Published in final edited form as:

Child Dev Perspect. 2019 June ; 13(2): 91–96. doi:10.1111/cdep.12316.

Toward a Unifying Model of Self-Regulation: A Developmental Approach

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Abstract

The ability to self-regulate is key to healthy, competent functioning. The breadth of evidence supporting the importance of self-regulation is matched by such a diversity of terms, concepts, measures, and levels of analysis that the National Institutes of Health called for progress toward a unifying model. In this article, we review a lineage of conceptual models and suggest a path toward a more unifying model of self-regulation that encompasses both the dynamics of moment-to-moment changes and age-related change. Drawing from these models, we define self-regulation as the influence of the recruitment of executive processes on prepotent responses. We define these terms, locating self-regulation in the dynamic relations between prepotent responses and executive processes, and offer a theoretical-mathematical approach to testing this model.

Keywords

self-regulation; child development; intraindividual dynamics

Self-regulation is essential for lifelong healthy, competent functioning. It is involved in preparing young children for the demands of formal schooling, helping school-age children learn new material, understanding adolescent and adult decision making, and interpreting aging adults' social selectivity (Bierman et al., 2008; Charles & Carstensen, 2007; Steinberg et al., 2017; Zimmerman & Schunk, 2001). Acknowledging the broad relevance of self-regulation for health outcomes, the National Institutes of Health (NIH) nonetheless lamented the plethora of terms, conceptualizations, and methods used to define and study self-regulation: "The current lack of consistency and conceptual integration in how self-regulation is studied across a range of disciplines hinders our understanding of the basic mechanisms underlying many important health and developmental outcomes" (HHS, n.d.).

Self-control, delay of gratification, temporal discounting, inhibitory control, executive functioning, effortful control, cognitive control, and other concepts have all been related to, and are often treated as synonymous with, self-regulation. Each construct entails different levels of measurement, ranging from self-reported traits to moment-to-moment physiological activity, and each is assessed in diverse situational and environmental contexts. This variety led the NIH to call for research that moves toward a unifying model of self-

regulation, and to efforts to address the nature of self-regulation and its constituent components (e.g., Gagne, 2017; Nigg, 2017; Zhou, Chen, & Main, 2012).

We take a developmental approach to studying self-regulation, with specific interest in how young children begin to regulate their own emotions, and we share the view that a unifying model must address the dynamic nature of the processes that comprise self-regulation. In this article, we highlight a rich scholarly lineage of self-regulation models that share a common conceptualization that top-down executive processes can modulate prepotent responses, including theories that emphasize the dynamic relation between executive processes and prepotent responses (e.g., Carver & Scheier, 2012; Lewis, 2005). Attention to these dynamic relations is critical because regulation inherently involves *change*. We share the view that a dynamic, process-oriented approach can advance studying the development of self-regulation and guide research using multiple ages, with different levels of analysis, and across many time scales (Cole & Hollenstein, 2018; Lewis, 2005). Fortunately, available methods allow us to investigate both the dynamics of moment-to-moment behavior and how they change with age. In this article, we present such an approach. We define prepotent responses and executive processes, highlight their prominence in developmental conceptualizations of self-regulation, emphasize how considering their dynamic interplay may reveal new information about self-regulation and its development, and outline a theoretical-mathematical model that can be used to examine the development of self-regulation dynamics.

Prepotent Responses

Prepotent responses are very probable actions that take priority over other responses under specific conditions (Arnold, 1960). Prepotency can be due to biological preparedness, learning, priming, or stimulus salience. Examples include spontaneous withdrawal from threat (e.g., jumping away from a snake) and intensifying effort to overcome an obstacle to a goal (e.g., shaking a vending machine to get a jammed snack). This capacity to act spontaneously and quickly, without forethought, is critical to survival. Although adaptive in some situations, prepotent responses can be problematic if they are impulsive, selfish, or irresponsible by social standards. Therefore, a developmental goal of early childhood is to acquire the ability to modulate the degree to which one enacts prepotent response tendencies to protect and maintain well-being, yet behaves in accordance with social propriety and authority.

Executive Processes

Cognitive processes—attention, memory, language, and reasoning, to name a few—aid in regulating whether and how a prepotent response is enacted: initiation of action when inhibition is prepotent (e.g., fear) and restraint when approaching is prepotent (e.g., frustration). Monitoring, attention shifting, planning, and reappraising can influence the performance of prepotent responses. This influence leads cognitive and neuroscience researchers to refer to these cognitive processes as executive (e.g., Hofmann, Schmeichel, & Baddeley, 2012; Miyake et al., 2000). Similarly, models of self-regulation from clinical and social psychology refer, directly or indirectly, to those executive processes (e.g., Bandura,

1986; Carver & Scheier, 1982). The engagement of executive processes is associated with top-down regulation, to be distinguished from more automatic bottom-up regulation (Bridgett, Burt, Edwards, & Deater-Deckard, 2015; Eisenberg et al., 2013). Any specific strategy may or may not index engagement of an executive process. For example, in the early childhood literature, thumb sucking is regarded as an automatic, noneffortful strategy, although at older ages, one could suck one's thumb intentionally and it could serve a regulatory function.

The Development of Self-Regulation

Developmental perspectives have a long history of conceptualizing self-regulation. Freud (1949) conceptualized the ego as the source of cognitive checks on the tendency to act impulsively to achieve pleasure. This view informed the concept of ego resiliency, a personality characteristic defined by the development of children's ability to control sanctioned behaviors elicited by a situation (Block & Block, 1980). The Blocks' model inspired some of the earliest empirical studies of children's self-regulation, using tasks requiring children to wait for something desirable (e.g., Vaughn, Kopp, & Krakow, 1984). Although Mischel rejected the focus on personality, emphasizing the role of situational cues in determining self-control, he also developed the classic marshmallow experiments, which examined cognitive mechanisms that enabled young children to delay acting on impulse (Mischel, 2014).

Kopp (1982) provided a framework for the development of self-regulation in early childhood that is cited most frequently. She posited that extrinsic and intrinsic factors interact to contribute to the emergence of children's autonomous modulation of their impulses. The socialization practices of caregivers constitute the main extrinsic influences. As caregivers socialize children, they draw on intrinsic factors, including children's emerging attention control, receptive and expressive language, memory, and reasoning skills. Together, these factors lead children to recruit their own internal resources to regulate their actions without direct instruction or monitoring.

Posner and Rothbart (2000) addressed the role of temperament—biologically primed predispositions in reactivity and regulation—in the development of self-regulation. Reactivity, referred to as negative affectivity, reflects prepotent readiness to react with anger or fear to environmental change. Regulation, referred to as effortful control, reflects the capacity to be soothed easily or regulate behavior readily. Consistent with Kopp's hypothesis, effortful control develops during the third year of life and is attributable largely to maturation of an executive attention neural network, which enables control of attention despite stimulus salience. Both the Kopp model and the model suggested by Posner and Rothbart situated self-regulation developmentally and inspired longitudinal research on the development of self-regulation in early childhood (e.g., Eisenberg, Smith, & Spinrad, 2016; Kochanska, Coy, & Murray, 2001). Other models elaborate on the biological contributions to self-regulation, including neural, cardiac, and neuroendocrine systems (Blair, 2016; Lewis, 2005; Perry & Calkins, 2018). They also distinguish bottom-up (more automatic) regulatory processes from top-down (executive) influences. Their appreciation of the nature of these

physiological systems leads to an emphasis on understanding self-regulation in terms of dynamic, temporal relations.

This brief summary of prominent concepts in the child development literature on self-regulation shows a lineage of ideas that converge. Specifically, these ideas regard self-regulation as a dynamic process that involves engaging executive processes to enact behavior that is not prepotent and to inhibit behavior that is. (For references from neuroscience and social, clinical, and cognitive psychology that define self-regulation similarly, see Supplemental Materials, Section A.) Each model refers to internal resources (i.e., cognitive processes) serving an executive role in modulating urges, impulses, and other automatic responses. And each model points toward a definition of self-regulation as *the engagement of executive processes to modify—forestall, modulate, or terminate—acting on prepotent response tendencies*.

Despite this theoretical consistency, child development research rarely captures the dynamic, systemic nature of regulation and its development (e.g., Cole, Martin, & Dennis, 2004). Commonly used questionnaires and observational methods focus on static individual differences, not on self-regulation as a process (Diaz & Eisenberg, 2015). Evidence indicates that well-adjusted, socially competent children display less negative emotion or misbehavior than other children, *suggesting* that they self-regulate more successfully. Although this is a reasonable assumption, it lacks direct evidence. Even studies in which children who used more strategies were also observed to engage in less undesirable behavior (e.g., Calkins & Johnson, 1998) do not demonstrate a causal link between engaging executive processes that change prepotent responses. Direct evidence of whether a putative regulatory strategy alters the ongoing ebb and flow of a prepotent response (e.g., an emotion primed by a laboratory task) requires a different approach.

Regulation is not located in strategy use or in reduced negative behavior. Regulation occurs in the *relation* between executive processes and prepotent tendencies—in the interplay of how one influences the other over time. A process-oriented, dynamic approach can reveal information that standard approaches do not. For example, 36-month-olds showed only a momentary decrease in prepotent responding after using a purported regulatory strategy, not more enduring damping of prepotent responding over the course of the task (Cole, Bendežú, Ram, & Chow, 2017). A dynamic approach offers opportunities to investigate in detail important elements of the development of self-regulation, such as how and why attempts at strategy use become effective as children age.

Self-Regulation as a Dynamic Process

Regulation involves change. We assume that prepotent responses have their own internal dynamics, their own ebb and flow, such as the natural decay of the probability of a prepotent response. The ebb and flow of prepotent responses does not depend on engaging executive processes. In parallel, cognitive processes (e.g., attention, memory, planning) have intrinsic dynamics and functions other than self-regulation. For example, the acuity of working memory is not constant over the course of a day. Self-regulation does not manifest in the intrinsic dynamics of prepotent responses or executive processes. Rather, it manifests in their

interplay, in how the dynamics of executive processes influence the intrinsic dynamics of prepotent responses, and how the dynamics of prepotent responses influence the engagement of executive processes.

We can capture these dynamics in the study of emotion regulation. We adopt a view of emotion as ongoing appraisal and action readiness—that is, prepotent responses reflecting the continuously changing relation between individual goals for well-being and actual or perceived circumstances (Arnold, 1960; Barrett & Campos, 1987). Self-regulation entails changes in prepotent emotions by virtue of the individual's recruitment of the executive capacities of human cognition (Cole et al., 2004; Kopp, 1989). Thus, self-regulation is not defined by the amount of emotion observed (by behavioral or physiological measures) or by the use of purported regulatory strategies. Rather, it is defined by the influence of executive processes on prepotent responses. Analytically, this influence is inferred from the temporal relation between observed strategies that index engagement of executive processes and behaviors, such as observed emotion, that index the prepotent responses primed by environmental demands. Furthermore, the influence of executive processes on prepotent response changes with age. With repeated assessments, we can evaluate the dynamics of self-regulation and study how those dynamics change with age (Morales et al., 2017).

Moment-to-moment changes in prepotent responses provoked by environmental demands and moment-to-moment changes in executive processes can unfold in any number of different ways (i.e., nondeterministic, stochastic reality of life). The interplay between executive processes and prepotent responses—the temporal dynamics of regulation—can be inferred from time-contingent relations among observable biological or behavioral indices. The patterns of change embedded in sequences of initiating and maintaining behaviors indexing executive processes must influence—within the person—behaviors indexing prepotent responses. We can test whether strategy use delays, minimizes, or ends prepotent reactions to approach or withdraw over the course of a situation.

A dynamic approach can advance our knowledge of self-regulation of emotion and its development in several ways. First, it can help address regulation as a within-person process and tackle the perennial problem of whether children who show little negative emotion to an induction are or are not regulating emotion. In microanalysis of time series data during a waiting task, few children expressed no negative emotion. Mainly, in some children, the initial negative reaction diminished and disappeared, while others were initially calm but became negative as the waiting endured and yet others appeared intermittently negative. When we summed the intervals of negative emotion across the task, these children may have appeared equally negative, although each expressed frustration uniquely. In contrast, tracking the sequence of behaviors allowed us to investigate whether strategy use influenced intrinsic emotion dynamics regardless of these individual differences.

Second, a dynamic approach can address when and how effective self-regulation manifests, and the many ways that behavior reveals competence and difficulty. For example, among 36-month-olds in one study, executive processes had momentary influence but not enduring damping of prepotent responses (Cole et al., 2017), and variations in their interplay were associated with particular between-person differences. The presence of externalizing

behavior problems predicted prepotent responses damping executive processes rather than the reverse, and higher temperamental negative affectivity predicted executive processes amplifying rather than diminishing prepotent responses. The dynamic approach revealed that very young children's regulatory attempts can be limited, that the interplay between prepotent responses and executive processes manifests in different ways, and that regulatory attempts can fail in different ways.

Third, a dynamic approach can advance our understanding of how self-regulation develops. Surprisingly, most longitudinal studies that assess self-regulation study it as a predictor, moderator, or outcome, and do not focus on how self-regulation changes with age. Evidence supports Kopp's (1982) proposition that young children initiate strategic attempts without adult direction, but evidence also indicates that their strategies are effective only momentarily (Buss & Goldsmith, 1998; Cole et al., 2017). Being able to tolerate challenges, in more than just a momentary way, is necessary to be ready for school (Blair & Raver, 2015). In one study, the intrinsic dynamics of, and relations between, prepotent responses and executive processes changed between ages 2 and 5 years (Morales et al., 2017).

Operationalizing a Developmental Model of Self-Regulation Dynamics

The mathematics of dynamic systems provide a framework for operationalizing a process-oriented model of self-regulation and its development. Borrowing from the biological and physical sciences, we formalize the definition of self-regulation mathematically as a set of coupled differential equations, wherein the within-person interplay between prepotent responses (PR) and executive processes (EP) is modeled generally as:

$$\frac{dPR}{dt} = f_1(PR) + f_3(EP), \quad (1)$$

and

$$\frac{dEP}{dt} = f_2(EP) + f_4(PR), \quad (2)$$

where $\frac{dPR}{dt}$ and $\frac{dEP}{dt}$ are observed *moment-to-moment changes* in PR and EP, respectively.

We describe these ongoing changes by a set of functions that we map to specific aspects of the theoretical model. The functions $f_1(PR)$ and $f_2(EP)$ are linear or nonlinear functions describing the intrinsic dynamics of PR and EP. For example, PR behavior may decay naturally as a person reaches a physiological limit, and EP may decay as a person fatigues. The interplay between PR and EP is described by a set of linear or nonlinear *influence functions*, $f_3(EP)$ and $f_4(PR)$, that describe specifically how PR and EP change as a function of each other. Developmentally, the parameters describing the extent to which children's executive processes alter prepotent responses, specifically $f_3(EP)$, change with age. Formally, we can embed the model of within-individual dynamics in a multilevel framework

that also models interindividual differences and intraindividual changes in *influence functions* (Boker & Laurenceau, 2006; Steele & Ferrer, 2011). For example:

$$f_3(EP)_{it} = \beta_{30} + \beta_{31}temperament_{it} + \beta_{32}age_{it}, \quad (3)$$

and

$$f_4(PR)_{it} = \beta_{40} + \beta_{41}temperament_{it} + \beta_{42}age_{it}, \quad (4)$$

where the influence functions for individual i at observation t are themselves a function of, for example, individuals' temperament and age at that observation.

This approach requires mapping observed data to latent PR and EP variables (i.e., a *measurement model* that maintains measurement equivalence across age), and choosing the specific linear or nonlinear influence functions (f_1 – f_4) that govern the changes, continuity, and dynamic interplay between PR and EP (i.e., a *dynamic model*). Several research groups are adapting mathematical functions from physics (coupled pendulums) and biology (predator-prey) to study individual and age differences in regulatory dynamics during challenging situations (e.g., Boker & Laurenceau, 2006; Butner, Berg, Baucom, & Wiebe, 2014; Chow, Ram, Boker, Fujita, & Clore, 2005). The specific functions governing the intrinsic dynamics and ongoing interplay between PR and EP are described by mathematical parameters to match the specific context in which individuals are observed (e.g., task, setting) and the type of time-series data obtained (e.g., physiology, emotion).

To illustrate how the general model of self-regulation guides formal examination of developmental changes and individual differences in self-regulation, we can, for example, consider behavior in a situation where children are required to wait for something they desire. Following the general model outlined earlier, we derive a set of differential equations that describe moment-to-moment changes in each child's PR and EP using six parameters, three of which quantify the interplay between PR and EP specifically. Moment-to-moment changes in PR, $\frac{dPR}{dt}$, are modeled as:

$$\frac{dPR}{dt} = r_i PR(t) \left(1 - \frac{PR(t)}{K(t)} \right) - q_i EP(t), \quad (5)$$

where the intrinsic dynamics of PR are defined by growth toward a task-relevant stimulus, $K(t)$ (e.g., the gift), and may be counteracted directly by bottom-up regulatory processes (e.g., a very young child's thumb-sucking). Individual or age differences in each child's intrinsic PR dynamics are indicated by the parameter r_i , and differences in efficiency of noneffortful regulation by q_i . Moreover, moment-to-moment changes in the salience of the task-relevant stimulus (e.g., the unopened gift), $\frac{dK}{dt}$, which are part of PR's intrinsic

dynamics, are governed by all the environmental affordances and constraints of the situation (e.g., task design, mother), designated as $A(t)$, and the top-down influence of EP:

$$\frac{dK}{dt} = m_i A(t) - n_i EP(t). \quad (6)$$

The parameter m_i accommodates the possibility of children's differential reactivity to the task environment, and the parameter n_i accommodates individual and age differences in top-down influences of EP on PR dynamics. Here, EP influences PR indirectly through modification of PR's intrinsic dynamics (e.g., through reduction of K) by, for example, redirecting attention away from and reducing the salience of the stimulus. Finally, we define EP as an effortful inhibitory agent that itself decays toward a resting state. Specifically, the moment-to-moment changes in EP, $\frac{dEP}{dt}$, are modeled as:

$$\frac{dEP}{dt} = b_i PR(t) - c_i EP(t), \quad (7)$$

where the child's proclivity to activate EP is indicated by the parameter b_i and the rate of EP fatigue is indicated by the parameter c_i . In summary, these equations illustrate the use of a general model of self-regulation (which is formalized more comprehensively in Supplemental Materials, Section B). The model allows us to formally examine developmental changes and individual differences in the intrinsic dynamics of PR and EP, as well as in the interplay that defines how self-regulation manifests in specific situations.

Conclusion

Self-regulation is a process at the interface between prepotent responses and executive processes. Rather than aggregating behaviors measured across time, we offer a model that we articulate explicitly as a model of change (rates of change, activation, inhibition). Prepotent responses and executive processes are modeled simultaneously, recognizing both their intrinsic dynamics and their reciprocal relations. Explicitly locating self-regulation in their interplay provides both a coherent view of self-regulation across many contexts and a rich, nuanced way to study the development of effective self-regulation. Operationalizing the key propositions of developmental and self-regulation theory in precise mathematical form provides new opportunities to test those propositions against empirical data. We look forward to what emerges when self-regulation is conceptualized and measured as a dynamic process on both short and long time scales.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The work reported in this article was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development under award number R01HD076994. The content is solely the responsibility of the authors and does not necessarily represent the official view of the National Institutes of Health.

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