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The Future of Emotion Regulation Research Is in How We Measure the Dynamics of Change

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Change is the sine qua non of emotion regulation (ER) and, thus, to understand ER we must analyze its temporal dynamics. Articles in the ER section of this special issue provide strong empirical evidence for the centrality of temporal dynamics in the development of ER on 3 levels: Rapid changes in spatial and temporal dynamics across multimodal systems underlying ER; more slowly emerging ER change over periods of time and development; and change in ER across contexts, including social interactions, culture, and coregulation in parent–child interactions. I describe how the articles by Guassi Moreira and colleagues (2019) and Lavelli and colleagues (2019) exemplify the methodological and conceptual focus on temporal dynamics. Taken together, the articles on ER demonstrate the importance of interweaving a microlevel focus on neural and biological development with a more macrolevel focus on the broader contexts of ER to advance the science of emotional development.

Keywords: emotion regulation, dynamics of change, temporal dynamics

> I realized that my prior projects were just finger warm-ups. Now I have to tackle complexity itself. But it took long, before I had assembled the courage to do so.
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> —Edsger W. Dijkstra

When I was a graduate student in the late 1990s and early aughts, I fell in love with the concept of emotion regulation (ER). With hindsight, I realize that what appealed to me most was that the study of ER both acknowledges and belies the fundamental complexity of our emotional lives. ER is expressed at multiple levels—biological, behavioral, social, affective, and cognitive—and develops through radical transformations in each of these domains, and in transaction with each other. We scientists respond to these intricate complications with elegant, parsimonious models that we can test and debate.

While these models have been crucial to the field and have yielded important empirical findings, they are often limited in their ability to drive a research agenda targeting the core of ER's complexity—that ER is fundamentally dynamic. Dynamic means change—change over time, developmental period, contexts, situation, and culture. Dynamic can be linear or nonlinear, continuous or interstitial. Patterns of variability in and of themselves are meaningful, and dynamic system transact with the world—shapes and are shaped by interactions. ER is complex because it is dynamic in all of these ways. Most of the times we can only pay lip service to the lofty goal of doing justice to the complexity of ER. How can our models and methods match the richness of what we know to be ER in the real world?

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Fast-forward almost 20 years from my graduate-school days and this special issue section provides compelling and promising evidence that the quest to match methods with an appreciation for the complex dynamics of ER is alive and well. The excellent and thought-provoking articles in this section highlight three dynamics we must consider in the developmental study of ER: (a) rapid changes in spatial and temporal dynamics across multimodal systems underlying ER; (b) more slowly emerging ER change over periods of time and development; and (c) change in ER across contexts, including social interactions, culture, and coregulation in parent–child interactions. Many if not all of the articles in the section also highlight dynamics at more than one of these levels of analysis. I focus in particular on two of the articles, one focusing on neural processes underlying ER (Guassi Moreira, McLaughlin, & Silvers, 2019) and one on intrapersonal coregulation (Lavelli, Carra, Rossi, & Keller, 2019).

Guassi Moreira and colleagues' study of variability in cortical activity during ER exemplifies examination of dynamics at more than one level of analysis. Spanning childhood and adolescence, the authors examined both spatial and temporal variability using fMRI measured during a cognitive ER task. They found that variability in the BOLD response across trials and across brain regions associated with effortful ER—the dmPFC and the SPL—decreased with age. In addition, those youth who reported feeling less negative after cognitive reappraisal showed a more consistent pattern of response (i.e., less variability) in another neural region associated with ER, the vlPFC.

This article uses novel methods and concepts on several levels. The modeling of brain dynamics as both spatial and temporal, and combined consideration of these "fast" dynamics with the "slow" dynamics of development represent an elegant approach to exploring the transactional nature of ER neurodevelopment. Moreover, the application of the Gini coefficient, a measure used in neuroscience that was derived from its original use in the study of income inequality within geographic locations (e.g., Pyatt, 1976), is an exemplar of how our field can capitalize on cross-disciplinary methods. These innovations have the further benefit of moving beyond the standard practice of characterizing brain function exclusively in terms of magnitude, which hampers efforts to capture the temporal aspects of ER (Dennis, Buss, & Hastings, 2012).

What does this novel approach yield? Guassi Moreira and colleagues provide evidence that by specifically targeting age-related changes in spatial and temporal variability, they are able to infer broader neurodevelopmental processes, such as neural specialization and maturation. If so, this suggests an array of next steps and applications, including studies examining the potential clinical relevance of individual differences in variability and neural training techniques that target such specialization. Of course, many exciting questions remain. Do age-related reductions in spatial and temporal neural variability reflect greater neural specialization and/or other processes? The authors consider a range of possibilities.

From the perspective of adolescent neural development (e.g., Somerville et al., 2013), they consider that less variable patterns of the BOLD response with age could reflect neural stability emerging from higher levels of synaptic pruning. In other words, as cognitive ER becomes more well-learned and repeated with age, synaptic pruning would support the selective and repeated activation of ER-related networks involving the dmPFC, resulting in less variable BOLD activation patterns. Taking a dynamic systems perspective (e.g., Smith & Thelen, 2003), they further posit that if a given region of interest (ROI) represents a hub in an ER network, then the optimal level of variability may vary across hubs and age. Normative or optimal levels of variability within an ROI can then be established and used as a metric of regulatory capacity or maturation.

A construct that intersects with these accounts and the concept of optimal variability is neural efficiency, or the adaptive ability to maintain performance while using fewer neural resources (Blair & Dennis, 2010; Denefrio, Myruski, Mennin, & Dennis-Tiwary, 2018; Dennis & Chen, 2009). Physiological measures of neural development have shown that with age, children evidence reduced magnitude of key neurocognitive responses related to emotional and self-regulation (e.g., Lamm & Lewis, 2010). If older adolescents are more expert in ER, they may show reduced variability because they exert less effort to regulate. Indeed, Guassi Moreira and colleagues' results support this latter interpretation because older versus younger individuals showed reduced trial-by-trial variability in some brain regions. In their study, however, there was no objective index of effective ER beyond subjective report, so it remains unclear whether patterns of reduced variability are necessarily adaptive. Identifying and testing a series of objective metrics, separately for unique brain regions, will be an important direction for future research.

These issues dovetail with the important points raised by the authors concerning the need to examine developmental specificity—whether adaptive patterns at one period in development continue to be adaptive at other periods. In raising this point, the authors consider the inverse of their argument—that adaptive neurodevelopment requires "variability tuning" involving intermediate levels of variability or even *greater* variability with age to effectively access distinct brain states or networks (e.g., Petroni et al., 2018). In other words, more variability allows for more neural complexity, which could enable a neural network to more effectively switch among different states (McIntosh, Kovacevic, & Itier, 2008).

The modeling of neural dynamics is relatively new to the study of ER, but there are parallels in other fields of study. The concept of neural quenching, for example, quantifies changes in variability to study perception-performance associations (Churchland et al., 2010). Neural quenching refers to the phenomenon that variance in trial-level cortical activity in response to perceptual stimuli, often measured using the high temporal resolution of EEG, is dramatically reduced or "quenched" within less than half a second after stimulus presentation. Neural quenching has been shown to confer perceptual and performance advantages such that greater quenching is associated with better performance on perceptual and cognitive tasks (e.g., Arazi, Censor, & Dinstein, 2017). On the other hand, the association between magnitude of quenching and performance may not be linear (Churchland et al., 2011) and might instead converge around a "sweet spot." The existence of sweet spots in the variability of other biological systems, such as metrics of cardiac functioning like respiratory sinus arrhythmia (e.g., Hastings et al., 2019) are increasingly being acknowledged, as are behavioral phenomena such as trial-level variability in behavioral measures of the anxiety-related threat bias (e.g., Egan & Dennis-Tiwary, 2018). As research on dynamic measures of ER evolves, the field will need to fully consider when and how variability might be too little, too much, or just right—or as the authors' note the "goldilocks" view of variability with both inadequate and excessive variability being detrimental (Dinstein, Heeger, & Behrmann, 2015). A crucial question for future research is whether such patterns generalize to other ER strategies, distinct brain regions, and neural measures.

In addition to focusing in on neurodevelopment, the section on ER also succeeds in pulling back to highlight the broader contexts of ER. Lavelli and colleagues report on a fascinating study of coregulation in Italian, Cameroonian, and West African Immigrant parent–infant dyads. This article takes ER outside of the individual and places it squarely in an intrapersonal context. Moreover, by focusing on rich cultural characterizations, and the socialization of emotion expression and communication, the study is multimodal on several levels—multimeasure and considering culture in terms of the experience of immigration, dual-culture adaptations, and parenting practices.

Findings show that as early as 4 weeks of age, infants and their mothers show distinct patterns of intrapersonal exchanges during face-to-face contact across the three cultures, which in turn predicted stable patterns of interaction. For Italian dyads, affectionate talking attracted infant attention and led downstream to stable sequences of positive infant–mother face-to-face coregulated exchanges. Unique patterns emerged for the Cameroonian/Nso immigrant dyads, in which coregulated exchanges emphasized sensorimotor coregulation such that maternal motor stimulation and rhythmic vocalizing was associated with active attention to the surrounding environment, rather than to the mother. Smiling and cooing from Nso babies were responded to with motor stimulation and, thus, did not foster sustained face-to-face interactions. An interesting find was that West African immigrant dyads showed a combination of these coregulated exchanges—emphasizing both face-to-face and sensorimotor.

This elegant demonstration of parent–child coregulation in early infancy gives the field an opportunity to rethink how we measure and conceptualize the quality of parent–child interactions. The tyranny of our assumptions about face-to-face communication can make us miss crucial foundations of ER in early childhood. Take for example the Still Face paradigm (Cohn & Tronick, 1988). Originally developed to study the impact of parental unresponsiveness to infants, infants' reactions to the lack of contingent facial and vocal responses—the still face—and their ability to recovery from that period of unresponsiveness had been used to study normative development, abnormal social-emotional trajectories, and disruptions in the parent–child relationship. In a recent study published along with my colleagues (Myruski et al., 2018) we created a modern analog to the Still Face in which we asked parents to use a mobile device in front of their infants and toddlers rather than hold their faces still. We reasoned that the ubiquitous use of mobile technology in some instances serves as a form of chronic parental withdrawal and unresponsiveness—a naturalistic Still Face. If so, then our Still Face with a device should elicit the same classic emotional and behavioral infant responses documented in decades of research on the Still Face paradigm.

As expected, we found classic Still Face responses–infants expressed more distress and explored less during parental device use compared with the free play, and these affective and behavioral disruptions bled into the reunion period. Important to our rationale, greater self-reported habitual use of mobile devices by parents outside the lab predicted less emotional recovery in infants during the reunion period. We concluded that like other forms of parental withdrawal and unresponsiveness, chronic parental mobile-device use while interacting with children could have a negative impact on social-emotional functioning and parent–child interactions. Yet, our study and others have systematically ignored that the quality of parent–child interactions is not limited to face-to-face reciprocity. Lavelli and colleagues' provide a call to action, showing us that we can no longer conduct rigorous science under such assumptions.

As a researcher who studies both neurocognitive and parenting contexts of ER, I believe that both the study by Guassi Moreira and colleagues (2019) and by Lavelli and colleagues (2019) reflect the mission we should have as developmentalists studying ER: to have the courage—and the methods—to tackle complexity. Taken together, this special issue section on ER takes many important steps toward an appreciation and understanding of the rich dynamics of ER. Rather than shying away from the challenge, these authors embrace it.

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