; Chow, 2019; Ou et al., 2019), which incorporates functions from the *fda* R package (version 2.4.8; Ramsay et al., 2009). Given the interest in the first derivatives representing the *velocity* (indicating both the direction and rate of change at a given moment) of variables, the time-series data were approximated using fifth-order B-splines functions with roughness penalty (penalizing the integrated squared third derivative). Guided by the generalized cross-validation index, the smoothing parameter λ was set at .1 for all three variables. The smoothed level and velocity for individual i at time t are written as $\mathrm{CLB}_i(t)$ and $\frac{d\mathrm{CLB}_i(t)}{dt}$ for challenging child behavior, $\mathrm{RSA}_i(t)$ and $\frac{d\mathrm{RSA}_i(t)}{dt}$ for maternal RSA, and $\mathrm{RES}_i(t)$ and $\frac{d\mathrm{RES}_i(t)}{dt}$ for maternal responsiveness. The predictive element of the models is embedded through the smoothed derivatives, which incorporate information from surrounding moments (temporally closer observations get greater weight) and reflect how the variable is changing at the moment. The hypotheses were then tested using a set of first-order ODEs within a multilevel modeling framework.

Intra-individual dynamic processes

The intra-individual dynamic processes (Hypotheses 1a to 1d) were examined using a set of ODE models specified as:

$$\frac{d\mathrm{RSA}_i(t)}{dt} = a_{1i} + b_{1i}\left(\mathrm{RSA}_i(t) - \overline{\mathrm{RSA}_i}\right) + p_i\mathrm{CLB}_i(t) + f_i\mathrm{RES}_i(t) + u_i(t), \quad (1)$$

$$\frac{d\mathrm{RES}_i(t)}{dt} = a_{2i} + b_{2i}\mathrm{RES}_i(t) + r_i\left(\mathrm{RSA}_i(t) - \overline{\mathrm{RSA}_i}\right) + v_i(t), \quad (2)$$

$$\frac{d\mathrm{CLB}_i(t)}{dt} = a_{3i} + b_{3i}\mathrm{CLB}_i(t) + c_i\mathrm{RES}_i(t) + w_i(t). \quad (3)$$

The velocity of maternal RSA for individual i at time t ($\frac{d\mathrm{RSA}_i(t)}{dt}$) was modeled as a function of the intercept (a_{1i}), the concurrent level of RSA (b_{1i}; relative to personal average $\overline{\mathrm{RSA}_i}$), challenging child behavior (p_i), maternal responsiveness (f_i), and the residual $u_i(t)$. The velocity of maternal responsiveness for individual i at time t ($\frac{d\mathrm{RES}_i(t)}{dt}$) was modeled as a function of the intercept (a_{2i}), the concurrent level of maternal responsiveness (b_{2i}) and RSA (r_i), and the residual $v_i(t)$. The velocity of challenging child behavior for individual i at time t ($\frac{d\mathrm{CLB}_i(t)}{dt}$) was modeled as a function of the intercept (a_{3i}), the concurrent level of challenging child behavior (b_{3i}) and maternal responsiveness (c_i), and the residual $w_i(t)$.The intercept parameters (a_{1i} to a_{3i}) represent the expected velocity of maternal RSA, responsiveness, and challenging child behavior when their levels are at set points and all other predictors are equal to 0. Meanwhile, b_{1i} to b_{3i} reflect the intrinsic dynamics of those variables (how their velocity is predicted by their momentary deviation from set points). It is expected that b_{1i}, b_{2i}, and b_{3i} would be negative, reflecting intrinsic forces to return to set points. The four core dynamic processes are represented by p_i (*perturbation as a function of child behavior*), r_i (*regulation of parenting behavior*), c_i (*regulation of child behavior*), and f_i (*self-regulatory feedback process*). Based on the hypotheses, p_i, r_i, and c_i are expected to be negative, whereas f_i is expected to be positive.

Each of the person-specific parameters was further modeled as a function of its sample-average value (γ_{a10}, γ_{a20}, γ_{a30}, γ_{b10}, γ_{b20}, γ_{b30}, γ_{p0}, γ_{r0}, γ_{c0}, γ_{f0}). Four random effects were estimated for the four parameters representing the dynamic processes of interest (e_{pi}, e_{ri}, e_{ci}, e_{fi}), representing inter-individual variations in p_i, r_i, c_i, and f_i. Hypotheses 1a–1d were examined based on estimates of γ_{p0}, γ_{r0}, γ_{c0}, and γ_{f0}, that is, the intra-individual processes of parental self-regulation for the prototypical mother of this sample.

Inter-individual differences in the dynamic processes

To test Hypotheses 2a and 2b, the summarized measures of parenting behaviors and experiences were entered as predictors of the four person-specific parameters representing the core dynamic processes (p_i, r_i, c_i, f_i). For instance, to examine how Predictor1 to Predictor$N$ were associated with c_i, Equation (3) was expanded as

$$\frac{d\mathrm{CLB}_i(t)}{dt} = \left(\gamma_{a30} + \gamma_{a31}\mathrm{Predictor1}_i + \ldots + \gamma_{a3N}\mathrm{Predictor}N_i\right) + \gamma_{b30}\mathrm{CLB}_i(t) + \left(\gamma_{c0} + \gamma_{c1}\mathrm{Predictor1}_i + \ldots + \gamma_{cN}\mathrm{Predictor}N_i + e_{ci}\right)\mathrm{RES}_i(t) + w_i(t),$$

where the main effects of the predictors on the velocity of challenging child behavior were estimated as γ_{a31} to γ_{a3N}, and their interactions with maternal responsiveness (i.e., how the predictors moderated maternal regulation of child behavior) were estimated as γ_{c1} to γ_{cN}.

First, the average level of maternal responsiveness and mothers' subjective negative emotions—parenting behaviors and experiences specific to the wait task—were entered as predictors, with the average level of challenging child behaviors included as a covariate. Then, parenting hassles—mothers' negative experiences related to everyday parenting challenges—was entered to predict the dynamic processes in separate models. All predictors were centered around sample means. The aim of these analyses was to evaluate whether the proposed dynamic processes of parental self-regulation were associated with the overall quality of parenting behaviors or experiences. Thus, we did not include other covariates that may be part of the etiology of these behaviors or experiences (e.g., child age, parental education). Child gender was explored as a potential moderator of the four core dynamic processes; race was not examined as a moderator due to limited variability in this sample.

All models were fit to the 88,331 repeated measures nested within 157 mothers using the *nlme* package (version 3.1-149; Pinheiro et al., 2017) in R, with restricted maximum likelihood estimation and with incomplete data treated using standard missing-at-random assumptions. Statistical significance was evaluated at $\alpha = .05$.

RESULTS

The bivariate correlations among the summarized measures are presented in Table 1. The average levels of child challenging behavior, mothers' subjective negative emotions, and maternal responsiveness were all positively correlated. That is, mothers whose children were rated by research assistants as more challenging reported feeling more negative emotions, but they showed more responsive parenting behaviors to attend to children's needs. Higher levels of self-reported parenting hassles were correlated with more challenging child behavior and maternal negative emotions during the task, but not with observed maternal responsiveness. Mothers' average RSA during the task was not correlated with challenging child behavior, maternal negative emotions, maternal responsiveness, or parenting hassles.

Intra-individual dynamic processes involved in parental self-regulation

Estimates of parameters indicating the intra-individual dynamic processes are presented in Table 2 and Figure 2. Regarding the intrinsic dynamics of the variables, as expected, both maternal RSA and responsiveness tended to return toward set points. That is, when mothers' RSA was higher than their task-average, their RSA tended to decrease; when RSA was lower than their task-average, it tended to increase ($\gamma_{b10} = -.0009$, $t(86,875) = -2.10$, $p = .04$). Similarly,

TABLE 1 Means, standard deviations (*SD*), and correlations of the overall quality of parenting behaviors and experiences

	1	2	3	4	5
1. Challenging child behavior	—				
2. Maternal RSA	−.02	—			
3. Maternal responsiveness	.54***	.14	—		
4. Maternal negative emotions	.44***	−.07	.22**	—	
5. Parenting hassles	.23**	−.13	.12	.21**	—
M	0.59	5.32	0.39	1.30	2.34
SD	0.47	1.15	0.31	1.25	0.58

Note: Challenging child behavior, maternal respiratory sinus arrhythmia (RSA), and maternal responsiveness were averaged across the wait task.
**$p<.01$; ***$p<.001$.

TABLE 2 Parameter estimates for the models examining intra-individual dynamic processes

Fixed effect	Estimate (*SE*)	*p*
Equation 1: Predicting RSA velocity		
γ_{a10} (intercept of RSA velocity)	**−.0029** (.0004)	<.01
γ_{b10} (intrinsic dynamics of RSA)	**−.0009** (.0004)	.04
γ_{p0} (perturbation by child behavior)	.0010 (.0008)	.20
γ_{f0} (self-regulatory feedback process)	**.0081** (.0010)	<.01
Equation 2: Predicting RES velocity		
γ_{a20} (intercept of RES velocity)	−.0016 (.0013)	.22
γ_{b20} (intrinsic dynamics of RES)	**−.0037** (.0014)	<.01
γ_{r0} (regulation of parenting behavior)	**−.0081** (.0017)	<.01
Equation 3: Predicting CLB velocity		
γ_{a30} (intercept of CLB velocity)	**.0115** (.0014)	<.01
γ_{b30} (intrinsic dynamics of CLB)	**.0057** (.0012)	<.01
γ_{c0} (regulation of child behavior)	**−.0372** (.0023)	<.01

Random effect	Estimate	95% CI
Standard deviation		
$\sigma_{e_{pi}}$ (perturbation by child behavior)	.0074	[.0062, .0089]
$\sigma_{e_{fi}}$ (self-regulatory feedback process)	.0103	[.0088, .0120]
$\sigma_{e_{ri}}$ (regulation of parenting behavior)	3.0088E-5	[2.7827E-12, 325.3228]
$\sigma_{e_{ci}}$ (regulation of child behavior)	.0218	[.0178, .0266]
σ_u (residual of RSA velocity)	.0899	[.0895, .0904]
σ_v (residual of RES velocity)	.3434	[.3418, .3451]
σ_w (residual of CLB velocity)	.3105	[.3091, .3120]
Correlation		
$r(e_{pi}, e_{fi})$	−.1589	[−.2956, −.0159]

Note: The estimate of $\sigma_{e_{ri}}$ was very small and thus written in scientific notation. Statistically significant fixed effect coefficients were bolded.
Abbreviations: CI, confidence interval; CLB, challenging child behavior; RES, maternal responsiveness; RSA, respiratory sinus arrhythmia; *SE*, standard error.

maternal responsiveness showed a tendency to return to 0 (i.e., no observable attention, speech, or behavior toward child; $\gamma_{b20} = -.0037$, $t(86,876) = -2.67$, $p<.01$). Meanwhile, contrary to prediction, children's challenging behavior tended to self-amplify ($\gamma_{b30} = .0057$, $t(88,172) = 4.73$, $p<.01$). After partialing out the effect of maternal responsiveness, when children showed challenging behaviors, the level of challengingness increased over time. The estimates of the intercepts suggested that maternal RSA tended to decrease ($\gamma_{a10} = -.0029$, $t(86,875) = -7.49$, $p<.01$) and challenging child behavior tended to increase ($\gamma_{a30} = .0115$, $t(88,172) = 8.01$, $p<.01$) when other predictors were at set points. There was no increasing or decreasing trend for maternal responsiveness ($\gamma_{a20} = -.0016$, $t(86,876) = -1.22$, $p = .22$).

Hypothesis 1a (i.e., *perturbation by child behavior*) was not supported, at least for the prototypical mother

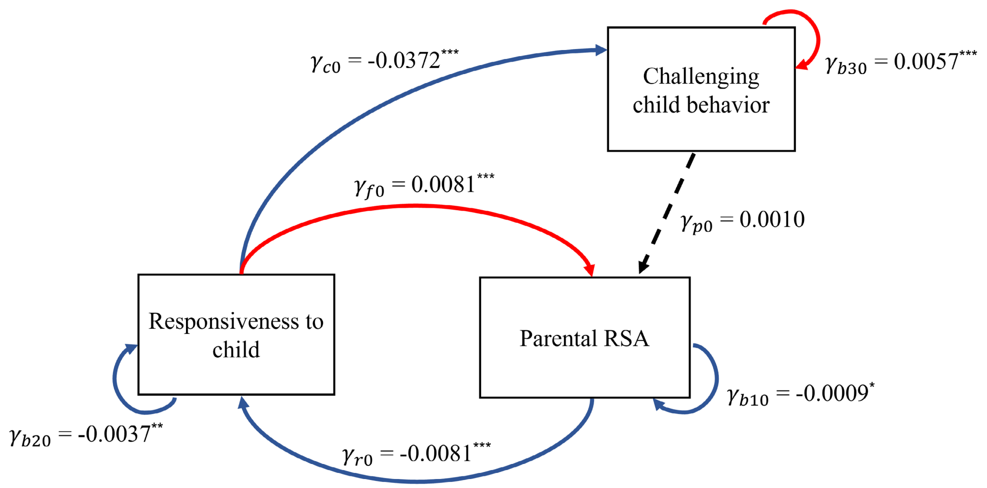

FIGURE 2 Dynamic processes supported by data from mothers and their preschool-age children during a wait task. *Note*: Each arrow indicates that the momentary level of one variable (start of arrow) is associated with the momentary velocity of the other variable (end of arrow). Solid lines represent statistically significant associations (red = positive association, blue = negative association). *$p<.05$. **$p<.01$. ***$p<.001$.

in this sample. The velocity of maternal RSA was not predicted by the momentary level of challenging child behavior (γ_{p0} = .0010, $t(86,875)$ = 1.29, p = .20). However, Hypotheses 1b, 1c, and 1d were all supported. For the prototypical mother, there was an increase in maternal responsiveness when maternal RSA was lower than task-average (γ_{r0} = −.0081, $t(86,876)$ = −4.86, $p<.01$; *regulation of parenting behavior*). In turn, when maternal responsiveness was at higher levels, there was a decrease in challenging child behavior (γ_{c0} = −.0372, $t(88,172)$ = −16.25, $p<.01$; *regulation of child behavior*) and an increase in maternal RSA (γ_{f0} = .0081, $t(86,875)$ = 8.46, $p<.01$; *self-regulatory feedback process*). To summarize, although the momentary velocity of maternal RSA was not associated with children's challenging behavior observed by research assistants, results were consistent with the negative feedback loop between maternal RSA and responsiveness, and the hypothesized relation between responsive parenting behavior and decreases in challenging child behavior.

It should be noted that although the model of Equation (2) converged, the standard deviation of the random effect ($\sigma_{e_{ri}}$) had a very wide confidence interval, suggesting that there was some uncertainty in estimating the amount of inter-individual differences in r_i (i.e., regulation of parenting behaviors). The estimated standard deviations of the other random effects ($\sigma_{e_{pi}}$, $\sigma_{e_{ci}}$, $\sigma_{e_{fi}}$) were all significantly different from 0, suggesting inter-individual differences in those dynamic processes.

Inter-individual differences in the dynamic processes

For parsimony, we only describe parameters reflecting how the predictors were associated with the four dynamic processes (Table 3).

The data did not provide strong support for Hypothesis 2a. First, the relation between task-average maternal responsiveness and how maternal RSA changed as a function of observed child behavior (i.e., perturbation as a function of child behavior) was consistent with the hypothesis (coefficient = −.0061, $t(86,869)$ = −2.32, p = .02). However, rather than being unperturbed, mothers with lower average responsiveness showed significant increases in RSA when child behavior was challenging (e.g., when mothers' task-average responsiveness was one standard deviation below sample mean, p_i was estimated to be .0033, SE = .0011, $p<.01$). Meanwhile, even mothers with the highest level of responsiveness observed in this sample did not show significant momentary decreases in RSA when child behavior was rated as challenging (p_i estimated to be −.0074, SE = .0039, p = .06). Second, the value of r_i was more negative as predicted (indicating a stronger regulation of parenting behaviors) among mothers with higher task-average responsiveness, but the association did not reach statistical significance (coefficient = −.0116, $t(86,873)$ = −1.83, p = .07).

Hypothesis 2b was partially supported. First, neither mothers' self-reported negative emotions during the task (coefficient = −.0005, $t(86,869)$ = −0.76, p = .44) nor parenting hassles in everyday life (coefficient = .0025, $t(86,873)$ = 1.92, p = .05) were significantly associated with a greater perturbation due to children's behavior. On the contrary, mothers who reported higher levels of parenting hassles showed a marginally significant tendency toward less perturbation. Second, parenting hassles, but not mothers' negative emotions during the task, was associated with lower efficiency in regulating the child (coefficient = .0091, $t(88,171)$ = 2.34, p = .02). It is worth noting though that the estimate of c_i was significantly negative even with the highest level of parenting hassles observed in this sample (c_i estimated to be −.0210, SE = .0073, $p<.01$), suggesting

TABLE 3 Associations between predictors and inter-individual differences in the dynamic processes

Intra-individual parameter Inter-individual predictor	Estimate (*SE*)	*p*
Parenting behaviors and experiences during the wait task		
p_i (perturbation by child behavior)		
Task-average challenging child behavior	.0007 (.0019)	.72
Task-average maternal responsiveness	**−.0061** (.0026)	.02
Maternal negative emotions	−.0005 (.0006)	.44
r_i (regulation of parenting behavior)		
Task-average challenging child behavior	.0037 (.0047)	.43
Task-average maternal responsiveness	−.0116 (.0063)	.07
Maternal negative emotions	.0007 (.0015)	.66
c_i (regulation of child behavior)		
Task-average challenging child behavior	.0038 (.0058)	.51
Task-average maternal responsiveness	−.0066 (.0079)	.40
Maternal negative emotions	.0017 (.0019)	.38
f_i (self-regulatory feedback process)		
Task-average challenging child behavior	.0005 (.0025)	.84
Task-average maternal responsiveness	−.0026 (.0035)	.46
Maternal negative emotions	**−.0018** (.0008)	.03
Parenting experiences in everyday life		
p_i (perturbation by child behavior)		
Parenting hassles	.0025 (.0013)	.05
r_i (regulation of parenting behavior)		
Parenting hassles	−.0001 (.0030)	.99
c_i (regulation of child behavior)		
Parenting hassles	**.0091** (.0039)	.02
f_i (self-regulatory feedback process)		
Parenting hassles	**−.0048** (.0017)	<.01

Note: Statistically significant coefficients were bolded.
Abbreviation: *SE*, standard error.

that responsive parenting behaviors were still related to decreases in children's challenging behavior. Lastly, as predicted, both maternal negative emotions (coefficient = −.0018, $t(86{,}869) = -2.20$, $p = .03$) and parenting hassles (coefficient = −.0048, $t(86{,}873) = -2.87$, $p < .01$) were associated with a weaker self-regulatory feedback process. While f_i was .0081 for the prototypical mother, it was estimated to be .0061 ($SE = .0014$, $p < .01$) when mothers' self-reported negative emotions were one standard deviation above sample mean, and down to .0010 ($SE = .0035$, $p = .78$) at the highest level of maternal negative emotions in this sample. Meanwhile, f_i was estimated to be .0055, still significantly positive ($SE = .0024$, $p = .02$), even at the highest level of parenting hassles observed in this sample.

As shown in Table 3, the task-average level of challenging child behavior was not associated with any of the four dynamic processes. The average level of maternal responsiveness was not related to the efficiency in regulating the child or mothers' self-regulatory feedback process. Mothers' subjective negative emotions and parenting hassles were not associated with the regulation of parenting behavior. Exploratory analysis suggested that only one dynamic process differed by child gender—the regulation of child behavior (higher levels of maternal responsiveness predicting decreases in challenging child behavior) was weaker for boys.

DISCUSSION

Taking a dynamic systems approach, this study proposed and tested a model of parental self-regulation processes and investigated how the dynamic processes were associated with the overall quality of parenting behaviors and experiences. Time-series data collected from mothers and their young children during a wait task revealed temporal dynamics that were generally supportive of the hypothesized dynamic processes driving moment-to-moment changes in maternal RSA and responsiveness. These dynamic processes were further associated with mothers' overall subjective negative emotions and responsiveness during the task, as well as self-reported parenting hassles in everyday life. This study provides the first conceptual account of how parental self-regulation unfolds in the challenging moments of parenting, enabling parents to attend to their children's needs and restore their own internal equilibrium. The findings highlight the value of dynamic analysis in unveiling potential mechanisms underlying at-risk parenting (e.g., low levels of responsiveness) and negative parenting experiences.

Characterizing the dynamic processes of parental self-regulation

As the hypothesized "trigger" of the regulatory processes, the *perturbation as a function of child behavior* was operationalized as mothers showing decreases in RSA when children showed behaviors that would challenge a typical adult. However, we did not find evidence for it based on research assistants' ratings of child behavior. One possibility is that those ratings do not always align with maternal appraisal of what is challenging in their children's behavior. It is difficult to directly access mothers' appraisal on a moment-to-moment basis, and research assistants' assessment of challengingness was made without the knowledge of what is typical or manageable for each child. Thus, the current measure may have limited power to detect parents' reactivity. Future research can try to capture mothers' subjective rating of what is challenging for them on a moment-to-moment basis (e.g., through retrospective self-report based on videotapes), although it may be subject to recall bias and feasibility issues (i.e., due to participant burden). Interestingly, lower task-average maternal responsiveness was associated with an *increase* in RSA when children's behavior was rated as challenging. This might be the physiological manifestation of these parents trying to stay uninvolved in the challenging moments. Notably, the wait task, which represents a common parenting challenge, differs from the typical tasks used to observe parental responsiveness (e.g., free play or teaching). Lower levels of maternal responsiveness during this task do not necessarily reflect unresponsiveness as a general characteristic of mothers. Some mothers may expect their children to cope with the situation independently if they do not intervene.

Although we did not find decreasing RSA as a function of observed child behavior, when maternal RSA did reach lower levels, there was an increase in maternal responsiveness, consistent with the hypothesized *regulation of parenting behavior*. This suggests that when parents' internal equilibrium is perturbed in a parenting situation, they could manage to react by being more attentive and responsive to their children—a child-centered way to cope with parenting challenges. Extending previous research linking parents' trait-like executive capacity (e.g., working memory, set-shifting) with parenting behaviors (Deater-Deckard et al., 2010; Sturge-Apple et al., 2019), we provide a way to infer the ongoing regulation of parenting behavior in challenging moments. In this sample, there was limited inter-individual variability in the regulation of parenting behavior (i.e., mothers rather uniformly showed increases in responsiveness when their RSA was below their task averages). This may explain the relatively weak association between task-average maternal responsiveness and the strength of the regulation process. Possibly, in samples including parents with higher risk, inter-individual differences in the regulation of parenting behaviors may be more salient.

Lastly, the findings provide an account for how parents balance attending to child's needs *and* restoring their own equilibrium. In this sample, maternal attempts to address parenting challenges in a child-centered way predicted decreases in children's challenging behavior and increases in mothers' own RSA, indicating a recovery from arousal. The association between maternal responsiveness and changes in child behavior was weaker among mothers who reported higher levels of parenting hassles, consistent with a common factor contributing to parenting stress—child behaviors that are difficult to manage (Crnic & Low, 2002). Our findings further suggest that self-regulatory feedback processes play an important role in parenting experiences, with a weaker feedback process related to both negative emotions and parenting hassles. Those parents may manage to response appropriately to their children (at least in the laboratory setting) but experience accumulating frustration during parenting challenges. Mothers' negative emotions were not related to the perturbation process. Thus, although studies often conceptualize parents' subjective negative emotions as how *reactive* parents are toward child behaviors (Dix, 1991; Rueger et al., 2011), our findings reveal that the subjective experiences may not capture the initial reactivity, but rather the efficiency of ensuing regulation processes.

Overall, the dynamic findings provide a consistent picture with the correlations among summarized measures. As shown in Table 1, mothers whose children were more challenging during this task reported feeling more negative emotions but managed to be more responsive to their children. Those correlations indicate the existence of some regulation that enabled mothers to maintain or increase responsive parenting behaviors in a challenging situation. The dynamic findings further reveal how the actual regulatory processes unfolded on a moment-to-moment basis, and how mothers balanced internal and external demands.

Limitations and future directions

The current study has some limitations that warrant caution in the interpretation and generalization of findings. First, we did not measure mothers' appraisals and subjective feelings on a moment-to-moment basis. Previous studies have measured these constructs dynamically by having parents review their own videos and recall emotional experiences at each moment (Lorber & Slep, 2005). However, due to concerns of participant burden and recall bias, we did not take that approach. Second, this study focused on parental self-regulation and considered children as sources of external demands that are regulated by parents. Future work could extend the model to include children as a more active part of the system with their own regulatory dynamics. Third, as a proof-of-concept study, we used data from a mostly White, college-educated convenience sample, which does not represent the range of parents there are in the world. However, this study offers a potential framework for studying parental self-regulation that can be applied to examining its variations by sociocultural factors or parenting-related risks.

Finally, this study only tested the model among mothers and preschool-age children during a specific laboratory task. More studies are needed to replicate the model in different parenting situations, among other parental figures, and among parents of children at different developmental stages. In addition to replicating and extending the model, another important future direction is to adopt experimental designs to investigate whether and how these dynamic processes can be manipulated or modified. For instance, studies could examine whether the regulation of parenting behavior and the restoration of internal equilibrium would be influenced after parents experience acute stressors, or when parents are instructed to use specific strategies to manage their emotions. Such studies would inform preventions and interventions to improve parental competence and further, children's psychosocial development.

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CONFLICT OF INTEREST

The authors declare that there are no potential or actual interest conflicts.

DATA AVAILABILITY STATEMENT

All the materials and measures (except for the established scales that are available through the original sources cited in the manuscript) have been reported or included in Supporting Information. Data are available through arrangement with the Development of Self-Regulation Dynamics Project investigators in accordance with all relevant IRB privacy protocols.

ETHICS STATEMENT

Study procedures were approved by the Institutional Review Board of The Pennsylvania State University (Study ID: STUDY00005112).

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