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Special Issue Article

Addressing educational inequalities and promoting learning through studies of stress physiology in elementary school students

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Abstract

To be ready to learn, children need to be focused, engaged, and able to bounce back from setbacks. However, many children come to school with heightened or diminished physiological arousal due to exposure to poverty-related risks. While stress physiology plays a role in explaining how adversity relates to processes that support students' cognitive development, there is a lack of studies of physiological stress response in educational settings. This review integrates relevant studies and offers future directions for research on the role of stress physiology in the school adaptation of elementary school students, focusing on these important questions: (a) What are the links between physiological stress response and learning-related skills and behaviors, and do they vary as a function of proximal and distal experiences outside of school? (b) How are school experiences associated with students' physiological stress response and related cognitive and behavioral adaptations? (c) How can we leverage measures of students' physiological stress response in evaluations of school-based interventions to better support the school success of every student? We hope to stimulate a new wave of research that will advance the science of developmental stress physiology, as well as improve the application of these findings in educational policy and practice.

Keywords: classroom context, elementary school students, inequality, learning, stress physiology

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Robust and persistent socioeconomic inequalities in educational opportunities and outcomes across the elementary school grades are well established in the United States (Reardon, 2019). While we know that stress physiology can have an important mediating or moderating role in explaining how environmental adversity relates to social and cognitive processes that support students' learning and academic achievement (Blair & Raver, 2012; Obradović, 2016), there is a lack of studies on the variability of physiological stress response in schools and classrooms. This review article integrates relevant studies and offers future directions for research on the role of stress physiology in the school adaptation of elementary school students, focusing on these important questions: (a) What are the links between physiological stress response and learning-related skills and behaviors, and do they vary as a function of proximal and distal experiences outside of school? (b) How are school experiences associated with students' physiological stress response and related cognitive and behavioral adaptations? (c) How can we leverage measures of students' physiological stress response in evaluations of school-based interventions to better support the school success of every student? This review addresses how school and classroom experiences can ameliorate family socioeconomic disadvantage through nurturing and supportive relationships and practices, as well as exacerbate it through systematic disparities in school quality and discriminatory treatment of students of color. Studying children's stress physiology in relation to elementary school experiences extends the pioneering work of Dr. Gunnar and colleagues, who examined children's stress physiology in child care and preschool settings to advance understanding of how public education systems can holistically support the learning and development of diverse students.

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The Relevance of Stress Physiology for Learning

Children whose families experience poverty and other socioeconomic risks perform worse than advantaged peers on direct assessments of attention, language, and executive functions (EFs) (Evans & Fuller-Rowell, 2013; Hackman, Gallop, Evans, & Farah, 2015; Raver, Blair, & Willoughby, 2013). Socioeconomic differences also register in the development and activity of brain areas that support these learning-related skills (Merz, Wiltshire, & Noble, 2019). Chronic exposure to family stressors has been shown to explain the association between distal measures of socioeconomic risk and brain functioning in children and adults (Farah, 2017; Kim et al., 2013), and researchers have proposed children's physiological stress response as a mediating pathway by which early adversity gets biologically embedded, undermining the development of cognitive and self-regulatory skills (Blair & Raver, 2012; Lupien, McEwen, Gunnar, & Heim, 2009). Given that attentional, language, and self-regulatory capacities are crucial for children's learning-related behaviors and academic achievement (Fuhs, Nesbitt, Farran, & Dong, 2014), more studies should examine how children's stress physiology explains socioeconomic educational disparities. In this section, we review extant research that shows links between experiences of adversity and stress physiology and between children's physiological responses and cognitive outcomes. We also propose future directions for research, with a focus on understanding how stressors outside the family context contribute to children's unequal opportunities to learn and thrive at school.

Adversity and stress physiology

The prefrontal cortex, a brain area that supports higher order cognitive skills, is particularly vulnerable to the upregulation of the hypothalamic–pituitary–adrenal axis (HPAA), a neuroendocrine stress response system that plays a central role in the body's response to chronic stressors. Elevated concentrations of the hormone cortisol, reflecting the activity of the HPAA, can undermine the development and functioning of the prefrontal cortex because of its high concentration of cortisol receptors (Lupien et al., 2009). Most studies linking adverse experiences to children's HPAA responsivity have examined cortisol concentrations in saliva. Early exposure to psychosocial adversity (e.g., limited family resources, maternal mental health problems, hostile parenting) is consistently associated with heightened cortisol reactivity to standardized laboratory stressors among infants and toddlers (Hunter, Minnis, & Wilson, 2011). Similarly, chronic adverse experiences, such as maltreatment, are linked to a general pattern of hyper-responsive HPAA activity in children and adolescents (Tarullo & Gunnar, 2006). In contrast, exposure to neglect, often experienced in foster care or institutional settings, has been linked to hypo-responsive HPAA activity (Bruce, Fisher, Pears, & Levine, 2009). A recent population-based study showed that many indices of socioeconomic adversity did not robustly relate to HPAA activity in elementary school-aged students, but concentrated neighborhood poverty was linked to altered diurnal cortisol output (Malanchini et al., 2020).

Stress reactivity can also be measured using indices of the sympathetic nervous system (SNS) and the parasympathetic nervous systems (PNS), which reflect more acute biobehavioral changes to environmental stressors and challenges (Obradović, 2012; Obradović & Boyce, 2009). Lower socioeconomic status (SES), as indexed by maternal education and household income, has been directly linked to higher baseline sympathetic arousal in early childhood (Giuliano et al., 2018) and lower baseline parasympathetic arousal in middle childhood (Becker et al., 2012; Hinnant & El-Sheikh, 2013). In adolescents, socioeconomic risk and psychosocial adversity are associated with elevated blood pressure, an integrated measure of both SNS and PNS (e.g., Wilson, Kliewer, Plybon, & Sica, 2000). In contrast, experiences of poverty and socioeconomic risk do not appear to be consistently linked with sympathetic or parasympathetic reactivity (Becker et al., 2012; Erath, Bub, & Tu, 2016; Hinnant, El-Sheikh, Keiley, & Buckhalt, 2013), but SNS and PNS reactivity have been shown to moderate the effects of adversity on children's outcomes (McLaughlin, Alves, & Sheridan, 2014; Obradović, Bush, Stamperdahl, Adler, & Boyce, 2010; Obradović, Portilla, & Ballard, 2016).

To capture the wear-and-tear of various physiological stress response systems in the context of chronic adversity, researchers have employed a cumulative index of allostatic load (McEwen, 1998). For example, children who grew up in socioeconomically disadvantaged homes had more markers of metabolic and cardiovascular risk in adolescence (Evans & Schamberg, 2009; Gallo et al., 2019) and in adulthood (Graves & Nowakowski, 2017). Recent work has examined cortisol concentrations in children's hair as an index of cumulative cortisol output over several months, a biomarker that partially reflects chronic adversity exposure (Bates, Salsberry, & Ford, 2017). Some studies have reported higher concentrations of hair cortisol in children whose families have lower income, less parental education, and fewer resources (Rippe et al., 2016; Vaghri et al., 2013; Vliegenthart et al., 2016); however, other researchers have found no significant associations between children's hair cortisol levels and family socioeconomic risk (Gerber et al., 2017; Ursache, Merz, Melvin, Meyer, & Noble, 2017). More research is needed to understand how hair cortisol concentration complements or diverges from salivary levels in measuring the effects of chronic stressors on HPAA activity.

Stress physiology and cognitive skills

Altered baseline cortisol levels have been linked repeatedly to heightened risk for emotion dysregulation and behavioral problems in children growing up in adverse settings (see Gunnar, Doom, & Esposito, 2015; Obradović, 2012 for reviews). Less work has tested how baseline cortisol levels relate to cognitive skills in school-aged children. One longitudinal study of low-income families showed that elevated baseline cortisol, measured at home at ages 2, 3, and 4 years, was associated with poor cognitive performance in preschool (Suor, Sturge-Apple, Davies, Cicchetti, & Manning, 2015). Similarly, elevated average diurnal cortisol was associated with lower parent-reported self-regulatory skills in preschoolers (Wagner et al., 2016). However, only a handful of studies have explicitly tested the hypothesis that elevated baseline cortisol may explain how poverty undermines the development of children's cognitive and self-regulatory capacities (Blair & Raver, 2012; Piccolo, Sbicigo, Grassi-Oliveira, & Fumagalli de Salles, 2014). Heightened baseline salivary cortisol in infancy mediated the association between lower parenting quality and poorer EF skills in preschoolers from low-income families (Blair et al., 2011). Similarly, baseline salivary cortisol levels in toddlerhood partially mediated associations between family instability and 1-year change in preschoolers' delay of gratification skills (Sturge-Apple, Davies, Cicchetti, Hentges, & Coe, 2016). It is critical that this work is extended beyond infancy and preschool. A multisystem index of allostatic load in middle childhood was shown to mediate the link between childhood poverty and young adults' working memory (Evans & Fuller-Rowell, 2013), indicating that stressful life experiences in the elementary school years may have long-term effects on cognitive capacities.

More research has examined how school-aged children's physiological responses to standardized laboratory challenges relate to cognitive and self-regulatory skills. Most such studies focus on PNS reactivity, as indexed by changes in respiratory sinus arrhythmia (RSA), a biomarker of cardiac vagal control that is sensitive to children's efforts to engage, pay attention, and regulate their emotions (Porges, 2007). In preschoolers, greater PNS reactivity to laboratory tasks is positively associated with parent reports of attention, engagement, and self-regulation (Calkins, Graziano, & Keane, 2007; Gentzler, Santucci, Kovacs, & Fox, 2009; Hastings et al., 2008; Kahle, Miller, Helm, & Hastings, 2018), and with teacher reports of on-task classroom behaviors (Blair & Peters, 2003). Meta-analysis has demonstrated a positive link between RSA reactivity and children's cognitive performance (Graziano & Derefinko, 2013). For example, greater RSA reactivity to an EF task was positively related to reading achievement in elementary school students (Becker et al., 2012). Studies also show a significant interplay between children's baseline and reactivity levels. Elementary school students who had higher baseline RSA *and* higher RSA reactivity during a laboratory stressor had the fastest growth in cognitive skills (Hinnant et al., 2013).

The differential susceptibility hypothesis (Ellis, Boyce, Belsky, Bakermans-Kranenburg, & van IJzendoorn, 2011) posits that the link between children's environmental adversity and cognitive skills varies as a function of children's physiology (Obradović, 2016). Studies have shown that family economic and psychosocial adversity is linked to children's EFs only in children who demonstrated heightened PNS and cortisol response to laboratory tasks (Obradović et al., 2010, 2016; Skowron, Cipriano-Essel, Gatzke-Kopp, Teti, & Ammerman, 2014). This research implies that heightened physiological reactivity may support better cognitive performance among children from advantaged family backgrounds, while undermining the cognitive performance of children from disadvantaged backgrounds. However, since physiological arousal is conceptualized as a moderator, these analyses of interactive effects do not explicitly test how the link between stress physiology and children's skills varies as a function of children's environmental risk. More research is needed to elucidate how physiological baseline arousal and physiological reactivity relate to children's abilities to pay attention, engage in schoolwork, regulate their behavior, and learn; and whether these links vary across different levels of socioeconomic risk. For example, blunted cortisol reactivity to a laboratory challenge was related to lower performance on a memory task only among 6-to 7-year-olds from lower-income families (Raffington, Schmiedek, Heim, & Shing, 2018). Researchers should acknowledge the likelihood of a nonlinear link between stress physiology and cognitive skills; the best performance may be associated with moderate levels of arousal (see Keller, El-Sheikh, Granger, & Buckhalt, 2012; Marcovitch et al., 2010).

Going beyond family context: neighborhood violence and educational disparities

The majority of extant psychophysiological research focuses on understanding how adverse family experiences and caregiving behaviors relate to children's stress physiology, and the implications for socioemotional behaviors. This important research has informed the design of family-based interventions that have improved caregiving practices and children's behavior, as well as children's stress physiology (Slopen, McLaughlin, & Shonkoff, 2014). Future research should build on this work in three key ways. First, studies need to examine environmental stressors beyond the family context (e.g., Malanchini et al., 2020) and explicitly test how structural inequalities and discriminatory experiences affect children's stress physiology. For example, Bush and colleagues found ethnic/racial differences in how family socioeconomic risk relates to cortisol diurnal output in kindergarten (Bush, Obradović, Adler, & Boyce, 2011). Second, studies should test the dynamic interplay between adverse events and stress physiology over different time intervals. In adolescents, daily reports of positive and negative affect and experiences were linked to changes in HPAA response during the same day and the following day (Armstrong-Carter, Ivory, Lin, Muscatell, & Telzer, 2020; Heissel, Sharkey, Torrats-Espinosa, Grant, & Adam, 2018; Kliewer, 2006). Third, researchers should examine whether and how physiological adaptations to environmental stressors undermine children's capacities to engage with and benefit from educational opportunities designed to reduce socioeconomic disparities in academic skills and performance. Next, we highlight an exemplar body of research that is addressing these needs.

Using a novel study design, Sharkey and colleagues have examined how community violence affects children's cognitive performance. By comparing performances of children who were tested either one week before or after a violent crime happened in their neighborhood, the researchers isolate an acute effect of neighborhood violence on children's test scores from other potentially co-occurring risk. In preschool children, a homicide near a child's home within a week before testing was related to lower levels of attention, impulse control, and pre-academic skills (Sharkey, Tirado-Strayer, Papachristos, & Raver, 2012). In school-age children, and especially in African American students, homicides or violent crimes that occurred before testing were linked to lower performance on vocabulary and reading tests and standardized English Language Arts assessments (Sharkey, 2010; Sharkey, Schwartz, Ellen, & Lacoe, 2014). A study of 8- to 12-year-olds showed that living within a half mile of crime that happened the week before testing was associated with faster and more error-prone responses (McCoy, Raver, & Sharkey, 2015). Trait anxiety moderated the effects of proximal community violence on children's selective attention and coping, providing evidence of differential susceptibility to neighborhood risk.

Sleep and stress physiology have been proposed as key mediating processes that explain how environmental stressors, such as neighborhood violence, contribute to the socioeconomic achievement gap (Heissel, Levy, & Adam, 2017). A small study of 11- to 18-year-olds found that children went to bed later than usual on the night after a violent crime in their neighborhood and had more disrupted cortisol response the next morning (Heissel et al., 2018). In a larger study of 18-year-olds, researchers found that community violence was associated with shorter sleep duration and poorer sleep quality only in African American adolescents (Philbrook, Buckhalt, & El-Sheikh, 2019). The link between community violence concerns and sleep in African American adolescents was further moderated by PNS functioning. Those who showed lower baseline RSA and higher RSA reactivity were most likely to experience poor sleep in the context of high community violence concerns, echoing previous research that found similar results in the context of high marital conflict (e.g., El-Sheikh, Hinnant, & Erath, 2011).

Children who attend school after a poor night of sleep can experience fatigue, dysregulated physiological arousal, or low attentional capacity, which in turn can limit their ability to learn (Heissel et al., 2017). Recent work by El-Sheikh and colleagues has demonstrated that chronic sleep disruption can have a cumulative negative effect on cognitive performance and academic achievement in elementary school students. In a study of low-income families, African American children and those facing higher economic risk reported greater daytime sleepiness over a period of 2 weeks at age 9 (Philbrook, Shimizu, Buckhalt, & El-Sheikh, 2018). Further, daytime sleepiness predicted a 2-year longitudinal decrease in children's performance on cognitive assessments in a laboratory setting, standardized reading and math tests, and teacher reports of academic functioning. Sleep efficiency and sleep problems were related to academic functioning among 8- to 10-year-old European American students in a linear fashion, but among African American students the effect was nonlinear, accelerating with the severity of problems (El-Sheikh, Philbrook, Kelly, Hinnant, & Buckhalt, 2019). Differences in how sleep affects academic learning may be explained by additional stressors faced by students of color outside their homes. For example, experiences of daily discrimination were linked to sleep disturbances in adolescents who reported ethnic/racial identity exploration, but not in those who reported ethnic/racial commitment (Yip, Cham, Wang, & El-Sheikh, 2020). The effect of community violence on children's sleep, stress arousal, and cognitive capacities may be further exacerbated by race-related stressors, and the interaction of these processes needs to be better understood.

Future studies should identify specific acute and chronic biobehavioral mechanisms that lead to disparities in children's day-to-day and longitudinal capacities to benefit from educational opportunities. Researchers should examine how across-student and within-student differences in physiological stress arousal at the beginning of the school day are related to students' learning-related behavior at school. Does dysregulated physiological arousal or reactivity following a night of poor sleep mediate the negative effect of sleepiness on children's cognitive processing and learning-related behaviors? Does dysregulated physiological arousal or reactivity at the beginning of the school day mediate or moderate the link between children's psychological stress and attentional control? Given the prevalence of food insecurity among elementary school students in the United States, how does hunger relate to children's engagement in school activities, and what is the role of physiological arousal in explaining this link or potentially exacerbating the associated fatigue? By understanding differences in students' biobehavioral readiness to learn, we may identify ways to reduce the socioeconomic achievement gap.

Although we need government programs and policies to address structural inequalities that contribute to community violence and discrimination, we also need to understand how educational programs and policies can affect those risks. For example, one study of New York City middle schools found that the effect of recent neighborhood violence on standardized achievement test scores was exacerbated by attending a school perceived as unsafe or having a weak sense of community (Laurito, Lacoe, Schwartz, Sharkey, & Ellen, 2019). Academic performance was lowest among boys and Latinx students in the least safe schools, whereas community violence had no effect on student achievement in schools with better climates. Next, we turn to research linking students' school experiences to their stress physiology.

Students' Physiological Stress Arousal in School Context

Two decades ago, Dr. Megan Gunnar and colleagues conducted a set of pioneering studies showing that experiences in childcare settings can significantly affect young children's stress response, as indexed by salivary cortisol measures of diurnal HPAA rhythm (Dettling, Gunnar, & Donzella, 1999; Tout, de Haan, Campbell, & Gunnar, 1998). Specifically, children aged 2 to 8 had higher salivary cortisol levels during the day in childcare than they did on weekends at home. In this section, we discuss studies that have extended that original finding, articulating new research directions that may further illuminate how primary school experiences may relate to children's stress physiology in ways that affect their learning and school success.

The school year as a distinct period of development and adaptation

A first wave of studies focused on the start of the preschool or childcare program year as an important transition period. Tests of children's cortisol before and after enrollment found significant differences in cortisol levels between the childcare setting and the home context during the first week of the program (Bruce, Davis, & Gunnar, 2002; Davis, Donzella, Krueger, & Gunnar, 1999). Studies with larger samples confirmed that young children display higher cortisol levels at school than at home during the transition to preschool and elementary school; however, the duration of this physiological response to school experience was less clear (Parent et al., 2019). Some studies reported no significant differences between school and home levels by the end of the first week (Bruce et al., 2002), while more recent studies have found that it may take 6 months of school for elevated cortisol levels to return to baseline (Hall & Lindorff, 2017; Turner-Cobb, Rixon, & Jessop, 2008; Yang, Lamb, Kappler, & Ahnert, 2017).

Initial studies found that children who were observed to have worse social skills displayed higher cortisol levels in childcare settings, suggesting that peer experiences and social stressors may be key mechanisms explaining environmental differences in stress physiology (Dettling et al., 1999; Tout et al., 1998). Similarly, children with a more difficult temperament were more likely to show elevated cortisol levels during the first week (Bruce et al., 2002; Davis et al., 1999). Later studies revealed a more complex interplay of children's physiological reactivity, temperament, and social status, which changed as children adapted differently to peer group dynamics (Obradović & Boyce, 2011; Tarullo, Mliner, & Gunnar, 2011). For example, socially dominant, exuberant children who were well integrated in the peer group showed declines in cortisol levels from fall to spring of the preschool year (Tarullo et al., 2011). Conversely, cortisol *increased* among highly inhibited children, especially those who engaged in social behaviors that resulted in having friends and being popular. Future studies need to explicitly address the timing of assessments in relation to the phases of the school year. Physiological response should be conceptualized as a set of dynamic longitudinal processes that are informed by individual differences, changes in social experiences and adaptations, and external supports.

Measuring physiological stress response in the school context

Extensive research over the last decade has linked various biomarkers of dysregulated stress physiology to variability in individual student experiences of peer rejection, exclusion, bullying, and victimization in school settings (Murray-Close, 2013; Vaillancourt, Hymel, & McDougall, 2013). This research has also established that indices of both HPAA and autonomic nervous system (ANS) stress response can function as mediators and moderators of associations between negative peer experiences and children's social, behavioral, and health problems (Lafko, Murray-Close, & Shoulberg, 2015; Lambe, Craig, & Hollenstein, 2019; Ouellet-Morin et al., 2011). However, most of this research focuses on the experiences and behaviors of middle school and high school students. Researchers should examine the relations between negative peer experiences and physiological stress arousal in an elementary school context, as well as the implications of physiological response to social stressors. It is important to extend current research that predominantly focuses on social and emotional behavioral outcomes to test how physiological stress response to negative social experiences may undermine students' ability to engage with class work, maintain focus, and retain new knowledge.

Further, most extant studies assess children's physiological arousal and reactivity in a controlled setting, in response to structured laboratory tasks, which limits our understanding of stress physiology in the school context. Oberle and colleagues have recently conducted studies that addressed these limitations by collecting saliva samples throughout the day in a typical classroom setting in a Canadian elementary school. Their first study showed that afternoon cortisol levels mediated the link between students' self-reported problems with anger regulation and peer reports of aggression (Oberle et al., 2017). In the second study, self-report of perspective-taking skills mediated the link between afternoon cortisol levels and peer reports of prosocial behavior (Oberle, 2018). Future studies should go beyond assessing changes in diurnal cortisol response during the school day to capture students' physiological reactivity to dyadic, small group, and whole classroom experiences.

Teacher behaviors and classroom quality

The initial studies by Gunnar and colleagues, conducted with small samples of preschoolers attending high-quality childcare programs, found that variation in childcare quality was related to children's cortisol responses (Dettling, Parker, Lane, Sebanc, & Gunnar, 2000; Watamura, Kryzer, & Robertson, 2009). Follow-up studies with larger samples identified specific aspects of classroom experience that were associated with students' cortisol response. Greater attachment security to the lead teacher was linked to declining cortisol across the preschool day, controlling for child temperament, maternal attachment security, and a global measure of classroom quality (Badanes, Dmitrieva, & Watamura, 2012). Teacher-reported conflict with students was related to elevated cortisol in preschoolers during their interactions with the teacher, and teacher report of over-dependent student behavior was related to preschoolers' elevated cortisol during the school day (Lisonbee, Mize, Payne, & Granger, 2008). Although these studies demonstrate that individual students' interactions and relationships with their teachers are important factors that contribute to physiological adaptation at school, this work needs to be replicated and extended across the elementary grades and across more diverse teacher–student experiences.

Researchers have also studied stress physiology in relation to teacher-level and classroom-level variables, which do not vary across individual students in the same class. In a study of 63 preschoolers in 14 classrooms, Hatfield and colleagues found that higher classroom levels of observed emotional support were associated with greater declines in student cortisol across the day and lower levels of SNS arousal, as indexed by alpha-amylase output (Hatfield, Hestenes, Kintner-Duffy, & O'Brien, 2013). Another recent study revealed significant interactions between children's temperament and classroom-level experiences in a sample of 338 kindergarteners in 29 classrooms (Roubinov, Hagan, Boyce, Essex, & Bush, 2017). The association between a difficult temperament, as indexed by negative emotionality, and overall cortisol output across three school days was evident only for students of teachers who displayed lower levels of emotional support and encouragement. The importance of measuring teacher experiences and stressors was further demonstrated by a study of 406 middle-grade students in 17 classrooms, which linked teachers' self-report of burnout to higher morning cortisol among students (Oberle & Schonert-Reichl, 2016). Given the large amount of time that children spend in school, we need to better understand how school-based experiences with peers and teachers elicit changes in students' physiological stress arousal; and, further, how the variability in physiological response to such experiences affects behavioral adaptation and learning.

Unequal and unjust school experiences

Research on children's physiological stress reactivity should also incorporate the fact that some demographic groups receive unequal and unjust treatment in schools. A meta-analysis of 35 studies showed that K-12 teachers treated Latinx and African American students worse than European American peers in many domains: holding lower expectations, asking fewer questions, providing less encouragement, making more referrals for special-needs testing, and making fewer referrals for gifted-and talented testing (Tenenbaum & Ruck, 2007). In a recent study of 156 Latinx third and fourth graders in 19 schools, 73% of students reported experiencing ethnic discrimination at school that more often came from teachers than from peers (Brown & Tam, 2019). A higher level of perceived teacher discrimination was related to longitudinal decreases in student-reported school belonging and academic interest, controlling for academic performance. The study also revealed an important interplay of school-level characteristics – teacher discrimination, percent of Latinx students, and observed multiculturalism – in predicting students' perception of whether their Latinx peers value working hard and doing well in school. Given that experiences of racial and ethnic discrimination are linked to lower academic self-esteem, attendance, achievement, and attainment among Latinx and African American adolescents (Benner et al., 2018), it is critical that we understand whether and how the stress of racism contributes to dysregulated stress physiology that in turn may undermine learning and worsen academic disparities.

Beyond discriminatory treatment by individual teachers and peers, we must also attend to systemic inequities in school disciplinary practices. Disparities in exclusionary discipline start in preschool and persist into higher grades, with African American students receiving disproportionately more out-of-school suspensions than white peers (Gregory & Fergus, 2017). Even after controlling for teacher report of individual student behavior and accounting for various teacher, classroom-level, and school-level factors, African American elementary school students were more likely to receive office disciplinary referrals (e.g., Rocque, 2010). While there has been some recent progress in understanding and addressing the link between racial discipline gap and racial achievement gap (Bottiani, Bradshaw, & Gregory, 2018; Gregory & Fergus, 2017), researchers know little about how these highly stressful and potentially traumatizing unjust practices affect the stress physiology and allostatic load of children who receive or witness such treatment on a daily basis.

Moderations by environmental risk

The association between young children's caregiving experiences and stress physiology also varies as a function of their exposure to environmental risk. In a large study of infants and toddlers, family socioeconomic risk, as indexed by parental income, education, occupational prestige, household density, and neighborhood noise and safety, moderated the association between how much time children spent in center-based care and their resting cortisol levels at home (Berry, Blair, Granger, & The Family Life Project Key Investigators, 2016). An increase in hours spent in childcare was linked to elevated cortisol only among children who experienced low socioeconomic risk at home. The opposite was true for children exposed to high socioeconomic risk, for whom more time in childcare was linked to lower cortisol. While this study did not address whether higher or lower resting cortisol levels were optimal in these samples, it highlights the importance of understanding the interplay of children's experiences across home, neighborhood, and educational settings.

Recently, Miles et al. (2018) found that differences in children's cortisol levels between home and childcare settings vary as a function of the children's ethnicity, immigration status, and poverty exposure. The children of Latinx immigrants, in contrast to non-immigrant and non-Latinx peers, did not exhibit a diurnal decline in cortisol level in childcare, even though they experienced a robust diurnal decline at home. Children in classrooms with peers who experienced higher poverty showed a flatter cortisol decline on childcare days, independent of their own poverty exposure and the observed childcare quality. Moreover, having a teacher who spoke Spanish moderated the effect of childcare exposure on cortisol response at school; children of both Latinx immigrants and Latinx Americans showed steeper cortisol declines at school, similar to home patterns. This study demonstrates that Spanish-speaking teachers may create a classroom environment that is physiologically less stressful for Spanish-speaking Latinx children. More studies should identify specific classroom practices that buffer socioeconomically disadvantaged children from experiencing the classroom environment as physiologically and psychologically stressful in a way that undermines their school success.

Acute stressors

Moderate levels of cortisol or PNS response have been linked to optimal performance on cognitive tests in preschool students (Blair, Granger, & Razza, 2005; Marcovitch et al., 2010). Although this research needs to be extended to elementary school students and to academic tests, the findings are consistent with adult and animal studies that show an inverted U-curve association between stress arousal and cognition (Lupien et al., 2009). Acute stressors such as high-stakes academic testing can elicit changes in physiological stress response that deviate from optimal, moderate levels, thus undermining performance on cognitive and achievement tests. Among low-income children attending 3rd through 8th grades, high-stakes testing was linked to heightened cortisol levels just before the test, relative to cortisol levels during non-testing weeks (Heissel, Adam, Doleac, Figlio, & Meer, 2019). Children who displayed the greatest positive or negative changes in cortisol levels scored significantly worse on the test. Moreover, elementary school students who lived in disadvantaged neighborhoods and experienced chronic adversity were particularly susceptible to the acute stress of high-stakes testing, exhibiting a greater deviation from baseline in their cortisol response. This is consistent with a study which found that experimentally manipulated financial worries negatively impacted performance on cognitive tests among adults who lived in poverty, whereas no effect was found for well-off adults (Mani, Mullainathan, Shafir, & Zhao, 2013). Ecologically valid conditions of scarcity were also found to reduce within-subject cognitive performance. Thus, students who face chronic family and neighborhood stressors and experience negative stereotypes and discrimination in school contexts can be further disproportionately affected by acute stressors, leading to underperformance on standardized tests and further excerbation of socioeconomic disparities in academic achievement.

However, educators can ameliorate the negative effect of acute stress on children's cognitive capacities. In a small study of 4- to 6-year-olds, researchers tested whether the examiner's demeanor moderated the association between children's physiological response to a fire alarm and their memory of this event 2 weeks later (Quas, Bauer, & Boyce, 2004). Among children who displayed heightened ANS response to the acute stressor, the presence of a supportive and emotionally responsive examiner was related to better memory of the event, whereas a serious, emotionally unsupportive affect was linked to less accurate recall. Recent studies of high school students indicate that individual differences in students' anxiety, self-regulation skills, and motivational orientation can further moderate links between physiological stress arousal and school functioning (Lee, Jamieson, Miu, Josephs, & Yeager, 2019). For example, adolescents who believed that intelligence could not be changed (i.e., endorsed a fixed mindset) exhibited higher diurnal cortisol on days when they received negative feedback about their school work (i.e., their grades were declining; Lee et al., 2019). This was not the case for adolescents who believed that intelligence could be developed. Together, these studies demonstrate that environmental supports and individual appraisal of acute academic stressors play a significant role in understanding students' physiological response to stress and its implications for cognitive performance.

Impact of School-Based Interventions on Students' Physiological Arousal

In light of the numerous connections between stress physiology and cognitive skills, it is important to identify scalable, affordable, and contextually appropriate strategies that positively affect children's stress physiology and resultant outcomes in educational settings. Measuring stress physiology as an outcome of school-based interventions has several advantages. First, school programs such as mindfulness or meditation exercises directly target children's physiological sensations as fundamental to the regulation of breathing, attention, emotions, and behavior. In many cases, indices of physiological arousal may be the most proximal metrics of program effectiveness. Measures of stress physiology are more objective than student or adult reports and can be more sensitive indicators of short-term change than Likert-scale ratings. Second, programs that target the quality of student–teacher relationships and classroom/school climate may indirectly affect students' physiological stress arousal by creating more supportive, validating, and safe learning contexts. The research reviewed above, linking stressful school experiences to students' stress physiology, underscores the need to identify ways of eliminating stressors and promoting more optimal physiological arousal in the school context. This is especially important for students who otherwise show positive behavioral and academic outcomes and thus may not receive the additional supports they need for healthy development and adaptation. Finally, physiological stress response measures can be used to identify students who benefit more from these programs. Understanding how the impact of an intervention varies as a function of students' stress arousal can lead to more effective interventions. Next, we review school-based programs that have incorporated measures of children's physiological arousal in evaluation studies and discuss how other programs should leverage physiological assessments to advance understanding of their impact on students' healthy development and learning.

Mindfulness practices

Over the past two decades, elementary schools have adopted classroom-based mindfulness practices to help students cope with daily stressors and challenges by improving their ability to stay focused, regulate emotions, and connect with others in a kind and empathetic manner. Practices vary from simple deep breathing or calming techniques integrated in the daily school schedule to multiweek special curricula that teach explicit mindfulness strategies, such as how to increase and maintain awareness of momentary physiological sensations, internal thoughts and feelings, and environmental stimuli. A few randomized control trials have demonstrated positive effects on directly assessed EF skills in preschoolers (Zelazo, Forston, Masten, & Carlson, 2018) and self-report of emotion regulation in elementary school (Black & Fernando, 2014; van de Weijer-Bergsma, Langenberg, Brandsma, Oort, & Bögels, 2012). Given the relative ease and scalability of mindfulness practices (e.g., Bakosh, Snow, Tobias, Houlihan, & Barbosa-Leiker, 2016), rigorous evaluation work should be conducted with socioeconomically and racially diverse students in large, public school districts. A study of 300 African American middle school students showed that universal stress reduction mindfulness training in Baltimore public schools significantly reduced self-report of internalizing symptoms and poor emotion regulation strategies such as negative coping and rumination (Sibinga, Webb, Ghazarian, & Ellen, 2016).

To better understand the benefits of such programs, future evaluation studies need to examine students' physiological stress responses. A meta-analysis of 45 randomized control trials conducted with adults found that meditation interventions significantly decreased various markers of physiological arousal (e.g., blood pressure, heart rate, cortisol) when compared to an active control condition (Pascoe, Thompson, & Ski, 2017). Among African American 9th graders, a 3-month breathing awareness intervention administered by health education teachers significantly decreased blood pressure and heart rate both during school hours and over a 24-hour period (Gregoski, Barnes, Tingen, Harshfield, & Treiber, 2011). The intervention, consisting of 10-min breathing sessions every day (including at home on weekends), was found to be more effective than life-skills training or regular health education classes. Notably, the effect was not detected on student-reported perceived stress, highlighting the importance of including direct physiological measures in addition to student questionnaires.

When selecting a physiological system and type of response marker to be measured, researchers should consider how that system and marker respond to different stressors and should understand the functional implications of different response patterns. Two examples here show the complexity of interpreting stress response patterns. In an evaluation study of a school-based mindful yoga intervention administered to high school students who were at risk of dropping out of school, the control group demonstrated a posttest decrease in SNS reactivity to an EF task, whereas the intervention group showed a nonsignificant increase (Fishbein et al., 2016). The authors interpreted the maintenance of higher SNS reactivity during the cognitively demanding task as evidence of sustained engagement, which could potentially protect against drug misuse behaviors associated with lower SNS arousal. Meanwhile, an evaluation of an elementary school mindfulness intervention found that the control group exhibited significant posttest changes in the diurnal cortisol pattern and a flatter slope, while the intervention group showed higher morning cortisol levels and a declining diurnal slope, similar to what was observed before the intervention (Schonert-Reichl et al., 2015). Given that the intervention had positive effects on EFs, well-being, social skills, peer relationships, and academic achievement, it is feasible that the declining cortisol pattern across the day is evidence of a buffering effect against the flattened diurnal cortisol pattern that have been associated with school stressors or lack of emotional support (e.g., Hatfield et al., 2013; Hatfield & Williford, 2017; Miles et al., 2018). Future studies should link the variability in children's physiological stress responses and intervention-related changes in physiological responsivity to other measures of students' experiences and behavior to fully understand the implications of stress physiology for school adaptation. This approach can help identify the most optimal patterns of physiological responsivity in this context.

Reappraisal of physiological arousal

Studies of college students have demonstrated the most direct links between acute stress arousal and performance on cognitive and achievement tests. Anticipation of and participation in a test-taking experience can elicit psychological symptoms of anxiety and stress as well as a heightened physiological stress arousal, which in turn can undermine optimal performance. Jamieson and colleagues have showed that college students' subjective appraisal of physiological arousal can be experimentally manipulated in a way that changes both their physiological arousal and performance on a test (Jamieson, Nock, & Mendes, 2012). College students who were taught to reappraise their physiological "jitters" as a sign of excitement that could enhance test performance demonstrated heightened SNS response as well as higher scores on both practice and actual GRE math tests, compared with students who were not assigned to the reappraisal condition (Jamieson, Mendes, Blackstock, & Schmader, 2010). Moreover, experimentally manipulated changes in SNS response in a laboratory setting positively predicted students' scores on a regular standardized math test. In a different study, college students in a reappraisal condition showed improvements in physiological arousal as well as attentional bias to negative emotional stimuli (Jamieson et al., 2012). Experimentally manipulated changes in cardiovascular reactivity were linked with lower threat-related attentional bias (Jamieson et al., 2012). Others have replicated the finding that reappraising test anxiety as positive excitement rather than stress leads to better performance on a college exam the next day (Brady, Hard, & Gross, 2018).

Given the prevalence of formative and summative direct assessments in elementary schools, it is important to extend this research to younger students. Laboratory studies of school-aged children show that cognitive reappraisal is associated with physiological stress arousal and the processing of emotion-laden content. In a community sample of children and adolescents, higher levels of self-reported cognitive reappraisal during a socially evaluative laboratory challenge were related to higher cortisol response (Johnson, Perry, Hostinar, & Gunnar, 2019). Further, cognitive reappraisal may have important implications for learning. Davis and colleagues found that 6- to 13-year-olds who were instructed to cognitively reappraise their emotions while watching a sad film had enhanced recall of information from an educational film that was shown immediately afterward, compared to children who were instructed to ruminate or received no instructions (Davis & Levine, 2013). Cognitive reappraisal of a sad film was also linked to lower RSA reactivity during the film in

5- to 6-year-olds, suggesting that reappraisal instructions can change PNS regulation of negative emotions (Davis, Quiñones-Camacho, & Buss, 2016). Further, the cognitive reappraisal strategies of preschoolers and elementary school students have been linked to changes in late positive potential amplitudes, a neural marker associated with the intensity of emotional response (e.g., DeCicco, O'Toole, & Dennis, 2014).

Together these studies suggest that teacher-instructed cognitive reappraisal of psychological stress and related physiological stress arousal may be an effective, scalable, affordable, and universally appropriate strategy to help elementary school students cope with acute learning-related challenges and educational assessments. These strategies do not require the adoption of a complex intervention program or extensive training; rather, they are conceived as simple and brief exercises that can precede everyday learning activities to help young children momentarily achieve a physiological state that supports, rather than undermines, learning objectives. For example, a teacher may ask students to notice and reappraise their fast heart rate as something that will help them do well on an activity, rather than a sign of being worried or unsure about their performance. Future studies should examine how individual differences in students' physiological and emotional reactivity as well as experiences of environmental stressors, including stereotype threat, may moderate the effectiveness of these approaches.

Teacher–student relationships, classroom practices, and school experiences

Programs and practices that directly target students' physiological arousal are not the only opportunities to understand how classroom-based interventions affect stress physiology and related functioning. A recent intervention designed to improve dyadic relationship quality between teachers and preschool students who were identified as showing disruptive behaviors showed a significant effect on children's cortisol decline during the preschool day (Hatfield & Williford, 2017). Students who were randomly assigned to the 7-week intervention program met with their teachers for a 10- to 15-minute private session outside the classroom two to three times per week. Teachers were instructed to let the child lead the activity during this protected time and to engage by observing, labeling, and reflecting on the child's actions and emotions. Preschoolers in the intervention had a significant decline in their morning cortisol levels, while preschoolers who participated in regular classroom programming exhibited an increase in cortisol across the morning. Although this finding needs to be replicated with larger, more diverse samples and extended to elementary school students, it is consistent with prior evidence that relationship-focused interventions for foster caregivers led to better regulated cortisol functioning in children (Bernard, Peloso, Laurenceau, Zhang, & Dozier, 2015; Slopen et al., 2014). A recent evaluation of the small-group mindfulness and reflection training found that this intervention did not improve preschoolers' EF skills more than the small-group literacy training, even though it was more effective than a business-as-usual control group (Zelazo et al., 2018). It may be that the personal attention and relationship building that happens in small-group activities has a greater effect on students' stress physiology than the content of the program.

Future research should seek to understand how efforts to improve classroom relationships can affect students' physiological stress-regulation, especially among students who are seen as disruptive and thus at higher risk for experiencing conflict with teachers (Portilla, Ballard, Adler, Boyce, & Obradović, 2014; Zimmermann, 2018). There is growing interest in helping educators recognize how experiences of trauma can have profound effects on students' physiological arousal, attentional biases, emotion processing, and behavioral control, and in providing educators with appropriately supportive pedagogies (e.g., Overstreet & Chafouleas, 2016). Since exposure to trauma disrupts the functioning of physiological stress systems that can influence children's adaptation, coping, and interactions with others (Tarullo & Gunnar, 2006), it is important to examine indices of physiological stress arousal in impact evaluations of trauma-informed school practices.

Measures of physiological arousal can also augment evaluations of culturally responsive interventions designed to address teachers' implicit biases, improve students' sense of belonging and safety, and reduce racial disparities in disciplinary referrals (Bottiani et al., 2018; Bradshaw et al., 2018; Okonofua, Walton, & Eberhardt, 2016). We need to identify school-based processes that can support students who face higher systemic inequalities and discrimination, in and out of school. African American students who show positive adaptation on cognitive and behavioral measures also often exhibit heightened levels of physiological stress response and elevated allostatic load that is linked to poor health outcomes in adulthood (Hostinar & Miller, 2019). For example, African American children in a low-income, rural setting who were rated by teachers as having high levels of self-control, academic skills, and social skills at age 11–13 exhibited high allostatic load at age 19, a marker that includes elevated blood pressure and overnight stress hormones (Brody, Lei, Chen, & Miller, 2014). There is a great need to identify school-based programs that can reduce the physiological trade-offs that are observed in African American students who are seen as successful and resilient according to more traditional school metrics.

School recess also offers a unique opportunity to understand the role of stress physiology in adaptation. Recess presents elementary school students with daily opportunities to practice regulating positive and negative emotions, resolving interpersonal conflicts, expressing respect and empathy, and engaging in positive peer relationships (Dusenbury & Weissberg, 2017; London, Westrich, Stokes-Guinan, & McLaughlin, 2015). Physical activity in school settings has been positively linked with school engagement and cognitive performance (Best, 2010; Owen et al., 2016). After engaging in physical activity at school, preschoolers displayed higher levels of EFs than after being sedentary (Palmer et al., 2013). Elementary school students randomly assigned to 90 min per week of physically active lessons showed greater improvement on standardized academic tests than the control group across a 3-year period (Donnelly & Lambourne, 2011). Further, studies show that children from lower-income families and children who display lower levels of working memory may benefit more from school-based physical exercise (Budde et al., 2010; Tine & Butler, 2012). In addition to supporting individual student health, school recess can promote a positive school climate. In economically disadvantaged schools, a program designed to improve student safety and inclusivity at recess was associated with teacher and principal perceptions of a positive, supportive school climate (London et al., 2015).

Even though regulation of physiological arousal may explain how recess beneficially affects students' acute cognitive performance and long-term school success, studies linking physical activity and physiological reactivity in the school context are limited and primarily focused on showing that physical activity can induce cardiovascular or hormonal responses (Budde et al., 2010; Tine & Butler, 2012). Future studies should examine whether acute or chronic changes in students' stress response may mediate or moderate the positive effects of physical activity on acute cognitive performance and cumulative academic achievement. Given that recess can also be a context for negative and discriminatory peer interactions that have been linked to students' stress physiology (Brody et al., 2014, 2016; Vaillancourt et al., 2013), researchers should consider whether the recess is organized as an inclusive experience that supports cognitive and academic performance of all students (London et al., 2015). Future research should test whether a well-managed recess reduce socioeconomic gaps in student achievement as well as in associated physiological trade-offs. This work should also address the impact of withholding recess as a punishment (London, 2019).

Methodological and Practical Considerations

Researchers who are examining students' physiological stress response in relation to learning-related skills, behaviors, and experiences must carefully consider: (a) which index of physiological stress response to use; (b) when to measure the stress response; and (c) how variability in the response should be interpreted. Since a detailed review of the methodological considerations for all physiological markers is beyond the scope of this paper, we encourage readers to consult other sources as they hone their study design (Adam et al., 2017; Dennis, Buss, & Hastings, 2012; Hinnant, Philbrook, Erath, & El-Sheikh, 2018; Obradović & Boyce, 2012). We also urge cross-disciplinary collaborations that include experts in education, developmental science, and psychophysiology, to ensure a high level of ecological validity, psychometric reliability, and analytic rigor. Further, researchers studying physiological stress response in schools should partner with local schools and communities to design studies that have clear implications for educational policy and practice.

Parasympathetic nervous system (PNS) responses

Variability in children's PNS arousal, as indexed by heart rate variability or RSA, has been linked to adaptive behaviors that support learning. For example, young children's greater PNS response during EF tasks is related to higher levels of concurrent EF performance (Becker et al., 2012; Graziano & Derefinko, 2013). Similarly, PNS response to other cognitive or socio-emotional laboratory challenges is positively linked to parent report of children's cognitive and emotional self-regulation, and teacher report of on-task behavior (Blair & Peters, 2003; Gentzler et al., 2009; Hastings et al., 2008; Kahle et al., 2018). Thus, PNS response has been identified as a physiological marker of sustained attention, self-regulation, and social engagement (Hinnant et al., 2018; Porges, 2007). Changes in PNS arousal can be elicited using mild-to-moderate challenges that children encounter while working on learning-related activities.

More basic research is needed to identify optimal levels of PNS reactivity for performance on cognitive and academic tests among diverse groups of elementary school students. It is important that this work investigate both between-subject and within-subject variability to confirm or qualify limited evidence suggesting a curvilinear association between PNS arousal and cognitive performance (Blair et al., 2005; Calkins et al., 2007; Marcovitch et al., 2010). Experimental manipulation of external learning supports can identify factors that promote or undermine children's learning and performance via changes in physiological arousal. In the classroom context, PNS measures can be employed to understand how physiological arousal interacts with students' self-regulatory capacities as well as classroom supports to promote focused attention, intrinsic motivation, classroom engagement, and dyadic interactions. PNS reactivity could be measured in response to specific classroom activities as well as assessment experiences. Further, measuring changes in RSA can elucidate how classroom exercises in breathing, mindfulness, or reappraisal can promote optimal physiological arousal for learning and test performance in elementary school students.

Recent advances in wearable technology make studying PNS response in educational settings more feasible, as new fitness trackers include measures of heart rate variability. However, the quality of raw heart rate variability data varies considerably in devices marketed to the general public. Some commercial trackers sample data at a much lower frequency than the research-based standard, and some apply proprietary algorithms to deal with missing or implausible data points. These features limit the accessibility and reliability of raw data and prevent the use of novel second-to-second analytic strategies, which can help researchers understand the dynamics of physiological adaptation (e.g., Gates, Gatzke-Kopp, Sandsten, & Blandon, 2015). Despite these limitations, commercial trackers can be used at scale to measure variability in overall patterns of physiological responses in the classroom environment. Such studies can help us understand how classroom-level factors differentially impact students' physiology and how physiology interacts with classroom experiences to further affect students' behavior. By measuring PNS arousal in all children at the same time, researchers will advance our understanding of the role of peers' stress physiology in co-regulating students' arousal, social affiliation, and engagement.

Sympathetic nervous system (SNS) responses

Most studies examining individual differences in children's SNS arousal have examined how this physiological response to environmental threats and rewards relates to children's emotional and behavioral dysregulation and symptoms of developmental psychopathology (Obradović & Boyce, 2012). Three biomarkers of SNS response have been employed by developmental researchers: cardiac measure of pre-ejection period, peripheral measure of skin conductance level, and salivary measure of alpha amylase. Momentary changes in the first two markers can be captured in response to specific stimuli. Pre-ejection period reactivity has been linked to children's sensitivity to rewards and behavioral approach tendencies, whereas skin conductance reactivity has been linked to children's sensitivity to fearful stimuli and behavioral measures of anxiety, inhibition, and behavioral problems (Brenner, Beauchaine, & Sylvers, 2005; Kalvin, Bierman, & Gatzke-Kopp, 2016; Murray-Close, 2013). In contrast, salivary alpha amylase reactivity is measured 5–10 min after the onset of a stressor, thus representing a cumulative marker of sympathetic response to the stressful experience (Granger, Kivlighan, El-Sheikh, Gordis, & Stroud, 2007). While elevated salivary alpha amylase response to laboratory challenges has been found among children who report high levels of social anxiety (Payne, Hibel, Granger, Tsao, & Zeltzer, 2014), more research is needed to understand the relevance of this biomarker for adaptation of elementary school students.

Most SNS research has been conducted with children diagnosed with, or at risk for, learning or behavioral problems (e.g., Lorber, 2004; Murray-Close, 2013) or in the context of family adversity (El-Sheikh et al., 2009). We need more community studies of diverse elementary school students. Assessment of cardiac pre-ejection periods is currently not practical outside of the laboratory; however, skin conductance levels can be studied at scale in classroom settings with wearable technology. Geršak et al. (2020) used wearable armband trackers with 7-year-old children to show that an active teaching style was associated with greater skin conductance reactivity and greater recall of geometry facts 6 months later, compared to a control group exposed to a traditional teaching method. Given the ease with which educational researchers can incorporate wearable trackers in field studies, more validation work is needed to demonstrate that these methods yield high-quality, reliable skin conductance data from children in educational settings. Skin conductance response is most reliably measured in the palm of the hand, which has a high density of eccrine sweat glands, but wearable trackers typically place sensors on wrists and palms, resulting in a lower signal.

Since skin conductance reactivity is associated with children's responses to threating and fearful stimuli as well as heightened state and trait anxiety (Obradović & Boyce, 2012), this biomarker could be used to study how unequal and unjust school experiences affect students' classroom engagement, academic performance, and general school belonging. Future research should also test how social buffers, such as warm and supportive teachers, can protect children at risk for test anxiety or stereotype threat. Parent–child relationship quality has been found to moderate the effect of temperament on skin conductance level reactivity to fear-inducing films, such that fearful children with low-quality parenting showed high reactivity, while the inverse was true for fearful children with high-quality parenting (Gilissen, Koolstra, van Ijzendoorn, Bakermans-Kranenburg, & van der Veer, 2007). Similar studies could help us understand physiological responses to school experiences, and their effects on learning-related behaviors.

Hypothalamic–pituitary–adrenal axis (HPAA) responses

In children, HPPA responses are typically studied by measuring salivary concentrations of cortisol, the human glucocorticoid hormone secreted by adrenal glands and passively diffused into saliva. Salivary cortisol levels naturally peak 30–40 min after waking, known as the cortisol awakening response, and they gradually decrease throughout the day until reaching a low point in the middle of the night, several hours after the onset of sleep (Obradović & Boyce, 2012). Cortisol response to specific stressors or challenges can be detected in saliva approximately 15–20 min after the onset of the experience, and the pattern of reactivity may vary across the day. Any study of cortisol levels needs to account for this daily rhythm by assessing cortisol response at the same time of day or by controlling for the time of sample collection. Researchers can measure cortisol awakening response, reactivity to a specific experience, or changes in the overall diurnal rhythm, but in all cases, they should take multiple measures to reliably capture variability in the response and to distinguish between variance which is situational and that which can be attributed to more stable factors. Longitudinal studies should also address how long-term stability and changes in HPAA functioning affect cognitive development and learning. In one study, young children who showed moderate fluctuations in baseline cortisol during the first 5 years of life performed better on EF tasks at age 5, compared to children with either highly stable or highly variable longitudinal profiles (Blair, Berry, & The Family Life Project Investigators, 2017).

In educational settings, cortisol responses have been employed to understand (a) how diurnal rhythm differs between school and home settings among preschoolers (Bruce et al., 2002; Davis et al., 1999; Parent et al., 2019); (b) links between the quality of classroom experiences and students' cortisol levels in preschool and elementary school (Badanes et al., 2012; Gunnar, Kryzer, Van Ryzin, & Phillips, 2010; Watamura et al., 2009); and (c) cortisol reactivity to acute learning-related laboratory stressors (Kahle et al., 2018; Obradović et al., 2010, 2016; Quas et al., 2004, 2006; Skowron et al., 2014) or learning-related interventions (Davis et al., 2016; Hatfield & Williford, 2017). This work needs to be extended to studies of larger, more diverse samples of students experiencing a greater range of educational opportunities and risks. Further, researchers should investigate how cortisol adaptations relate to behavioral outcomes. For example, in a study of preschoolers' cortisol responses to family daycare experiences, researchers found that elevated cortisol placed girls at risk for anxious, vigilant behavior and boys at risk for angry, aggressive behavior (Gunnar et al., 2010). New research should focus on learning-related classroom behavior such as classroom engagement, frustration tolerance, and participation in group activities.

Cortisol response is particularly sensitive to experiences of social evaluation and to perceived or actual threats to psychological or physical safety. As such, cortisol response could be especially useful for studying whether educational settings are safe, nurturing, and validating spaces that promote the learning of all students. Researchers could use cortisol response to evaluate dyadic interventions that target student-teacher relationship quality, group interventions that target collaborative power dynamics and communication among peers, classroom-level interventions that aim to create a more inclusive and supportive climate, or school-level policies that address discriminatory disciplinary practices or trauma-informed pedagogies. Researchers should analyze short-term and long-term physiological changes and adaptation to these interventions. While large-scale evaluations may be impeded by methodological, practical, and ethical concerns around saliva collections during the school day, promising new technologies may address those issues – for example, through a skin patch that continuously records levels of cortisol in sweat (Parlak, Keene, Marais, Curto, & Salleo, 2018; Yang et al., 2019).

Interpretation considerations

Researchers who are interested in embedding measures of stress physiology in real-world settings where children develop and learn need to consider additional factors which may impact the validity and applicability of their findings. First, when using a new technology, unless it is explicitly designed for use with children, researchers should verify that the technology captures reliable and valid data from children in naturalistic settings. Second, studies should control for experiences that can evoke changes in physiological response but are not the target of the investigation or intervention, such as body posture, body temperature, and rate of speech (Bush et al., 2011). Third, the timing of data collection should account for changes in social and behavioral dynamics across the school year (Hall & Lindorff, 2017; Obradović & Boyce, 2011; Tarullo et al., 2011; Yang et al., 2017). For example, one study of low-income preschoolers in a

Head Start program found that cortisol levels were lower in students who had just attended an art class, compared to peers who attended a homeroom class, but the effect was significant only at the middle and end of the school year (Brown, Garnett, Anderson, & Laurenceau, 2017). Fourth, researchers studying how stress physiology explains socioeconomic educational gaps should consider that elementary school teacher reports of student behavior and achievement show systemic racial/ethnic and gender disparities, after controlling for performances on direct assessments (e.g., Garcia, Sulik, & Obradović, 2019). Linking variability in students' physiological responses to direct assessments of behaviors and skills will be critical to translating research findings to inform more equitable educational practice. Finally, researchers should follow new science which shows that children's stress physiology is a dynamic process of adaptation to environmental experiences, rather than a biological trait indicating individual vulnerability or sensitivity (Obradović, 2016).

Conclusion

To be ready to learn, children need to be focused, engaged, and able to bounce back from setbacks. However, many children come to school with heightened or diminished physiological arousal due to chronic exposure to poverty-related risks. Interventions at the school and classroom level can help students achieve physiological responses that promote learning and well-being, and through such strategies we can reduce disparities in educational experiences and outcomes. Studying stress physiology in public elementary schools has potential to address the known inequities in developmental psychology research (Brown, Mistry, & Yip, 2019), without placing undue burden on the families of underserved students. Larger and more representative samples will provide a more complete understanding of multifinality and equifinality processes that underlie adaptive functioning across a more diverse set of experiences, and thus can inform the development and implementation of culturally responsive interventions. By highlighting novel extant research and articulating future directions, we hope to stimulate a new wave of research that will advance the science of developmental stress physiology, as well as improve the application of these findings in educational policy and practice. For this to happen, the work needs to be situated in genuine research–practice partnerships where school leaders, teachers, and students collaborate with scientists to design studies that yield actionable results.

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