Development of Emotion Regulation Dynamics Across Early Childhood: a Multiple Time-Scale Approach

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Abstract

Children should become more effective at regulating emotion as they age. Longitudinal evidence of such change, however, is scarce. This study uses a multiple-time scale approach to test the hypothesis that the self-regulation of emotion—the *engagement of executive processes to influence the dynamics of prepotent emotional responses*—becomes more effective as children move through early childhood. Second-by-second time-series data obtained from behavioral observation of 120 children (46% female) during an 8-min frustration-eliciting wait task completed at four ages (24 months, 36 months, 48 months, 5 years) were modeled using bivariate coupled differential equation models designed to capture age-related changes in the intrinsic dynamics and bidirectional coupling of prepotent and executive processes. Results revealed indirect influences of executive processes on the intrinsic dynamics of children's desire and frustration increased with age but also revealed complex and non-linear age-related changes in how specific aspects of the dynamic interplay between prepotent responses and executive processes influence the effectiveness of regulation at different ages. The findings illustrate the utility of using a dynamics system approach to articulate and study how specific aspects of emotion regulation change with age.

Keywords Emotion regulation development · Early childhood · Dynamic systems modeling · Damped oscillator model

Individual differences in children's ability to regulate their emotions are associated consistently with many developmental outcomes. But there is a paucity of evidence about how this ability develops. Studies have focused on the correlates of between-person differences, with little attention to the within-person aspects of emotion regulation. Consequently, we do not know when and how children's use of purported regulatory strategies actually influences their emotions (Cole,

Martin, & Dennis, 2004; Cole, 2016). We employ a theoretically driven framework that conceptualizes self-regulation in terms of the *relation* between engaging executive processes (indexed by children's strategy use) and displaying prepotent responses (indexed by children's desire and frustration when their goal is blocked). We test the developmental hypothesis that strategies that engage executive—i.e., higher-order cognitive—processes come to moderate the intrinsic fluctuations of prepotent desire and frustration more effectively over the course of early childhood.

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Within-Person Emotion Dynamics

Increasingly, scholars appreciate that emotion is not defined by a feeling or expression. Rather feelings and expressions provide glimpses into a dynamic psychological process (Davidson, 1993; Gross, 2001; Hoeksma, Oosterlaan, & Schipper, 2004; Kuppens, Oravecz, & Tuerlinckx, 2010; Lewis, 2005). It entails appraising one's circumstances and readying to act to gain, sustain, or regain goals for well-being (Barrett & Campos, 1987; Ekman & Cordaro, 2011;

Tooby & Cosmides, 2000). This process is dynamic because it changes moment to moment. Observational studies of children document how their emotions change and fluctuate over the moments of a single situation or reaction (Grolnick, Bridges, & Connell, 1996; Potegal, Kosorok, & Davidson, 2003). We need to capitalize on those temporal dynamics to move beyond interpreting greater total amount of negative emotion as evidence of less well-regulated emotion. We need to demonstrate the effects of strategy on emotion dynamics. Studies that assess children's strategies find inverse correlations between amount of strategy use and overall level of negative emotion. Yet, the *direction of influence* is unknown. Emotion regulation is located in the influence of strategies, particularly those that engage executive processes, on prepotent emotion dynamics. Its study requires analytic approaches that articulate and test how strategy use comes to moderate moment-to-moment changes in emotion.

Children's Self-Regulation of Emotion

Most models of self-regulation propose that the engagement of executive processes, such as attention control and language-mediated reasoning, can delay, minimize, or end enactment of prepotent responses (Cole, Ram, & English, 2019). Prepotent responses are behaviors that are highly probable in specific circumstances, such as frustration when a goal is blocked (Arnold, 1960; Dillon & Pizzagalli, 2007; Miyake et al., 2000). For example, a strategy such as distraction, i.e., effortfully shifting attention from a blocked goal that stimulates prepotent desire and frustration, depends on the executive attention network (Rothbart, Sheese, Rueda, & Posner, 2011).

Kopp (1982) posited that as young children develop, their language and cognitive development provides internal resources that enable them to generate strategies that regulate their prepotent responses. They may verbalize their needs or seek information from an adult or redirect their attention (e.g., Buss & Goldsmith, 1998; Calkins & Johnson, 1998; Cole et al., 2011; Gilliom, Shaw, Beck, Schonberg, & Lukon, 2002; Grolnick et al., 1996). Whereas self-soothing is usually a relatively automatic, non-effortful strategy, verbalizations such as "I can play after I finish my dinner?" require language-based reasoning, and distraction requires attention control (Perry & Calkins, 2018; Rothbart et al., 2011).

Children as young as 3 and 4 years can distract themselves from something they want but cannot have (e.g., Cole et al., 2011; Gilliom et al., 2002; Stansbury & Sigman, 2000). However, the effectiveness of their strategies on their desire and anger about not getting what they want is only momentary (Cole, Bendežú, Ram, & Chow, 2017). By the time they reach kindergarten age, they need a more enduring effect of their efforts—teachers expect children to follow directives even if doing so prevents them from doing something they prefer

(Blair & Raver, 2015; Denham, Bassett, Zinsler, & Wyatt, 2014). Theory and practice suggest that the *effectiveness* of children's use of executive process-based strategies on the dynamics of their prepotent emotions must improve between ages 24 and 60 months.

Theoretical models of self-regulation imply that executive processes directly influence prepotent responses, i.e., as one process increases, it "pushes down" the other process. But the challenge for young children is not eliminating desire (a direct effect) but being able to modulate their desire and frustration (an indirect effect). Moreover, we know some children have difficulty regulating emotion. Prepotent emotions may influence, directly or indirectly, the engagement of executive processes, e.g., interfere with maintaining a strategy (Cole et al., 2017).

Modeling the Development of Emotion Regulation Dynamics

Our aim in this paper is to provide initial empirical evidence that, among children, there is (a) within-person influence of engagement of executive processes (strategy use) on prepotent responses (emotion dynamics) and (b) systematic age-related change in effectiveness (strategy use moderating emotion dynamics) of that influence. To demonstrate that strategies engaging executive processes *change* prepotent responses requires demonstrating that specific changes in one stream of behavior (strategic effort) changes another stream of behavior (emotions) (Cole et al., 2004). Advances in mathematical modeling describe dynamic systems and test regulatory relations between executive process and prepotent responses and how those relations change with age (Cole et al., 2017; Morales et al., 2018).

Several scientific disciplines use dynamic systems modeling approaches to describe and test hypothesis about change processes. Particularly useful for studying human regulatory processes is a second-order ordinary differential equation (ODE) describing oscillatory movement toward an equilibrium state, i.e., the damped linear oscillator model (Boker & Nesselroade, 2002). This model has been useful in representing changes in individuals' emotions in a variety of settings, including co-regulation between partners (Butner, Diamond, & Hicks, 2007) and regulation of fear in novel situations (Morales et al., 2018). Here, we used a damped oscillator model and multiple timescale study design (Ram & Diehl, 2015) to examine age-related changes in the moment-to-moment dynamics of children's executive processes and prepotent responses.

We constructed the mathematical model to specifically articulate emotion regulation as the *engagement of executive processes to both influence and moderate intrinsic dynamics of prepotent responses*, and examine three types of dynamics: (1) the internal dynamics of executive

processes and prepotent responses, which capture changes in each process that are unrelated to the other process (intrinsic dynamics); (2) the direct influence of one process on the other, to include the possibility that executive processes directly push down prepotent responses (extrinsic dynamics); and (3) indirect influences wherein one process moderates the intrinsic dynamics of the other process, including how engagement of executive processes facilitates the intrinsic decay (waning) of prepotent responses over time. Based on available conceptual models and empirical evidence, we posited that, as children age, their engagement of executive processes would indirectly and increasingly cause their prepotent responses to wane. Placing the dynamic model in a developmental framework, we used longitudinal data to test whether these different patterns of relations between executive processes and prepotent responses changed with age, such that children were most effective at self-regulation of emotion at age 5 years relative to prior ages of 24, 36, and 48 months.

Method

Data are drawn from a longitudinal study of development of children's emotion regulation. Details relevant to the present analysis are given here.

Participants

Participants were 120 children (46% female) and their families living in economically strained households in rural and semi-rural communities in central Pennsylvania. At initial recruitment (age 18 months), average family annual income was \$40,459 ($SD = \$14,170$) with most mothers (64%) and approximately half of fathers (54%) completing at least some college education. Mothers described themselves as homemakers (29%), working part-time (31%), or working full-time (40%); and most fathers described themselves as working full-time (90%). Mean family income-to-needs ratio, a measure of the ability to meet basic needs relative to US poverty standards, was 2.32 ($SD .87$), indicating economic strain. The children's racial identity was typical of the region in which families lived (93% white; 7% biracial).

The present analysis uses repeated measures data obtained during a wait task procedure administered during laboratory visits when children were age 24 months ($n = 111$), 36 months ($n = 120$), 48 months ($n = 120$), and 5 years ($n = 96$). Attrition was not related to outcome variables, income, mother's and father's level of education and employment type, or child gender and race (all $ps > .17$).

Wait Task Procedure

At each laboratory visit children and their mothers completed a wait task wherein the child is faced with a blocked goal (e.g., frustrated; Vaughn, Kopp, & Krakow, 1984). A research assistant seated the mother and child at separate tables in an observation room. After giving the child a boring toy to play with (cloth cymbal at age 24 months, toy car without wheels at 36 months, toy horse with missing legs at 48 months, and an easy puzzle at 5 years), and the mother some questionnaires to fill out, the research assistant placed a package wrapped in shiny paper on the table near the child and indicated that it was a gift for the child. When the research assistant left the room, the mother (as previously instructed) told the child to wait until she had finished her work to open the gift. After 8 min (480 s) the research assistant returned and prompted the mother to direct the child to open the gift. Throughout the task, child behavior was videotaped for later coding and analysis.

Measures

Children's nonverbal emotion expressions and strategies in each of the 480 s at each visit were coded by independent teams. Coders were trained to at least 80% agreement with master coders and met weekly to resolve questions and receive feedback on maintaining interrater reliability (15% of sample).

Prepotent Responses (PR) Children's PR in each second of the task was indexed using a composite of behaviors indicating desire for the gift and frustration about having to wait: *angry bids to the mother* about the demands of the wait (e.g., "I want it!"), *attention focused on the gift* (staring at, touching, and trying to open the gift), *disruptive behavior* (throwing the boring toy, interfering with mother's work), and *intensity of anger expressions*, defined by facial and vocal cues such as brow furrowing, pursed, or pressed lips, clenched jaw, square open mouth, harsh loud vocal quality (0 = *no anger*, 1 = *mild anger*, 2 = *moderate anger*, and 3 = *strong anger*; ICC = .87). For each of the 480 s of the task, presence of behavior (all Cohen's $\kappa > .83$) and intensity of anger were summed to obtain a PR score. Higher scores indicate higher PR (possible range = 0 to 6).

Executive Processes (EP) In parallel, children's EP in each second of the task was indexed using a composite of behaviors indicating use of specific strategies. An EP index was created from binary codes (e.g., Gottman, Murray, Swanson, Tyson, & Swanson, 2002; Thomas & Martin, 1976) by assigning each strategy a rank score based on what is known about the developmental ordering of the emergence of different strategies (Calkins & Johnson, 1998; Cole et al., 2011; Grolnick et al., 1996; Rothbart, Ziaie, & O'Boyle, 1992; Sethi, Mischel, Aber, Shoda, & Rodriguez, 2000): 0 = *no strategy*, 1 = *self-soothing* (e.g., thumb-sucking), 2 = *calmly seeking mother's*

attention, 3 = *calmly seeking task-relevant information* (e.g., ‘I can open it when you’re done, right?’), 4 = *brief, unfocused distraction* (e.g., shift of attention away from the gift), and 5 = *focused distraction* (e.g., engagement in another object or activity). For seconds in which a child engaged in more than one strategy, the EP score was based on the higher ranked strategy. Higher scores indicate use of strategies that require greater EP.

Age Chronological *age* was coded as a categorical variable (24 m, 36 m, 48 m, or 5 years) and invoked using a set of contrast codes that facilitated comparison of regulatory dynamics at age 5 years with earlier ages (age60 = [−0.33, −0.33, −0.33, 1.0]), 48 months with all earlier ages (age48 = [−0.5, −0.5, 1.0, 0]), and between 24 months and 36 months (age36 = [−1.0, 1.0, 0, 0]).

Data Analysis

Analysis of age-related changes in regulation made use of the PR and EP time-series obtained from each child at each visit, examples of which are shown in Fig. 1. The time-series data were analyzed using a two-stage functional ordinary differential equation mixed effects (*FODEmixed*) approach (Chow, Bendezú, Cole, & Ram, 2016). In Stage 1, functional data analysis methods are used to recast the observed time series

as an ensemble of smoothed derivatives. Specifically, derivatives indicating, separately for each individual i at each age a , the location of EP and PR at each of the $t = 1$ to 480 s (0th derivative) velocity at each second (1st derivative), and acceleration at each second (2nd derivative) are calculated using a functional data analysis procedure (implemented in R using the *fda* package, Ramsay, Hooker, & Graves, 2009). In brief, the EP and PR time series are approximated using sixth-order penalized B-splines with knot-points at all observed time points and smoothing parameter $\lambda = 0.1$. The resulting basis weights indicate the value of each of the derivatives at each of the 480 s in the time series.

In Stage 2, the time series of derivatives were person-centered and modeled as a bivariate system of differential equations that describes the *intrinsic dynamics* and *bidirectional coupling* of children’s PR and EP during the wait task. More specifically, the relations among the time series of the PR and EP derivatives were examined using a multivariate multilevel model that is parameterized to describe age-related changes in specific aspects of self-regulation.

Intrinsic Dynamics (+ Age Differences) First, a model was constructed to articulate the intrinsic dynamics of PR and EP, and to test for age differences in these dynamics. The associations among the PR derivatives were modeled as

$$\left(\frac{d^2 PR}{dt^2}\right)_{iat} = -[\eta_{PR0} + \Delta\eta_{PR1}age60_{iat} + \Delta\eta_{PR2}age48_{iat} + \Delta\eta_{PR3}age36_{iat}][PR_{iat}] - [\zeta_{PR0} + \Delta\zeta_{PR1}age60_{iat} + \Delta\zeta_{PR2}age48_{iat} + \Delta\zeta_{PR3}age36_{iat}]\left[\left(\frac{dPR}{dt}\right)_{iat}\right] + [u_{PRi}(PR_{iat})] + e_{PRiat} \quad (1.1)$$

Fig. 1 Composite time series data (level) for one child at each age. PR = prepotent response, and EP = executive process

where i indexes child, a indexes age and t indexes second. In parallel, the relations among the EP derivatives were modeled as

$$\begin{aligned} \left(\frac{d^2 EP}{dt^2}\right)_{iat} = & -[\eta_{EP0} + \Delta\eta_{EP1}age60_{iat} + \Delta\eta_{EP2}age48_{iat} + \Delta\eta_{EP3}age36_{iat}][EP_{iat}] \\ & -[\zeta_{EP0} + \Delta\zeta_{EP1}age60_{iat} + \Delta\zeta_{EP2}age48_{iat} + \Delta\zeta_{EP3}age36_{iat}]\left[\left(\frac{dEP}{dt}\right)_{iat}\right] + [u_{EP_i}(EP_{iat})] + e_{EP_{iat}} \end{aligned} \quad (1.2)$$

In Eqs. 1.1 and 1.2, the accelerations/decelerations of PR and EP at epoch t , $\left(\frac{d^2 PR}{dt^2}\right)_{iat}$ and $\left(\frac{d^2 EP}{dt^2}\right)_{iat}$ respectively, are modeled as a function of their corresponding level (0th derivative) and rates of change (1st derivative), and (following the traditional repeated measures ANOVA setup) random effects for the η_{PR0} and η_{EP0} parameters ($u_{PR_i}[PR_{iat}]$ and $u_{EP_i}[EP_{iat}]$) and dynamic noise ($e_{PR_{iat}}$ or $e_{EP_{iat}}$). The average *intrinsic return strength* of each process across ages is described by the η_{PR0} and η_{EP0} parameters, so that (in this parameterization), higher (more positive) values of η_{PR0} and η_{EP0} indicate faster return/oscillation. Age-related changes in the intrinsic return strength for PR and EP are, respectively, described by $\Delta\eta_{PR1}$ and $\Delta\eta_{EP1}$ (age 5 years compared to younger), $\Delta\eta_{PR2}$ and $\Delta\eta_{EP2}$ (age 48 months compared to younger), and $\Delta\eta_{PR3}$ and $\Delta\eta_{EP3}$ (age 36 months compared to 24 months). The average *intrinsic damping* of PR and EP across all ages are described by the ζ_{PR0} and ζ_{EP0} parameters, respectively. The model assumes that the system seeks to bring PR and EP back to baseline—intrinsic damping—which would be indicated (in this parameterization) by positive values for ζ_{PR0} and ζ_{EP0} . Aged-related changes in the intrinsic damping for PR and EP are, respectively, described by $\Delta\zeta_{PR1}$ and $\Delta\zeta_{EP1}$ (age 5 years compared to younger), $\Delta\zeta_{PR2}$ and $\Delta\zeta_{EP2}$ (48 months compared to younger), and $\Delta\zeta_{PR3}$ and $\Delta\zeta_{EP3}$ (36 months compared to 24 months).

In practice, Eqs. 1.1 and 1.2 are combined and estimated simultaneously in a single multilevel model with heterogeneous variances using data that are restructured so that the two outcome variables, $\left(\frac{d^2 PR}{dt^2}\right)_{iat}$ and $\left(\frac{d^2 EP}{dt^2}\right)_{iat}$, are collected into a single repeated-measures variable, Z_{iat} , along with dummy indicators, PR_ind and EP_ind , that indicate whether the specific observation of Z_{iat} belongs to the PR or EP process variable and that serve to “turn on” and “turn off” specific parameters for each row in the data (Bolger & Laurenceau, 2013; MacCallum, Kim, Malarkey, & Kiecolt-Glaser, 1997).

Bidirectional Coupling (+ Age Differences) Eqs. 1.1 and 1.2 articulate only the intrinsic dynamics of PR and EP, meaning that these equations do not capture the influence of EP on the acceleration/deceleration of PR or, vice versa, the influence of PR on the acceleration/deceleration of EP. As described earlier, we assume that EP and PR influence each other in two ways. First, each process has a *direct influence* on the acceleration/deceleration of the other process. For example, higher levels of EP may drive deceleration of PR. Second, each process has a *moderating influence* on the intrinsic dynamics of the other process. For example, higher levels of EP may facilitate the intrinsic damping of PR. The model was expanded to include both types of bidirectional influences. Specifically, Eq. 1.1 was expanded to

$$\begin{aligned} \left(\frac{d^2 PR}{dt^2}\right)_{iat} = & -[\eta_{PR0} + \Delta\eta_{PR1}age60_{iat} + \Delta\eta_{PR2}age48_{iat} + \Delta\eta_{PR3}age36_{iat}][PR_{iat}] \\ & -[\zeta_{PR0} + \Delta\zeta_{PR1}age60_{iat} + \Delta\zeta_{PR2}age48_{iat} + \Delta\zeta_{PR3}age36_{iat}]\left[\left(\frac{dPR}{dt}\right)_{iat}\right] \\ & -[\beta_{PR0} + \Delta\beta_{PR1}age60_{iat} + \Delta\beta_{PR2}age48_{iat} + \Delta\beta_{PR3}age36_{iat}][EP_{iat}] \\ & -[\delta_{PR0} + \Delta\delta_{PR1}age60_{iat} + \Delta\delta_{PR2}age48_{iat} + \Delta\delta_{PR3}age36_{iat}]\left[\left(\frac{dEP}{dt}\right)_{iat}\right] \\ & -[\pi_{PR0} + \Delta\pi_{PR1}age60_{iat} + \Delta\pi_{PR2}age48_{iat} + \Delta\pi_{PR3}age36_{iat}][(EP_{iat})(PR_{iat})] \\ & -[\xi_{PR0} + \Delta\xi_{PR1}age60_{iat} + \Delta\xi_{PR2}age48_{iat} + \Delta\xi_{PR3}age36_{iat}]\left[(EP_{iat})\left(\frac{dPR}{dt}\right)_{iat}\right] + [u_{PR_i}(PR_{iat})] + e_{PR_{iat}} \end{aligned} \quad (2.1)$$

and Eq. 1.2 was expanded to

$$\begin{aligned}
 \left(\frac{d^2 EP}{dt^2} \right)_{iat} = & -[\eta_{EP0} + \Delta\eta_{EP1}age60_{iat} + \Delta\eta_{EP2}age48_{iat} + \Delta\eta_{EP3}age36_{iat}][EP_{iat}] \\
 & -[\zeta_{EP0} + \Delta\zeta_{EP1}age60_{iat} + \Delta\zeta_{EP2}age48_{iat} + \Delta\zeta_{EP3}age36_{iat}] \left[\left(\frac{dEP}{dt} \right)_{iat} \right] \\
 & -[\beta_{EP0} + \Delta\beta_{EP1}age60_{iat} + \Delta\beta_{EP2}age48_{iat} + \Delta\beta_{EP3}age36_{iat}][PR_{iat}] \\
 & -[\delta_{EP0} + \Delta\delta_{EP1}age60_{iat} + \Delta\delta_{EP2}age48_{iat} + \Delta\delta_{EP3}age36_{iat}] \left[\left(\frac{dPR}{dt} \right)_{iat} \right] \\
 & -[\pi_{EP0} + \Delta\pi_{EP1}age60_{iat} + \Delta\pi_{EP2}age48_{iat} + \Delta\pi_{EP3}age36_{iat}][(PR_{iat})(EP_{iat})] \\
 & -[\xi_{EP0} + \Delta\xi_{EP1}age60_{iat} + \Delta\xi_{EP2}age48_{iat} + \Delta\xi_{EP3}age36_{iat}] \left[(PR_{iat}) \left(\frac{dEP}{dt} \right)_{iat} \right] + [u_{EP_i}(EP_{iat})] + e_{EP_{iat}}
 \end{aligned} \tag{2.2}$$

In Eqs. 2.1 and 2.2, the parameters describing intrinsic dynamics are the same as those from Eqs. 1.1 and 1.2. Two additional sets of parameters capture bidirectional coupling. The average direct *extrinsic push* of PR on EP and of EP on PR across all ages are captured by β_{PR0} and β_{EP0} . Age-related changes in direct extrinsic pushes for PR and EP are, respectively, captured by $\Delta\beta_{PR1}$, $\Delta\beta_{PR2}$, $\Delta\beta_{PR3}$, and $\Delta\beta_{EP1}$, $\Delta\beta_{EP2}$, and $\Delta\beta_{EP3}$. The average *extrinsic damping* of PR on EP and EP on PR across all ages are captured by δ_{PR0} and δ_{EP0} . Age-related changes in the strength of extrinsic damping are captured by $\Delta\delta_{PR1}$, $\Delta\delta_{PR2}$, $\Delta\delta_{PR3}$, and $\Delta\delta_{EP1}$, $\Delta\delta_{EP2}$, and $\Delta\delta_{EP3}$. The moderating effects of one process on the other processes' intrinsic dynamics are captured by the last set of parameters. Specifically, π_{PR0} and π_{EP0} capture how the intrinsic return strength of PR and EP are moderated by the other process. Age-related changes in the extent of this moderation are captured by the $\Delta\pi_{PR1}$, $\Delta\pi_{PR2}$, $\Delta\pi_{PR3}$, and $\Delta\pi_{EP1}$, $\Delta\pi_{EP2}$, $\Delta\pi_{EP3}$ parameters. Finally, ξ_{PR0} and ξ_{EP0} capture how the intrinsic damping of PR and EP are moderated by the other process, with the corresponding age-related changes in this moderation captured by the $\Delta\xi_{PR1}$, $\Delta\xi_{PR2}$, $\Delta\xi_{PR3}$, and $\Delta\xi_{EP1}$, $\Delta\xi_{EP2}$, $\Delta\xi_{EP3}$ parameters.

During model building we first fit the simpler model to the data (i.e., bivariate model with no bidirectional coupling, as in Eqs. 1.1 and 1.2), established that the fitting procedures were working as expected, and identified useful sets of starting values. Then, we fit and interpreted the more complex model (bivariate model with direct and moderating influences) shown in Eqs. 2.1 and 2.2. Models were estimated in R using the *nlme* package (Pinheiro et al., 2016), with restricted maximum likelihood estimation and with incomplete data treated as missing at random. The possibility for inflation in Type-I error rates due to testing of the many (i.e., 48) fixed effects parameters was controlled using a standard Bonferroni correction (p -values adjusted with alpha level of .05/48 $\approx$.001).

The estimated model parameters governing the dynamics of PR and EP at each age were used to simulate scenarios of how emotion regulation might proceed under a variety of hypothetical perturbations (e.g., PR perturbed away from equilibrium).

For specific display of age-related changes in system dynamics, implied trajectories for each age were derived by perturbing PR 1.00 unit away from equilibrium and calculating how PR and EP evolved over the next 100 time-steps (in the absence of any further input). Code for all procedures is available on the QuantDev website (quantdev.ssri.psu.edu).

Results

Descriptive Statistics

Table 1 provides descriptive statistics for PR and EP at each of the four age points. PR level differed with age, $F(3, 431) = 31.85$, $p < .001$. As expected, pairwise comparisons with Bonferroni correction showed that the PR level was significantly higher at age 24 months compared to age 36 months, 48 months, and 5 years ($ps < .001$), although, contrary to expectations, average level of PR at age 5 years did not differ significantly from ages 36 months ($p = 0.10$) or 48 months ($p = 0.90$). These age-related changes in PR level are illustrated in Fig. 1, with PR (red line) showing a higher level overall at 24 months compared to later ages.

EP level also differed with age, $F(3, 431) = 24.62$, $p < .001$. In line with expectations, EP levels were significantly lower at age 24 months compared to 36 months, 48 months, and 5 years ($ps < .01$), and significantly higher at 48 months and 5 years compared to 36 months ($ps < .001$). EP levels did not differ between ages 48 months and 5 years ($p = .13$). These age-related changes in EP level are also illustrated in Fig. 1, with EP (blue line) showing a higher overall level at 36 months, 48 months, and 5 years compared to age 24 months.

The extent of within-person association between PR and EP, which can be interpreted as bidirectional coupling, is shown in the upper triangle of the correlation matrix in Table 1. The prototypical within-person correlation was -0.59 at age 24 months, -0.54 at 36 months, -0.58 at 48 months, and -0.64 at 5 years. The similar magnitude of these within-person correlations at

Table 1 Sample Descriptive Statistics for Prepotent Responses (PR) and Executive Processes (EP) at Ages 24 Months, 36 Months, 48 Months, and 5 Years

Variable	<i>M</i> (<i>SD</i>)	1. PR 24 months	2. EP 24 months	3. PR 36 months	4. EP 36 months	5. PR 48 months	6. EP 48 months	7. PR 5 years	8. EP 5 years
1. PR 24 months	0.91 (0.88)	–	– 0.59 [– 0.97, 0.16]						
2. EP 24 months	1.83 (1.74)	– 0.79*	–						
3. PR 36 months	0.43 (0.58)	0.03	– 0.03	–	– 0.54 [– 0.99, 0.00]				
4. EP 36 months	2.22 (1.78)	– 0.17	0.20*	– 0.65*	–				
5. PR 48 months	0.38 (0.54)	0.10	– 0.15	0.01	– 0.14	–	– 0.58 [– 0.97, 0.19]		
6. EP 48 months	2.72 (1.81)	– 0.04	0.10	– 0.02	0.26*	– 0.65*	–		
7. PR 5 years	0.28 (0.45)	0.15	– 0.11	0.33*	– 0.32*	0.25*	– 0.11	–	– 0.64 [– 0.99, – 0.10]
8. EP 5 years	3.01 (1.78)	– 0.19	0.11	– 0.33*	0.36*	– 0.29*	0.19	– 0.69*	–

Age 24 months $n = 111$, 36 months $n = 120$, 48 months $n = 120$, and 5 years $n = 96$; $*p < .05$. *M* and *SD* indicate sample-level mean and standard deviation, respectively. Lower triangle contains sample-level correlations between individuals' average PR and EP levels. Upper triangle contains average within-person correlation [with sample range in brackets]

each age suggests that there were no age-related differences in the bidirectional coupling of PR and EP. These correlations of averages, however, do not capture associations in the *dynamics* of the processes. The between-person association between PR and EP (averaged across the 480 s) is shown in the lower triangle of Table 1 for each age (– 0.79 at 24 months, – 0.65 at 36 months, – 0.65 at 48 months, and – 0.69 at 5 years). At each age, children with higher overall PR tended to have lower EP (and vice versa).

Dynamic Model

Age-related changes in the intrinsic dynamics and bidirectional coupling of PR and EP were examined with the coupled damped linear oscillator model shown in Eqs. 2.1 and 2.2. Results are shown in Table 2. For ease of interpretation of age-related changes, implied parameter values and implied trajectories for each of the four ages are shown in Table 3 and Fig. 2. Results and interpretations for each parameter (i.e., each type of dynamic) are described in turn.

Age-Related Change in How EP and PR Change (Intrinsic Dynamics) The first set of parameters describe the intrinsic dynamics of PR (η_{PR0} , ζ_{PR0}) and EP (η_{EP0} , ζ_{EP0}), and their age-related changes. These parameters capture changes in PR and EP that are unrelated to the other process and establish the underlying dynamics that must be considered before pursuing the crucial questions about emotion regulation and how each process influences the other.

Age-Related Change in Intrinsic Return Strength (η) Return strength is an index of how quickly (how strongly) PR and EP

return to equilibrium. The stronger the return strength, the shorter bouts of PR or EP are.

Across all ages, there was significant intrinsic return strength for both PR and EP ($\eta_{PR0} = 0.54$, $p < .001$; $\eta_{EP0} = 0.57$, $p < .001$). However, the speed of their returns differed by age. As expected, the intrinsic return of PR was significantly faster at age 5 years compared to all earlier ages combined ($\Delta\eta_{PR1} = 0.05$, $p < .001$), and faster at age 48 months compared to all earlier ages combined ($\Delta\eta_{PR2} = 0.03$, $p < .001$), with no difference between ages 24 and 36 months ($\Delta\eta_{PR3} = 0.008$, $p = .03$). Most easily seen in Table 3, the increases in intrinsic return strength of PR with age (from 0.50 at 24 months to 0.59 at 5 years) indicate that PR bouts became shorter as children aged, particularly from 36 months onward. In parallel, the intrinsic return of EP was significantly faster at age 5 years compared to all earlier ages combined ($\Delta\eta_{EP1} = 0.03$, $p < .001$). Thus, as seen in Table 3, the increases in intrinsic return strength of EP with age (from 0.55 at 24 months to 0.60 at 5 years) indicate that the EP bouts also became shorter as children aged.

The developmental changes in PR and EP intrinsic return strength are shown in the implied trajectories in Fig. 2. Both PR (red) and EP (blue) oscillate more quickly at older ages. Specifically, the distance between the peaks of the oscillations is slightly but significantly shorter at age 5 years relative to earlier ages. It should also be noted that, although the prototypical trajectory is shown in Fig. 2, there were significant between-person differences in children's average intrinsic return strength in both PR ($\sigma_{uPR} = 0.18$, 95% CI [0.14, 0.22]) and EP ($\sigma_{uEP} = 0.13$, 95% CI [0.11, 0.14]). Thus, the normative age-related changes in length of PR and EP bouts must be understood in relation to the presence of individual differences.

Table 2 Results from the Multilevel Model Examining Age Differences in Self-Regulation Dynamics

Parameters	Estimates	95% CI	Parameter Label
Fixed Effects for PR (Eq. 2.1)			
Intrinsic Dynamics for PR			
η_{PR0}	0.54*	[0.51, 0.57]	Return strength
$\Delta\eta_{PR1}$	0.05*	[0.04, 0.07]	Age Δ in return strength (5 years vs. all other ages)
$\Delta\eta_{PR2}$	0.03*	[0.02, 0.04]	Age Δ in return strength (48 months vs. younger)
$\Delta\eta_{PR3}$	0.008	[0.001, 0.02]	Age Δ in return strength (36 months vs. 24 months)
ζ_{PR0}	0.21*	[0.20, 0.21]	Damping
$\Delta\zeta_{PR1}$	0.09*	[0.08, 0.10]	Age Δ in damping (5 years vs. all other ages)
$\Delta\zeta_{PR2}$	− 0.02	[− 0.03, − 0.01]	Age Δ in damping (48 months vs. younger)
$\Delta\zeta_{PR3}$	0.00	[− 0.01, 0.003]	Age Δ in return strength (36 months vs. 24 months)
Extrinsic Direct Influences for PR			
β_{PR0}	0.01*	[0.01, 0.02]	Extrinsic push from EP
$\Delta\beta_{PR1}$	0.00	[− 0.001, 0.01]	Age Δ in extrinsic push (5 years vs. all other ages)
$\Delta\beta_{PR2}$	0.00	[0.00, 0.00]	Age Δ in extrinsic push (48 months vs. younger)
$\Delta\beta_{PR3}$	− 0.004*	[− 0.006, − 0.002]	Age Δ in return strength (36 months vs. 24 months)
δ_{PR0}	0.01*	[0.009, 0.012]	Extrinsic damping from EP
$\Delta\delta_{PR1}$	0.02*	[0.01, 0.02]	Age Δ in extrinsic damping (5 years vs. all other ages)
$\Delta\delta_{PR2}$	− 0.01*	[− 0.01, − 0.01]	Age Δ in extrinsic damping (48 months vs. younger)
$\Delta\delta_{PR3}$	− 0.01*	[− 0.01, − 0.01]	Age Δ in return strength (36 months vs. 24 months)
Extrinsic Indirect Influences for PR			
π_{PR0}	− 0.01*	[− 0.009, − 0.004]	EP Moderating return strength
$\Delta\pi_{PR1}$	0.002	[− 0.003, 0.00]	Age Δ in moderated return strength (5 years vs. all other ages)
$\Delta\pi_{PR2}$	0.00	[− 0.004, 0.00]	Age Δ in moderated return strength (48 months vs. younger)
$\Delta\pi_{PR3}$	0.02*	[0.02, 0.02]	Age Δ in moderated return strength (36 months vs. 24 months)
ξ_{PR0}	− 0.003	[− 0.01, 0.00]	EP Moderating damping
$\Delta\xi_{PR1}$	0.03*	[0.02, 0.04]	Age Δ in moderated damping (5 years vs. all other ages)
$\Delta\xi_{PR2}$	− 0.05*	[− 0.05, − 0.04]	Age Δ in moderated damping (48 months vs. younger)
$\Delta\xi_{PR3}$	− 0.03*	[− 0.04, − 0.03]	Age Δ in moderated damping (36 months vs. 24 months)
Fixed Effects for EP (Eq. 2.2)			
Intrinsic Dynamics for EP			
η_{EP0}	0.57*	[0.54, 0.59]	Return strength
$\Delta\eta_{EP1}$	0.03*	[− 0.002, 0.01]	Age Δ in return strength (5 years vs. all other ages)
$\Delta\eta_{EP2}$	0.01	[− 0.002, 0.01]	Age Δ in return strength (48 months vs. younger)
$\Delta\eta_{EP3}$	0.00	[− 0.003, 0.01]	Age Δ in return strength (36 months vs. 24 months)
ζ_{EP0}	0.03*	[0.02, 0.03]	Damping
$\Delta\zeta_{EP1}$	− 0.05*	[− 0.06, − 0.04]	Age Δ in damping (5 years vs. all other ages)
$\Delta\zeta_{EP2}$	0.01*	[0.09, 0.10]	Age Δ in damping (48 months vs. younger)
$\Delta\zeta_{EP3}$	0.00	[− 0.01, 0.004]	Age Δ in damping (36 months vs. 24 months)
Extrinsic Direct Influences for EP			
β_{EP0}	0.17*	[0.15, 0.18]	Extrinsic push
$\Delta\beta_{EP1}$	0.08*	[0.04, 0.12]	Age Δ in extrinsic push (5 years vs. all other ages)
$\Delta\beta_{EP2}$	− 0.03	[− 0.06, − 0.01]	Age Δ in extrinsic push (48 months vs. younger)
$\Delta\beta_{EP3}$	− 0.02	[− 0.04, 0.002]	Age Δ in extrinsic push (36 months vs. 24 months)
δ_{EP0}	− 0.02	[− 0.04, 0.00]	Extrinsic damping
$\Delta\delta_{EP1}$	− 0.04	[− 0.08, 0.01]	Age Δ in extrinsic damping (5 years vs. all other ages)
$\Delta\delta_{EP2}$	0.22*	[0.18, 0.25]	Age Δ in extrinsic damping (48 months vs. younger)
$\Delta\delta_{EP3}$	− 0.18*	[− 0.21, − 0.16]	Age Δ in extrinsic damping (36 months vs. 24 months)

Table 2 (continued)

Parameters	Estimates	95% CI	Parameter Label
Extrinsic Indirect Influences for EP			
π_{EP0}	− 0.01	[− 0.02, 0.00]	Moderated return strength
$\Delta\pi_{EP1}$	− 0.01	[− 0.03, 0.00]	Age Δ in moderated return strength (5 years vs. all other ages)
$\Delta\pi_{EP2}$	− 0.01	[− 0.02, 0.00]	Age Δ in moderated return strength (48 months vs. younger)
$\Delta\pi_{EP3}$	0.00	[− 0.01, 0.01]	Age Δ in moderated return strength (36 months vs. 24 months)
ξ_{EP0}	− 0.06*	[− 0.07, − 0.04]	Moderated damping
$\Delta\xi_{EP1}$	− 0.14*	[− 0.16, − 0.12]	Age Δ in moderated damping (5 years vs. all other ages)
$\Delta\xi_{EP2}$	0.09*	[0.08, 0.11]	Age Δ in moderated damping (48 months vs. younger)
$\Delta\xi_{EP3}$	0.01	[− 0.01, − 0.04]	Age Δ in moderated damping (36 months vs. 24 months)
Random Effects			
$\sigma\eta_{PR0}$	0.18	[0.14, 0.22]	Residual between-person differences
$\sigma\eta_{EP0}$	0.13	[0.11, 0.14]	
$r(\varphi_{PR}, \varphi_{EP})$	0.55	[0.24, 0.75]	
σe_{PR}	0.47	[0.47, 0.48]	Residual within-person time-specific differences
σe_{EP}	1.39	[1.38, 1.40]	
$r(e_{PR}, e_{EP})$	− 0.07	[− 0.07, − 0.06]	
Model Fit			
AIC	979,387.60		
BIC	979,977.20		
LogLikelihood	− 489,639.80		

$N = 480$ repeated measures nested within 120 persons, PR = Prepotent Response, EP = Executive Process, CI = 95% confidence interval, AIC = Akaike Information Criteria, BIC = Bayes Information Criteria, * $p < 0.001$

Age-Related Change in Intrinsic Damping (ζ) Damping is an index of how oscillations in PR and EP wane over time. The stronger the damping, the faster PR or EP wanes.

Across all ages, there was significant intrinsic damping of both PR and EP ($\zeta_{PR0} = 0.21$, $p < .001$; $\zeta_{EP0} = 0.03$,

$p < .001$). As seen in Table 3, implied parameter values for ζ_{PR} from age 24 months to 5 years were [0.19, 0.18, 0.16, 0.30], with PR damping stronger at age 5 years compared to all earlier ages combined ($\Delta\zeta_{PR1} = 0.09$, $p < .001$).

Table 3 Implied Age-Specific Parameter Values Derived from the Multilevel Model Examining Age-related Changes in Self-Regulation Dynamics

	24 months	36 months	48 months	5 years
PR				
Return strength (η_{PR})	0.50	0.51	0.54	0.59
Damping (ζ_{PR})	0.19	0.18	0.16	0.30
Extrinsic push from EP (β_{PR})	0.02	0.01	0.01	0.02
Extrinsic damping from EP (δ_{PR})	0.02	0.00	− 0.01	0.03
EP moderated return strength (π_{PR})	− 0.03	0.01	− 0.01	− 0.01
EP moderated damping (ξ_{PR})	0.04	− 0.02	− 0.06	0.03
EP				
Return strength (η_{EP})	0.55	0.56	0.56	0.60
Damping (ζ_{EP})	0.00	0.00	0.14	− 0.02
Extrinsic push from PR (β_{EP})	0.17	0.14	0.11	0.25
Extrinsic damping from PR (δ_{EP})	0.07	− 0.30	0.21	− 0.05
PR moderated return strength (π_{EP})	0.00	0.00	− 0.01	− 0.02
PR moderated damping (ξ_{EP})	− 0.06	− 0.05	0.09	− 0.20

PR = Prepotent Response, EP = Executive Process

Fig. 2 The predicted trajectories of the prepotent response (PR) and executive processes (EP) based on the estimated parameters from the multilevel model with bidirectional coupling, with starting values for PR and dPR/dt of 1.00 and 0.00, respectively, and for EP and dEP/dt of 0.00 and 0.00, respectively

The intrinsic damping of EP was significantly weaker at age 5 years compared to all earlier ages combined ($\Delta\zeta_{EP1} = -0.05$, $p < .001$), such that there was modest intrinsic EP *amplification* (i.e., EP increased rather than waned), indicating continued activation of EP at age 5 years. As seen in Table 3, however, the general developmental decrease in EP's intrinsic damping (from 0.00 at 24 months to -0.02 at 5 years) was nonlinear. Notably, EP intrinsic damping was stronger at age 48 months compared to earlier ages ($\Delta\zeta_{EP2} = 0.01$, $p < .001$), and did not differ between ages 24 and 36 months. The strong damping at 48 months is starkly evident in Fig. 2 with EP (blue) damped to equilibrium almost completely within 70 s of an initiating event that occurred at $t = 0$.

Age-Related Change in How EP and PR Influence Each Other (Bidirectional Coupling) Having established (1) how each process fluctuates on its own, we turn to examining (2) the direct influence of one process on the other, including whether executive processes directly push down prepotent responses; and (3) indirect influences wherein one process moderates the intrinsic dynamics of the other process, including how engagement of executive processes facilitates the intrinsic decay (waning) of prepotent responses over task time. *Direct*

influences index the extent to which changes in PR trajectory are specifically due to EP and changes in EP trajectory are specifically due to PR. *Moderating influences* index the extent to which one process indirectly influences the other. Our focal interest is in effectiveness, i.e., how engagement of executive processes in children's strategy use directly or indirectly influence changes in the intrinsic ebb and flow of children's desire for and frustration about the restricted gift, and the extent to which their desire and frustration (i.e., PR) directly or indirectly influence engagement of executive processes. We examine age-related changes for all these types of dynamics.

Age-Related Change in Direct Influences (β, δ) EP had a direct influence on the acceleration/deceleration of PR at all ages ($\beta_{PR0} = 0.01$, $p < .001$), such that when EP was higher it pushed PR toward baseline. Although relatively stable from age 24 months to 5 years, the implied values for β_{PR} (0.02, 0.01, 0.01, 0.02; see Table 3) indicate some developmental nonlinearity, with the strength of EP's extrinsic push on PR being significantly but only slightly weaker at age 36 months compared to 24 months ($\Delta\beta_{PR3} = -0.004$, $p < .001$).

Similarly, EP had a direct influence on PR damping (how quickly PR waned) at all ages ($\delta_{PR0} = 0.01$, $p < .001$). Again,

although relatively stable from age 24 months to 5 years based on the implied values for δ_{PR} (0.02, 0.00, -0.01 , 0.03, see Table 3), there was some developmental nonlinearity, with the strength of EP's influence on damping of PR weakening from age 24 to 36 months ($\delta_{PR3} = -0.01$, $p < .001$) and 48 months ($\delta_{PR2} = -0.01$, $p < .001$), before strengthening again at age 5 years ($\delta_{PR1} = 0.02$, $p < .001$).

There was also evidence that PR provided a direct push on EP at all ages ($\beta_{EP0} = 0.17$, $p < .001$), such that when PR was higher, it pushed EP back toward equilibrium. That is, PR tends to inhibit EP. Although the model implied values for β_{EP} shown in Table 3 (0.17, 0.14, 0.11, 0.25) suggest some age-related decrease in the extrinsic push of PR on EP from age 24 months to 48 months, most of these changes were not significant. The only significant difference was, contrary to expectations, that the extrinsic push of PR on EP was stronger at age 5 years than all earlier ages ($\beta_{EP1} = 0.08$, $p < .001$). In contrast, there was no evidence of a direct influence of PR on damping of EP ($\delta_{EP0} = -0.02$, $p > .05$). Although, as indicated by the implied parameter values for δ_{EP} in Table 3 (0.07, -0.30 , 0.21, -0.05), extrinsic damping of EP by PR fluctuated substantially from age 24 months to 5 years ($\delta_{EP2} = 0.22$, $p < .001$; $\delta_{EP3} = -0.18$, $p < .001$).

While these direct effects could indicate effectiveness of children's self-regulation of emotion, there is a limitation of our assessment method that must be noted. Some, although not all, codes used to capture EP and PR were mutually exclusive. Specifically, attention focused on the demands of waiting counted in PR and distraction from those demands went into EP. A child cannot focus on the gift and be distracted from the gift at the same time. Therefore, to a certain extent, the coding contributes to finding direct relations between the two processes. Our focus, however, is on the moderating influences of EP on PR intrinsic dynamics as best capturing emotion regulation and its development.

Age-Related Change in Effectiveness (Moderating Influences; π , ξ) A key test for our conceptualization of emotion regulation development is that of age-related changes in how EP indirectly influences the dynamics of PR (regulatory effectiveness), with consideration of how PR may also indirectly influence dynamics of EP, as in the case of emotions interfering with strategy use.

EP moderating PR dynamics On average across all ages, EP moderated the intrinsic return strength of PR ($\pi_{PR0} = -0.01$, $p < .001$), such that PR exhibited weaker return strength (longer bout) when EP was higher, perhaps indicating lack of *regulatory effectiveness* of strategy use among such young children. The model implied values for π_{PR} shown in Table 3 (-0.03 , 0.01, -0.01 , -0.01) suggest relative stability across ages. However, a significant difference in moderation between 36 and 24 months ($\Delta\pi_{PR3} = 0.02$, $p < .001$) signals some gain in effectiveness of children's strategy use by 36 months. These

gains are in line with theory suggesting that increased availability of cognitive resources occurring around age 3 years supports development of emotion regulation (Kopp, 1982).

Contrary to our expectations, on average across ages, EP did not moderate the intrinsic damping of PR at any age ($\xi_{PR0} = -0.003$, $p > .05$). However, the extent of moderation differed between all ages ($p < .001$ for all). As seen in Table 3, the extent of moderation, ξ_{PR} , at each age (0.04, -0.02 , -0.06 , 0.03) revealed that EP effectively facilitated intrinsic damping of PR at 24 months and 5 years of age, but hindered PR intrinsic damping at ages 36 and 48 months. This pattern of changes in moderation of intrinsic damping of PR (ξ_{PR}), in conjunction with the pattern of age-related changes in moderation of return strength of PR (π_{PR}), suggests there may be some compensatory tradeoffs in how effective children's deployment of EP actually is. Perhaps the changes in how deployment of strategies facilitates or hinders intrinsic PR dynamics are related to how children's repertoire of strategies change over time, or that some specific strategies facilitate PR return strength while others facilitate damping.

PR Moderating EP Dynamics On average across ages, there was no evidence that PR moderated the intrinsic return strength of EP ($\pi_{EP0} = -0.01$, $p = .03$), and no evidence of age-related changes in the absence of moderation ($p > .001$ for all of $\Delta\pi_{EP1}$, $\Delta\pi_{EP2}$, and $\Delta\pi_{EP3}$). In contrast, on average across ages, PR moderated the intrinsic damping of EP ($\xi_{EP0} = -0.06$, $p < .001$), such that when PR was high, EP did not wane as quickly. In other words, when PR was activated, EP also remained activated—an indication of *regulatory facilitation* (Cole et al., 2017). As seen in Table 3, the age-related changes in extent of moderation, ξ_{EP} , exhibited developmental nonlinearity (-0.06 , -0.05 , 0.09, -0.20), with PR significantly more facilitative of intrinsic damping of EP at age 48 months compared to earlier ages ($\Delta\xi_{EP2} = 0.09$, $p < .001$), and significantly more facilitative of intrinsic *amplification* of EP at age 5 years compared to earlier ages ($\Delta\xi_{EP1} = -0.14$, $p < .001$). These age-related changes are most evident in Fig. 2 by comparing the total damping of EP in the pattern at 48 months, and the continued oscillation of EP in the 5-year trajectory. Independent of the effectiveness of children's regulation, this pattern of results suggests further consideration of how efficiency of regulation changes as children's repertoire of and growing experience with strategies develops over time.

Discussion

We used a theoretical-mathematical self-regulation framework, locating regulation in the *relation* between young children's strategy use (engagement of executive processes) and display of prepotent responses (intrinsic emotion dynamics). We capitalized on intensive observations of the temporal dynamics of children's

behavior to address a fundamental problem presented by static approaches to studying emotion regulation. Moving beyond examining the total number of seconds in which children display emotion, we used a multiple time-scale study design and modeling approach to investigate how strategy use comes to moderate the ongoing dynamic changes in emotion. Our hypothesis was that the extent to which young children's strategies recruit executive processes will more effectively moderate the intrinsic dynamics of their desire and frustration as they transition from toddlerhood to kindergarten age. We found evidence for age-related development of indirect effects of strategy use on children's emotions, providing partial support for our hypothesis.

Intrinsic Emotion Dynamics Children's overall level of desire and frustration declined between ages 24 and 36 months, becoming stable thereafter. This is consistent with evidence that children's negative emotions decrease during the early preschool years (Brownell & Kopp, 2007). Despite this decline, we observed desire for and frustration about the gift at all ages. After 24 months, age-related changes were not in overall level but in emotion dynamics. Emotion bouts became shorter as children got older and, by age 5 years, waned more quickly. In terms of emotion regulation, however, we need evidence of the influence of strategies on emotion dynamics.

Intrinsic Strategy Dynamics The extent to which children's strategies recruited executive processes increased between 24 and 36 months and between 36 and 48 months. This is the first evidence indicating that children become increasingly able to recruit internal resources as Kopp (1982) suggested, i.e., language (in the form of calmly asking for support and information) and executive attention (in the form of distraction). Moreover, strategy bouts waned more quickly between 36 and 48 months of age, which could suggest more efficient strategy use. However, by age 5 years, strategy bouts did not wane, which may reflect more sustained use of distraction relative to verbalizing to mother when she is working (Perry & Calkins, 2018).

Moderating Influences of Strategy Use on Emotion When strategy use was higher, it pushed down emotion and vice versa across ages. However, interpretation of this direct influence is tempered by measurement issues. If a child focused attention on the gift (prepotent response), the child could not be coded as distracting from the gift (strategy). Importantly, as predicted, at age 5 years, higher strategy use *moderated* the extent to which emotions waned. Unexpectedly, this effect was also significant at age 24 months, which may reflect age differences in dominant strategy. A more executive strategy such as distraction leads to emotion waning at age 5 years, whereas self-soothing and support-seeking may lead to faster emotion waning at 24 months, given mothers often ignored toddler verbalizations. Future research can address the moderating influences of different types of strategies at different ages.

Moderating Influences of Emotion on Strategy Use Children's emotions influenced the dynamics of their strategy use. At age 48 months, when strategies involved more executive process engagement, they nonetheless waned quickly when emotions were high. This finding highlights the possibility that higher levels of emotion can overwhelm and diminish younger children's strategic efforts (Calkins & Fox, 2002; Cole et al., 2017). However, at age 5, when emotions were higher, strategy use lasted longer. This may indicate developmental progress in children's ability to sustain strategies even when desire and frustration increase. Notably, despite using better strategies, children at age 5 years still experienced the tension between wanting the gift and having to wait.

Limitations and Future Directions

We studied the development of emotion regulation dynamics with children from lower income rural and semi-rural families during a frustrating wait task. The results of the dynamic modeling approach highlight the promise of the method, but it is not yet known how the findings generalize across samples or situations. The same modeling approach showed developmental change between ages 2 and 5 years in a fear-inducing context in which middle income children were exposed to novel characters (Morales et al., 2018). Thus far, the initial evidence reveals the value of using a dynamic approach in obtaining a more nuanced and meaningful picture of how emotion regulation emerges in the moment and changes with age.

The general model of self-regulation guiding our work focuses on two processes, prepotent responses and executive processes. This guided our creation of higher order variables from standardized second-by-second behavior and emotion coding schemes. Studies of early childhood emotion regulation typically rely on binary or ordinal codes to indicate if a strategy was used or the intensity of emotion expression. These measures do not match the continuous scale measurement needed for a differential equation modeling approach. Researchers should consider tracking ongoing changes in target variables along one or more continuous dimensions (Girard, 2014). Changes in how coding is done may facilitate use of dynamic modeling.

Tasks might also be redesigned to facilitate observation of regulation. Typically, studies use tasks purposively designed to be shorter than 5 min and only include a single challenge. While we avoid overtaxing children and ending visits prematurely, tasks might be redesigned to obtain longer time-series and observe how children respond to multiple perturbations as is done in strange situation (Ainsworth, Blehar, Waters, & Wall, 1978) and disappointment tasks (Cole, Zahn-Waxler, & Smith, 1994). Rather than assuming the stimulus situation is unchanging, repeated perturbations over a longer period can create and recreate the desired conditions for observing systematic regulatory action.

Finally, the dynamic systems model we used was a coupled 2nd-order differential equation model with interaction terms that specifically facilitated examination of both direct and moderating influences of EP on PR (and vice versa). This is just one of many possible mathematical instantiations that can be mapped to study of regulation. Future studies should consider further how other mathematical models can be used to extract and quantify meaningful aspects of the processes of interest.

This study advances how dynamic systems approaches can be used to observe and quantify how specific aspects of children's self-regulation of emotion change across early childhood. Working from a general model that locates self-regulation in the interplay between prepotent responses and executive processes, we used a bivariate system of differential equations to describe the *intrinsic dynamics* and *bidirectional coupling* of children's PR and EP during a frustration-inducing wait task at ages 24 months, 36 months, 48 months, and 5 years. We offer initial evidence of how emotion regulation develops with age and open the possibility for further refinement of theory about how individuals regulate their emotions in the moment and how specific aspects of that process change with age.

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Conflict of Interest The authors have no conflicts of interest.

Ethical Approval This project was approved by The Pennsylvania State University's Institutional Review Board for Human Subjects Research.

Informed Consent Informed consent for parents, and by parents for their children, was obtained from all participants in accordance with protocols approved by the University's Institutional Review Board for Human Subjects Research.

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