CHAPTER 5

Psychophysiology of Aggression

SUSAN BRANJE and HANS M. KOOT

Brief Introduction

In this chapter we review psychophysiological studies of the development and maintenance of aggression in childhood and adolescence. As aggression is likely to be a function of a complex interplay between individual and social factors, this review is concerned with the role of psychophysiological or neurobiological systems in aggressive behavior of children and adolescents, as well as with the interactions of these systems with social factors. The autonomic nervous system (ANS) and the hypothalamic–pituitary–adrenal (HPA) axis both play important roles in the regulation of stress and decision making, and these stress-regulating mechanisms are thought to be important in understanding individual differences in aggressive behavior (Van Goozen, Fairchild, Snoek, & Harold, 2007). Therefore, we focus on the roles of the ANS and the HPA axis in particular.

Main Issues

Although a large body of literature has addressed psychophysiological correlates of aggressive behavior, the results of these studies are at times quite inconsistent. Contributing to this inconsistency in findings is the heterogeneity in studies in terms of methodological and theoretical issues. We pay attention to a number of these issues, which include the heterogeneity in behavioral constructs and the roles of sex and age.

Different Forms of Antisocial and Aggressive Behavior

Regarding heterogeneity in behavioral constructs, many studies focus on antisocial behavior more generally and do not distinguish aggressive behaviors from other antisocial or externalizing behaviors. Although externalizing behaviors are often significantly and strongly correlated, failing to distinguish them might obscure research findings and interpretations. Different forms of externalizing behavior have a divergent developmental course (Bongers, Koot, van der Ende, & Verhulst, 2004). For example, developmental trajectories of physical violence and theft during adolescence and early adulthood are different and differently related to neurocognitive functioning (Barker et al., 2007). It is thus important to compare the role of psychophysiological processes in externalizing behavior more generally with their role in aggressive behavior more specifically.

Even within the construct of aggression, it is important to distinguish between types of aggressive behaviors, as aggressive acts can differ in their developmental origins, can serve various purposes, and can have diverse consequences (Mullin & Hinshaw, 2007). Different types of aggression, such as reactive and proactive aggression, might have diverging underlying psychophysiological processes. *Reactive aggression* is a defensive response linked to frustration or threat and is exhibited in reaction to provocation. Reactive aggression is impulsive and often accompanied by disinhibition and affective instability and high levels of bodily arousal, but not necessarily by antisocial tendencies. *Proactive aggression,* in contrast, is nonimpulsive, goal directed, and controlled and involves calculated efforts to obtain resources important for the self (Dodge, Harnish, Lochman, Bates, & Pettit, 1997). Proactive aggression often occurs in the context of persistent antisocial behavior. Proactive aggressive individuals are less likely to have unstable affects, and their level of arousal is usually low (Vitiello & Stoff, 1997). Therefore, it is not surprising that the psychophysiological correlates of reactive and proactive aggression differ substantially.

Sex Differences

Research on the associations between aggressive behavior and psychophysiological measures generally tends to focus on boys more than on girls. As recent studies suggest that there are fundamental sex differences in the neural regulation of dominance and aggression (e.g., Terranova et al., 2016), it is important not to generalize findings for boys to girls. Instead, sex differences in the psychophysiological processes underlying aggression need to be taken into account.

Research on the associations between aggressive behavior and psychophysiological measures also tends to focus on aggressive behaviors more typical or salient for boys than for girls (Rappaport & Thomas, 2004). Whereas *physical aggression* is defined as behavior that harms others through damage to their physical well-being, *relational aggression* includes behavior that harms others through damage to relationships or feelings of acceptance, friendship, or group inclusion (Crick & Grotpeter, 1995). When examining gender differences in psychophysiological correlates of aggressive behavior, it is important to consider aggressive behaviors that are more typical for girls as well. Psychophysiological measures might predict different forms

of aggression for boys and girls (Powch & Houston, 1996) that are relatively normative and effective in the context of their gender-segregated peer groups (Crick & Grotpeter, 1995).

Age Differences

In addition, it is important to consider age differences in the role of psychophysiological processes in aggressive behavior. Although psychophysiological processes are often thought to be an underlying mechanism explaining aggressive behavior, these processes might play a more or less important role in aggression at different points in childhood and adolescence (Lorber, 2004). Moreover, there are clear developmental changes in psychophysiology (Beauchaine & Webb, 2016). Studies addressing the psychophysiology of aggression should account for the fact that developmental changes in tonic and phasic psychophysiological responding are quite common. These changes occur through various mechanisms, including increased body and brain size and associated alterations in cardiodynamics, or changes in neural architecture such as maturation of frontal brain structures implicated in self-regulation with effects on autonomic function and other neural systems. These developmental changes have ramifications for measures involving both the ANS and the HPA axis and are important for interpretation of age differences in associations between aggression and psychophysiological measures. It is therefore essential to address developmental issues in the associations between o psychophysiological processes and aggression.

Theoretical Considerations

The ANS and Aggression

The ANS has been thought to play an important role in aggressive behavior. The parasympathetic and sympathetic branches of the ANS are thought to control the "fight-or-flight" stress reaction (Porges, 2007). The sympathetic nervous system (SNS) prepares the body for fight or flight in situations of threat or danger. It is associated with responses such as increased heart rate, blood pressure, cardiac output, and skin conductance. The parasympathetic nervous system (PNS) conserves energy and restores the body to a calm state. It is associated with vagally mediated responses, such as decreased heart rate and blood pressure, and increased heart rate variability, or the variation in intervals between heartbeats that varies as a function of respiration. The SNS and PNS in a resting state may reflect individual differences in the capacity to respond adaptively to internal and external demands. Resting activity of the SNS may reflect the individual's preparedness for responding to threat, and resting activity of the PNS may reflect the ability to restore the body's functions after a danger has occurred. SNS-linked cardiac activity has been associated with approach motivational processes, whereas PNS-linked cardiac activity consistently predicts emotion regulation capabilities (Beauchaine, Gatzke-Kopp, & Mead, 2007). However, in young children, better emotion regulation has also been related to greater sympathetic recovery (Kahle, Miller, Lopez, & Hastings, 2016).

Reactive aggression might be related to autonomic hyperarousal (Scarpa & Raine, 1997). According to frustration–anger models, reactive aggression is associated with heightened emotional and physiological arousal. Such autonomic hyperarousal is thought to reflect an automatic stress response (i.e., a defensive motivational state) and negative emotionality to which children react with aggressive behavior. Aggressive individuals might exhibit exaggerated fight-or-flight responses to provocation (Beauchaine, Katkin, Strassberg, & Snarr, 2001; Rappaport & Thomas, 2004). When aggressive individuals perceive stimuli as threatening, their fight-or-flight systems might be activated, involving parasympathetic withdrawal and relatively dominant sympathetic influence on cardiac activity. These changes result in increases in blood pressure (Gump, Matthews, & Raikkonen, 1999) and heart rate (Beauchaine et al., 2001).

Proactive aggression, in contrast, is thought to be related to autonomic underarousal (Scarpa & Raine, 1997). According to *stimulation-seeking theories,* children might attempt to compensate for physiological underarousal by seeking stimulating and risky situations, such as aggressive acts, to raise their arousal to optimal levels (Raine, Venables, & Mednick, 1997; Zuckerman, 1979). Alternatively, *fearlessness theory* (Raine, 1997, 2002) suggests that underarousal might be an indicator of fearlessness. Fearless children are thought to be more likely to engage in aggression to obtain rewards and status because they are relatively insensitive to the potential negative consequences of aggressive behaviors, such as punishment. A third explanation suggests that individuals with low ANS arousal have difficulty attending and reacting to environmental stimulation and might therefore have a higher chance to develop aggressive behavior (Wilson & Gottman, 1996). These theories suggest that physiologically underaroused children have more difficulty attending to the antecedents or consequences of aggressive behavior because of general low levels of arousal across systems (Van Goozen et al., 2007).

The HPA Axis and Aggression

Whereas the ANS reacts very quickly to threatening events, the HPA axis responds somewhat slower and functions as a "backup" and balancing system (Alink et al., 2006; Sapolsky, Romero, & Munck, 2000). The HPA axis controls a series of neurophysiological processes in response to stressful stimuli (De Kloet, 1991). After exposure to a stressor, stress signals trigger the hypothalamus to secrete corticotropin-releasing hormone, which in turn activates the anterior pituitary to secrete adrenocorticotropic hormone (ACTH) (Vazquez, 1998). ACTH subsequently triggers the release of cortisol by the adrenal glands (Chrousos & Gold, 1992). When cortisol secretion reaches a certain level, it binds to glucocorticoid and mineralocorticoid receptors in the brain, which activate a regulatory feedback mechanism inhibiting the production of the corticotropin-releasing hormone, ACTH, and cortisol, in order to return the system to a prestress or basal state (De Kloet, 1991).

The HPA axis also maintains an underlying diurnal/circadian cortisol rhythm that is independent of stress responses but linked to activity level. At awakening, secretion of cortisol increases, followed by a decrease throughout the day (Edwards, Clow, Evans, & Hucklebridge, 2001), with lowest levels at nighttime, at the start of the sleep cycle. As individual differences exist in the functioning of every step in

the circadian rhythm, including the sensitivity to these feedback signals (De Kloet, Joëls, & Holsboer, 2005), links of aggression to both HPA axis reactivity to stress and HPA axis circadian functioning have been examined (Cicchetti & Rogosch, 2001). As with the ANS, aggressive behaviors have been theorized to be associated with both low and high activity of the HPA axis. According to the hypo(re)activity hypothesis of the fearlessness theory (Raine, 1997), a significant negative correlation of cortisol with proactive and reactive aggression will be found. This inverse relation between cortisol (re)activity and aggressive behavior has also been labeled the *blunted stress response* (Van Goozen et al., 2007).

Interaction Effects between Psychophysiological Systems

The combined activity of different psychophysiological systems might predict aggressive behavior better than the activity of either subsystem alone. Activity of both the HPA axis and the SNS generally increases in response to stress. According to the *additive model,* and in line with the low-arousal theory, concurrent low reactivity in both systems is related to elevated levels of (proactive) aggressive behavior (Bauer, Quas, & Boyce, 2002). An alternative hypothesis is, however, that aggressive children are characterized by a mismatch or imbalance in the interplay between different physiological systems involved in the regulation of stress. According to the *interactive model,* asymmetry between the HPA axis and the SNS, with low reactivity in one system together with concurrent high reactivity in the other system, may predict aggressive behavior (Bauer et al., 2002). In this model it is thus suggested that the relation between either of the two systems and disruptive behavior is moderated by the other system.

The balance or interaction between the SNS and PNS within the ANS might also play a role in aggressive behavior. Although, generally, the SNS and PNS display well-coordinated, reciprocal actions, with SNS activity increasing when PSN activity decreases and vice versa, it has been argued that the SNS and PNS can function as two separate dimensions (Berntson, Cacioppo, & Quigley, 1991). These nonreciprocal actions may result in concurrent increases or decreases in both systems and lead to ambiguous effects on physiological arousal (Berntson, Cacioppo, & Quigley, 1993). Indeed, several studies have indicated that concurrent low levels of SNS and PNS are related to juvenile disruptive behavior (Beauchaine et al., 2007; Boyce et al., 2001).

A Biosocial Perspective on Childhood Antisocial Behavior

Psychophysiological factors are thought not only to affect aggressive behavior directly but also to interact with social factors in affecting aggressive behavior (Raine, 2002; Raine, Fung, Portnoy, Choy, & Spring, 2014). According to Raine's (2002) biosocial model, the presence of both biological and social risk factors exponentially increases the extent of antisocial and violent behavior. At the same time, when predicting psychophysiological functioning, social factors moderate the relation between psychophysiological factors and antisocial behavior such that these relations are strongest in those from benign social backgrounds. The latter finding is explained by the "social push" hypothesis, suggesting that when antisocial children lack social factors that "push" or predispose them to antisocial behavior,

biological factors are more likely to explain antisocial behavior. Also, the association between life adversities and antisocial behavior might depend on reactivity of the ANS. Children who show blunted physiological responses to stressful life events might be unable to adequately respond to stressful situations (Beauchaine, 2001).

Moreover, the role of social factors in developmental changes in psychophysiology should be considered. Experiences during development might affect psychophysiological functioning and thereby change the role of psychophysiology in aggression. In particular, perinatal and early life adversities might be associated with blunted responses of the ANS, but, in cases of extreme adversities, also with increased ANS reactivity (Obradović, 2013). Because plasticity of the ANS decreases with age, stressful experiences later in life are less likely to affect the reactivity regulation mechanisms of the ANS (Boyce & Ellis, 2005; Gunnar, Wewerka, Frenn, Long, & Griggs, 2009). Prenatal influences, such as fetal exposure to cigarettes or alcohol, or early life stressful experiences are thought to inhibit autonomic functions (Fries, Hesse, Hellhammer, & Hellhammer, 2005), resulting in a low resting heart rate in antisocial individuals. However, it is not clear whether ANS reactivity mediates the relation between early life adversities and antisocial behavior.

The propensity to aggression originating from arousal and heightened or lowered stress reactivity is moderated by cognitive factors. Children displaying antisocial behavior show cognitive deficits in executive functioning and verbal intelligence, which are important for the inhibition of impulses and the finding of alternative forms of social interaction, respectively. Social cognitions are deviant in that aggressive children tend to attribute hostile intent to actions of peers and to expect more instrumental gain from their aggressive actions, are more impaired in moral reasoning, show less sensitivity to others' distress, hold more positive views of aggressive means to obtain goals, tend to blame others for their aggression, and emphasize revenge. Moreover, they have difficulties in reversal learning of tasks involving both rewards and punishments (Kimonis, Frick, & McMahon, 2014).

An important notion is that aggressive behavior has to be unlearned (cf., Tremblay, 2003). Children normally learn to inhibit their natural aggressive impulses in the first 5 years of life (e.g., Alink et al., 2006), mainly based on their interactions with primary caregivers that have an organizing effect on different brain structures, including the HPA axis. Genetic, prenatally acquired, and temperament-based risks that underlie aggression need to be regulated by socialization. Several peculiarities in social cognitions that enhance psychophysiology-dependent aggressive impulses are based on deficits in this learning process, possibly because it contributes to or interacts with deficits in responding to social cues (Blair, 2007).

Measures and Methods

Measures of the ANS

Heart Rate

Heart rate is often used as an indicator of the ANS. Heart rate is controlled by both the parasympathetic and sympathetic branches of the ANS. The heart is subject to influence from the sympathetic and parasympathetic branches of the ANS, and

it is subject to neuroendocrine influences as well. Chronotropic (i.e., rate-related) cardiac effects such as heart rate variability are controlled primarily by the PNS, whereas inotropic effects such as contractile force and stroke volume are controlled primarily by the SNS.

Respiratory Sinus Arrhythmia

Respiratory sinus arrhythmia (RSA) is naturally occurring heart rate variability in synchrony with respiration. This is measured by periodic changes in heart rate during a resting state of cardiovascular activity. RSA represents the functionality of vagal tone, which serves as the key component of the PNS. An increase in vagal tone both slows the heart and makes heart rate more variable. During a breathing cycle, the R–R interval, or the time between two of the distinctive, large, upward *R* spikes on an electrocardiogram, is shortened during inhalation, as inhalation temporarily suppresses vagal activity, causing an immediate increase in heart rate. The R–R interval is prolonged during exhalation, which decreases heart rate as it causes vagal activity to resume. Vagal tone (and specifically its influence on heart rate) represents an index for the functional state of the entire PNS.

Resting heart rate and electrodermal activity (EDA) measures reflect the assessment of autonomic activity in the absence of any obvious external stimuli. Heart rate and EDA in response to experimental stimuli are frequently measured in raw form during tasks (task physiology) or expressed as a change from baseline or prestimulus levels (physiological reactivity).

Cardiac Pre-Ejection Period

SNS-linked cardiac activity can also be assessed using the pre-ejection period (PEP), an index of the time elapsed between left ventricular depolarization and ejection of blood into the aorta. Shorter intervals represent greater SNS activity.

Salivary Alpha-Amylase

Salivary alpha-amylase is an enzyme produced in the oral mucosa and is an assumptive marker of the adrenergic component of the stress response. Salivary alpha-amylase levels are associated with activity of the sympathetic adrenal medullary system, which is activated by the SNS under stress. Salivary alpha-amylase levels increase under stressful conditions that are also associated with increases in plasma catecholamines, heart rate, systolic blood pressure, PEP, and cardiac output (Skosnik, Chatterton, Swisher, & Park, 2000). However, salivary alpha-amylase can be elevated in response to a stressor independently of serum catecholamines and may reflect a general marker of sympathetic adrenal medullary system activity (van Stegeren, Rohleder, Everaerd, & Wolf, 2006).

Skin Conductance Activity

Skin conductance activity is also referred to as EDA or electrodermal response (EDR). Skin conductance is an indication of psychological or physiological arousal.

Skin resistance varies with the state of sweat glands in the skin. Sweating is controlled by the SNS. If the sympathetic branch of the ANS is highly aroused, sweat gland activity increases, which in turn increases skin conductance. EDA is thus under exclusive control of the SNS (Blascovich & Kelsey, 1990).

Measures of the HPA Axis

Cortisol

Activity of the HPA axis can be estimated using measures of cortisol, which can be assessed in saliva, plasma, or urine. Typically, both basal and stress-induced cortisol levels are used to examine association with aggressive behavior. *Basal* cortisol is often assessed with the cortisol awakening response (CAR). The CAR is superimposed on the circadian rhythm of cortisol secretion, and, in addition to basal activity as reflected by daytime cortisol, it also reflects the reactivity or flexibility of the HPA axis (Fries, Dettenborn, & Kirschbaum, 2009). Basal cortisol is usually assessed with morning cortisol. Cortisol is typically measured in saliva, with samples collected immediately after awakening, then 30 minutes and 60 minutes later (Pruessner et al., 1997). Cortisol *reactivity* is typically assessed as a response to stressful tasks, such as public speaking. Saliva samples are collected at different points during the task to obtain participants' cortisol levels at baseline and at several intervals after the task.

Central Research Findings

ANS (Re)activity

Autonomic Response Measures: Cardiovascular and Electrodermal Activity

Studies of children and adolescents exhibiting antisocial behavior have yielded consistent evidence of lower levels of autonomic activity in comparison with control youth, although associations depend on type of antisocial behavior and psychophysiological measures (Ortiz & Raine, 2004). A relation between resting heart rate and aggressive behavior has been consistently found in several meta-analyses. A meta-analysis of 95 studies (Lorber, 2004) investigated the relations of heart rate with aggression, psychopathy, and conduct problems, thereby distinguishing resting heart rate, test heart rate, and heart rate reactivity. Based on 16 studies, the meta-analysis revealed that lower resting heart rate was weakly related to higher aggression. Age did not significantly moderate this relation. However, whereas higher aggression was reliably associated with heart rate in children and adults, the association was not significant in samples including adolescents. Lower resting heart rate was also negatively related to conduct problems, but not to psychopathy. Heart rate during task activity was not significantly related to aggression, conduct problems, or psychopathy, and this effect was also not moderated by age.

A second meta-analysis, including 46 studies on children and adolescents (Ortiz & Raine, 2004), showed a significant negative relation between resting heart rate and levels of antisocial behavior. This effect was not significantly moderated

by gender differences, by use of a psychiatric versus nonpsychiatric control group, by method of assessing heart rate, or by age. Using a sample of 9 studies, antisocial behavior was also found to be negatively associated with heart rate in a stress condition. The meta-analysis did not examine the moderating effect of type of antisocial behavior.

A more recent systematic review and meta-analysis of the relation between resting heart rate and antisocial behavior (Portnoy & Farrington, 2015) included 115 independent effect sizes and yielded a significant negative effect size of $d = -0.20$. Sex and age did not moderate the relation between resting heart rate and antisocial behavior. Antisocial behavior type did not moderate the association. Summary effect sizes were significant for aggression, violence, and behavior problems.

In sum, these meta-analyses demonstrated that the relation between low resting heart rate and antisocial behavior is highly replicable and applies to multiple types of antisocial behavior, including aggression. The relation is also consistently found across children, adolescents, and adults, although some individual studies show exceptions to this pattern. For example, in a recent study among 412 children, lower resting mean heart rate at age 14 months did not predict aggression at age 3 years (Dierckx et al., 2014). The lack of sex differences in the relation between heart rate and antisocial behavior is consistent with the claim that the same risk factors apply to antisocial behavior in both males and females (Moffitt, Caspi, Rutter, & Silva, 2001), despite the fact that females have a higher resting heart rate than males (Voors, Webber, & Berenson, 1982).

Thus studies have consistently shown that children and adolescents who exhibit antisocial behavior, and aggressive behavior more specifically, have lower resting levels of heart rate than control youth (Lorber, 2004; Ortiz & Raine, 2004). The finding of low resting heart rate among children with aggressive behavioral tendencies suggests chronic underarousal in aggressive individuals (Scarpa & Raine, 1997). In response to stressors, children who display aggressive conduct problems tend to have an enhanced heart rate (Lorber, 2004).

Because heart rate is determined by both sympathetic and parasympathetic influences, and because dysregulation in the SNS appears to have different implications for adjustment than dysregulation in the PNS (Beauchaine et al., 2007), several studies have focused on measures more specifically related to SNS or PNS. To study parasympathetic mediation of cardiovascular activity, heart rate reactivity and RSA suppression have been examined most often. Heart rate reactivity, that is, enhanced heart rate variability under circumstances involving stressors or challenges, has been associated with aggressive behavior of children and adolescents (Beauchaine et al., 2001), which suggests weaker vagal–parasympathetic regulation of heart rate activity in exhibiting aggressive conduct problems. Low heart rate variability has also been associated with externalizing problems (Pine, Shaffer, Schonfeld, & Davies, 1997). The meta-analysis by Lorber (2004) found that higher heart rate variability was not significantly associated with higher levels of aggression nor psychopathy, although it was significantly related to higher conduct problems among children and adolescents. Also, aggressive boys have been found to exhibit lower RSA suppression, which is related to attentional and emotional processes, than nonaggressive boys (Calkins & Dedmon, 2000). Similarly, boys who were high on aggression exhibited lower RSA across baselines than boys who were low on

aggression. In contrast, no difference in baseline RSA was observed for girls who were high versus low on aggression (Beauchaine, Hong, & Marsh, 2008). In sum, findings with respect to autonomic reactivity to noxious or threatening stimuli have been more mixed, in particular for heart rate reactivity. Lower RSA suppression seems to be more consistently related to more aggressive behavior.

Considering measures of SNS, there is evidence that low skin conductance activity, which is linked to lower behavioral inhibition, accounts for variation in antisocial behavior. In the meta-analysis by Lorber (2004), low resting skin conductance activity was associated with psychopathy and with conduct problems in children, but not with aggressive behavior. Similarly, low task skin conductance activity was associated with psychopathy among adults and with conduct problems in children, but not with aggressive behavior. Higher skin conductance reactivity was positively associated with aggression among adults and negatively associated with psychopathy. Low skin conductance activity has been found to predict the onset of aggression in children and adults. For example, skin conductance activity in 70 typically developing 1-year-old infants at baseline, during an orienting habituation paradigm, and during a fear challenge was significantly and negatively related to mother-reported aggressive behavior at 3 years of age (Baker, Shelton, Baibarazova, Hay, & Van Goozen, 2013). Some studies reported sex differences in associations of skin conductance with aggression. Boys with high levels of aggression did not differ from boys with low levels of aggression in patterns of skin conductance across baselines. In contrast, girls who were aggressive exhibited initially high levels of skin conductance, which then decreased across repeated baseline assessments, whereas girls with low aggression exhibited initially low levels of skin conductance, which then increased across repeated baseline assessments (Beauchaine et al., 2008).

Baseline PEP has been related to reward sensitivity during incentive conditions. Baseline PEP was not significantly related to aggression, but under reward conditions there was significantly less PEP shortening among participants who were high on aggression than among participants who were low on aggression (Beauchaine, 2001). In addition, for male participants only, whereas those who were low on aggression exhibited initial PEP reactivity to incentives, which habituated across trials, those high on aggression exhibited no PEP reactivity to reward (Beauchaine et al., 2008).

In conclusion, studies of parasympathetic and sympathetic activity have generally revealed that aggressive children and adolescents exhibit lower baseline levels of autonomic arousal but higher autonomic reactivity to stressful events. Enhanced heart rate variability under stressful conditions suggests that children and adolescents with aggressive conduct problems have weaker vagal–parasympathetic regulation of heart rate activity (Beauchaine et al., 2001). In addition, lower resting heart rate suggests that these children experience chronic underarousal, and lower skin conductance reflects weak inhibitory capacity, all of which might lower the threshold for impulsive aggressive behavior (Beauchaine et al., 2001). In sum, these findings suggest that aggressive children have difficulties regulating emotions such as anger and tend to react defensively under conditions of threat.

A few studies have examined the role of sensation seeking in the association between parasympathetic and sympathetic activity and aggressive behavior to test whether underarousal leads to more stimulation seeking in order to raise arousal

levels (Zuckerman, 1979). A longitudinal study among participants at the ages of 11, 13½, and 16 examined whether fun seeking mediated the relationship between heart rate and antisocial behaviors (Sijtsema et al., 2010). Results showed that heart rate at age 11 was negatively associated with fun seeking at age 13½, and that fun seeking at age 13½ was positively associated with rule breaking at age 16 for both boys and girls. In boys, fun seeking mediated the relation between heart rate and rule breaking but not the relation between heart rate and aggression. Moreover, in girls, heart rate was not significantly associated with aggression at all. Another study examined sensation seeking as a moderator instead of a mediator. A significant relation between low resting heart rate and increased aggression was found, but only for individuals with low levels of sensation seeking (Wilson & Scarpa, 2014). In sum, there seems to be some evidence of relations between heart rate, fun seeking, and conduct problems, but the findings are inconsistent across constructs and gender.

Autonomic Functioning in Proactive and Reactive Aggression

Several researchers have examined whether autonomic functioning is differently related to proactive and reactive aggression. In a meta-analysis including four studies, no significant difference in resting heart rate was found (Portnoy & Farrington, 2015). In a study among 8-year-old children who participated in a task in which they lost a board game and prize to a confederate who cheated, reactive aggression, but not proactive aggression, was significantly and positively related to skin conductance reactivity and negatively to heart rate reactivity (Hubbard et al., 2002). In this study, proactive and reactive aggression were included as predictors simultaneously in the regression to account for the large amount of shared variance between proactive and reactive aggression. Among 42 children ages 6–13 years, resting heart rate was significantly correlated with reactive but not proactive aggression, and no significant correlations were found with skin conductance and heart rate variability (Scarpa, Chiara Haden, & Tanaka 2010). When proactive and reactive aggression were simultaneously included as predictors, reactive aggression was again significantly related to decreased heart rate variability, whereas proactive aggression was significantly related to increased heart rate variability and skin conductance. This pattern of autonomic activity, with parallel effects for parasympathetic and sympathetic activity, is in contrast with predictions made by general arousal theory that heightened sympathetic activity will necessarily be associated with reduced parasympathetic activity.

Additional support for distinct physiological processes underlying different forms of aggression can be found in a growing literature suggesting that callous–unemotional (CU) behaviors and oppositional defiant disorder (ODD) behaviors are associated with distinct psychophysiological profiles (Frick, Ray, Thornton, & Kahn, 2014). Particularly, CU behaviors, including a lack of empathy, lack of guilt, and low emotional responsiveness, tend to be characterized by reduced baseline functioning and blunted physiological responses to stressors. Kavish and colleagues (2017) found that in adolescence lower resting heart rate was related to higher scores on CU and sensation seeking in males, but not in females. Lower baseline RSA, but not heart period, across infancy was found to be associated with both ODD and

CU behaviors in childhood (Wagner et al., 2017). In a different sample, no group differences were observed in children at 6 months of age, but at 15 months of age children with later conduct problems with CU displayed lower levels of heart period and RSA and higher cortisol levels compared with children with conduct problems only and children with no conduct problems (Mills-Koonce et al., 2015). Among male adolescents with disruptive behavior disorder (DBD), adolescents with high CU showed lower resting RSA and less heart rate change from baseline in reaction to sadness than respondents with low CU and controls (De Wied, van Boxtel, Matthys, & Meeus, 2012). Resting heart rate was not different between DBD groups but was significantly lower in adolescents with DBD and with high CU traits compared with controls. Comparably, children with conduct disorder (CD) and high CU traits displayed lower magnitude of heart rate change than both children with CD only and controls (Anastassiou-Hadjicharalambous & Warden, 2008). In sum, the antisocial behavior of children high on CU traits might be due to a combination of underarousal, as indicated by low autonomic activity, and emotional dysregulation, as indicated by their low RSA scores. Children high on CU traits seem to show lower levels of fearfulness and insensitivity to punishment (Fanti, 2016; Frick et al., 2014), and, in line with fearlessness theory, their antisocial and aggressive behavior might result from underarousal.

A study including both physical and relational aggression provided support for the hypothesis that heightened cardiac reactivity to provocation is associated with relational aggression among girls. In contrast, for boys, lower cardiac reactivity was associated with physical aggression. These results suggest that the association between cardiovascular reactivity and aggression differs for males and females and that reactivity following relational provocation may be an especially important predictor of relational aggression among girls (Murray-Close & Crick, 2007).

HPA-Axis Activity

Associations of Aggressive Behavior with Basal Cortisol Levels

Several studies have shown a relation between basal cortisol levels and aggressive behavior. A meta-analysis on the relation between basal cortisol and externalizing behavior showed a significant but small negative relation (Alink et al., 2008). The age of children significantly moderated this relation: Externalizing behavior was associated with higher basal cortisol (hyperactivity) in preschoolers, and with lower basal cortisol (hypoactivity) in elementary school-age children. Among adolescents, cortisol was not significantly related to externalizing behavior. The meta-analysis did not find differences in effects for aggressive behavior compared with other types of externalizing behavior. Similarly, a meta-analysis reported a small to moderate effect across clinical studies in the direction of an inverse relationship between basal cortisol levels and DBD symptoms (Van Goozen et al., 2007). The moderating effect of age on the association between cortisol and aggressive behavior has been attributed to common factors affecting conduct problems and HPA-axis functioning. In early childhood, stress—for example, resulting from harsh and inconsistent parenting—is associated with both conduct problems and heightened cortisol levels. In case of prolonged stress, that is, in case of allostatic load, the HPA

axis may downregulate, resulting in lower levels of basal cortisol or hypoactivity (Fries et al., 2005).

Comparable results were reported in a number of recent longitudinal studies. Cortisol levels show modest stability over time, and a study using latent state–trait modeling to distinguish state-like from trait-like sources in basal cortisol levels in youth from the general population revealed that 70% of the variance in cortisol levels could be attributed to state-like sources and 28% to trait-like sources. For boys only, higher levels of externalizing problem behaviors were consistently associated with lower cortisol attributable to trait-like sources across 3 years of behavioral assessment (Shirtcliff, Granger, Booth, & Johnson, 2005). Similarly, a study among 390 adolescents ages 15–17 revealed that adolescents who showed persistent aggressive behavior across the years had decreased cortisol levels at awakening consistently over the years as compared with adolescents with low aggression (Platje et al., 2013). In the same way, low cortisol in preadolescence was associated with more aggressive behavior 5 years later, during middle adolescence. In a sample of adolescent boys, low self-control was identified as the primary personality mediator of the relation between low cortisol and later aggressive behavior (Shoal, Giancola, & Kirillova, 2003). Cortisol was not related to negative emotionality or any of its factors (including trait aggression). Also, young adolescent girls with externalizing behavior problems revealed a significantly higher CAR than girls without behavior problems or girls with comorbid externalizing and internalizing behavior problems. This effect was absent in boys, however (Marsman et al., 2008).

In contrast, several studies showed positive relations between cortisol levels and externalizing behavior in elementary school-age children and adolescents. A study among 1,768 Dutch preadolescents from the general population found small but significant positive correlations between both baseline morning and evening salivary cortisol levels and disruptive behaviors (Sondeijker et al., 2007). Similarly, in a population-based sample of boys who were followed longitudinally from childhood to adolescence, higher cortisol levels at age 13 were found in boys with CD than in boys without CD. In addition, boys with an aggressive form of CD had higher cortisol levels than boys with a covert form of CD (van Bokhoven et al., 2005). Associations between heightened cortisol levels and aggressive behavior have also been reported. For example, in this population-based sample of boys, *reactive* aggression was strongly correlated with heightened cortisol (van Bokhoven et al., 2005). Additionally, a study examining changes in aggressive behavior between the ages of 8 and 10 revealed that boys whose cortisol levels rose most between the ages of 8 and 10 were also those whose aggressive behavior increased most during the same time frame (Azurmendi et al., 2016).

Proactive and Reactive Aggression

A few studies have examined associations between cortisol and aggression separately for proactive and reactive aggression. Among girls admitted for acute psychiatric inpatient treatment, the significant negative correlation between cortisol and aggression seems to be present for both proactive and reactive aggression (Stoppelbein, Greenig, Luebbe, Fite, & Becker, 2014). Tests of indirect effects from cortisol to aggression through subdimensions of psychopathy indicated significant

pathways via narcissism to proactive and reactive aggression. Among 245, 15-year-olds from an epidemiological cohort study of children at risk for psychopathology, both reactive and proactive aggression were significantly negatively correlated with plasma cortisol levels in males, but not in females (Poustka et al., 2010). This association between cortisol levels and aggression was found to be mediated by impulsivity rather than by psychopathic traits.

In conclusion, these results suggest that HPA-axis functioning may be differentially relevant in clinical or high-risk samples than at the general population level. Whereas in clinical samples, hypoarousal might be more characteristic of children with high levels of aggression, in population samples, higher aggression might go together with hyperarousal.

Associations of Aggressive Behavior with Cortisol Levels in Reaction to a Stressor

A meta-analysis showed that there was no association between cortisol reactivity and externalizing behaviors, but, again, this meta-analysis did not distinguish between different types of externalizing behaviors (Alink et al., 2008). Reactive aggression significantly predicted total and peak poststress cortisol regardless of stress modality. Proactive aggression was not a predictor of any cortisol index. A comparison of pure reactive, proactive, combined, or nonaggressive children indicated that reactive aggressive children had higher cortisol reactivity than proactive and nonaggressive children. This suggests that an overactive HPA-axis response to stress is associated with reactive aggression, whereas stress-induced HPA-axis variability does not seem to be related to proactive aggression (Lopez-Duran, Hajal, Olson, Felt, & Vazquez, 2008).

Future Directions

The Combined Activity of Different Psychophysiological Systems

The combined activity of different psychophysiological systems might predict aggressive behavior better than the activity of either subsystem alone (Bauer et al., 2002). According to the dual hormone hypothesis, social dominance, including aggressive behavior, is jointly regulated by the hypothalamic–pituitary–gonadal and HPA axes (van Honk, Harmon-Jones, Morgan, & Schutter, 2010). Specifically, testosterone predicts high levels of physical aggression particularly when levels of cortisol are low (Popma et al., 2007). In a nonclinical sample of 259 boys and girls age 17 years, a positive testosterone/cortisol ratio, that is, high testosterone relative to cortisol, was found to be associated with more aggressive behavior. The interaction between testosterone and cortisol was, however, not related to aggressive behavior (Platje et al., 2015). The ratio may reflect an imbalance, leaving the individual more prone to rewarding aspects than to negative implications of aggressive behavior.

Interactions between cortisol and estradiol have also been reported. Among 105 adolescents, those with high estradiol and low cortisol concentrations were found to be at highest risk for externalizing problems, but *only* when personality traits of disagreeableness and emotional instability were high (Tackett et al., 2015).

The asymmetry between salivary cortisol and alpha-amylase reactivity to stress might also be important in understanding aggressive behavior. In a sample of maltreated early adolescents and a control group, interactions between the HPA axis and the SNS were linked with aggressive behavior (Gordis, Granger, Susman, & Trickett, 2006). At lower levels of alpha-amylase reactivity, lower cortisol reactivity corresponded to higher parent-reported adolescent aggression, but at high alpha-amylase reactivity levels, cortisol reactivity was not related to parent-reported adolescent aggression. Thus symmetry in the direction of low activity in both systems was associated with more aggression. Youth with HPA-axis hypoactivity may be less inhibited from engaging in aggressive behavior, but high sympathetic arousal may buffer this effect and protect against development of aggression (Raine, 2005). Youth who have low activity in both systems may be particularly uninhibited and fail to learn from punishment, resulting in higher aggression.

These findings suggest that we need to consider interactions between the HPA axis and the hypothalamic–pituitary–gonadal axis, as well as interactions between the HPA axis and the SNS in understanding aggression. Not all studies find evidence for interaction effects, however. For example, among 48 delinquent male adolescents with and without a DBD and 16 matched normal controls, alpha-amylase and cortisol reactivity, but not heart rate and heart rate variability, were significantly and negatively associated with disruptive behavior, but no significant interactions between these parameters in relation to disruptive behavior were found (de Vries-Bouw et al., 2012). Further research is needed to acquire a better understanding of the ways different psychophysiological systems interact in affecting aggressive behavior.

A Biosocial Perspective on Childhood Antisocial Behavior

Recent studies have examined a wide range of interactions between psychophysiology measures and environmental factors in explaining antisocial behavior and aggression. Several researchers have found that perinatal adversities put youth at a greater risk for antisocial behavior (Beck & Shaw, 2005; Tremblay, 2010). However, not all studies support an interaction between perinatal adversities and psychophysiological functioning in explaining antisocial behavior (e.g., Sijtsema et al., 2015).

Adversities in childhood have also been studied in relation to psychophysiological factors. Marital conflict in childhood affected externalizing problems more strongly among youth with blunted SNS and RSA reactivity (El-Sheikh, Hinnant, & Erath, 2011; Obradović, Bush, & Boyce, 2011). Also, among 334 Hong Kong schoolchildren ages 11–17 years, low resting heart rate interacted with high psychosocial adversity in explaining higher reactive (but not proactive) aggression (Raine et al., 2014). Moreover, adversities during childhood and adolescence were related to antisocial behavior at age 16 only in boys with blunted RSA reactivity and PNS reactivity as shown by PEP reactivity and smaller PEP differences from rest to recovery (Sijtsema et al., 2015). In contrast, for girls with heightened RSA reactivity and larger PEP differences from rest to recovery, childhood adversities were associated with antisocial behavior. Furthermore, negative interaction with parents predicted relative decreases in externalizing behavior for adolescent girls low in resting RSA, whereas the association was nonsignificant for girls with high RSA (van der Graaff

et al., 2016). Additionally, among 358 Dutch adolescents, morning cortisol moderated the longitudinal effects of neighborhood density on parent-reported delinquency and aggression and adolescent self-reported delinquency (Yu et al., 2016). More specifically, for adolescents with high levels of cortisol, higher neighborhood density significantly predicted higher levels of parent-reported and adolescent self-reported delinquency and aggression, whereas the association was reversed or nonsignificant for adolescents with low cortisol.

These examples show that there are complex interactions between environmental factors and psychophysiological processes in explaining behavior and that these interactions might differ depending on children's age and gender. More research is needed to acquire a better understanding of the interplay of different factors.

Conclusions

Summarizing the findings presented in this chapter, antisocial behavior in children and adolescents is consistently related to lower levels of autonomic activity and decreased HPA axis activity, although associations tend to vary by type of antisocial behavior and psychophysiological measure (Lorber, 2004; Ortiz & Raine, 2004). The most consistent relations are those between low resting heart rate and cortisol at awakening and antisocial behavior. This relation has been found for various types of antisocial behavior, including aggression, and suggests chronic underarousal in aggressive individuals. Lower RSA suppression also seems to be consistently related to more aggressive behavior. Results for heart rate in reaction to stressors are more inconsistent but suggest enhanced heart rate responses to stressors in children exhibiting aggressive conduct problems specifically (Lorber, 2004). In conclusion, aggressive children and adolescents tend to have lower baseline levels of autonomic arousal yet higher autonomic reactivity to stressful events. Enhanced heart rate variability under stressful conditions might indicate that children and adolescents with aggressive conduct problems have weaker vagal–parasympathetic regulation of heart rate activity (Beauchaine et al., 2001). In addition, lower resting heart rate might indicate that these children experience chronic underarousal, and lower skin conductance might indicate a weaker capacity to inhibit impulses. These processes might lower the threshold for impulsive aggressive behavior (Beauchaine et al., 2001). In sum, these findings suggest that children who display higher levels of aggression have difficulties with regulating emotions such as anger, resulting in enhanced defensive reactivity under conditions of threat.

The association between low heart rate and antisocial behavior can be explained by different theories. First, according to stimulation-seeking theory, low arousal represents an unpleasant physiological state, and antisocial individuals seek stimulation to increase their arousal levels to an optimal or normal level (e.g., Ortiz & Raine 2004; Raine, 2002). The relation between heart rate and antisocial behavior has indeed been found to be mediated by fun seeking (Sijtsema et al., 2010). Second, according to fearlessness theory (Raine, 1997), low levels of arousal during stressful situations are indicative of low levels of fear. This lack of fear is thought to make children less likely to respond to socializing punishments, which may subsequently contribute to poor fear conditioning and poor conscience development.

Third, biosocial theory predicts that psychophysiological factors interact with psychosocial risk factors in predicting antisocial behavior (Raine, 2002). Increasing numbers of researchers have investigated these biosocial interactions, but more research is needed to understand the interplay between biological and social factors.

It is important to note that the functioning of the HPA axis or the ANS might not play a causal role in aggressive behavior, but instead might be a marker for other unmeasured underlying processes that are involved in antisocial behavior, such as genetic factors (see Brendgen, Vitaro, & Boivin, Chapter 4, this volume). Moreover, psychophysiological factors can be both a cause and a consequence of behavior. Most studies on the relation between psychophysiological factors and aggressive behavior are cross-sectional, and we are in need of more longitudinal studies that can inform us about the direction of developmental change between aggressive behavior and psychophysiological processes.

Studies also depicted a differential pattern of psychophysiological activity for reactive versus proactive aggression. These differences are found mainly for psychophysiological reactivity. Reactive aggression seems to be related to decreased heart rate variability and higher cortisol reactivity, whereas proactive aggression appears to be related to increased heart rate variability and lower cortisol reactivity. This suggests that an overactive HPA axis response to stress is associated with reactive aggression, whereas stress-induced HPA axis variability does not seem to be related to proactive aggression (Lopez-Duran et al., 2008). Proactive aggression might occur in situations that require activation of the entire ANS to be prepared to respond to danger but also maintain a calm state in order to intimidate or obtain a goal (Raine, 2002). For situations involving reactive aggression, reduced heart rate variability may reflect heightened negative emotionality. In line with the neurobiological model of reactive aggression (van Goozen et al., 2007), sympathetic underactivity may increase sensitivity to stressors. This apparent discrepancy is in line with the multidimensional nature of autonomic responding, in which the sympathetic and parasympathetic branches of the ANS do not always have to function as coupled dimensions (Berntson et al., 1991). The extent to which high autonomic reactivity is related to aggressive behavior might also be moderated by social context (Ellis & Boyce, 2008). Both supportive, low-stress environments and stressful environments can promote high autonomic reactivity, but only in stressful environments might highly reactive individuals show aggressive behavior. Moreover, the discrepant findings regarding autonomic functioning in reactive aggression and proactive aggression might reflect differences in emotional control or emotion regulation (Beauchaine, 2001). Proactive aggression tends to be associated with higher heart rate variability and enhanced vagal tone, and as such it might be associated with better emotion regulation. Although higher emotional control is generally adaptive, in proactive aggression it might reflect the abilities to show goal-directed aggressive behavior and delay gratification. In contrast, the lower heart rate variability and vagal tone that characterizes reactive aggression might reflect decreased emotion regulation, which might play a role in aggressive outbursts.

In conclusion, research suggests small associations between psychophysiological processes and aggressive behavior, but the patterns of association differ depending on type of aggression. Longitudinal studies are needed in order to delineate

the developmental psychophysiological processes that underlie impulsive reactive aggression versus more callous–instrumental forms of proactive aggression.

REFERENCES

Alink, L. R. A., Mesman, J., van Zeijl, J., Stolk, M. N., Juffer, F., Koot, H. M., et al. (2006). The early aggression curve: Development of physical aggression in 10- to 50-month-old children. *Child Development, 77,* 954–966.

Alink, L. R. A., van IJzendoorn, M. H., Bakermans-Kranenburg, M. J., Mesman, J., Juffer, F., & Koot, H. M. (2008). Cortisol and externalizing behavior in children and adolescents: Mixed meta-analytic evidence for the inverse relation of basal cortisol and cortisol reactivity with externalizing behavior. *Developmental Psychobiology, 50,* 427–450.

Anastassiou-Hadjicharalambous, X., & Warden, D. (2008). Physiologically indexed and self-perceived affective empathy in conduct-disordered children high and low on callous–unemotional traits. *Child Psychiatry and Human Development, 39,* 503–517.

Azurmendi, A., Pascual-Sagastizabal, E., Vergara, A. I., Muñoz, J. M., Braza, P., Carreras, R., et al. (2016). Developmental trajectories of aggressive behavior in children from ages 8 to 10: The role of sex and hormones. *American Journal of Human Biology, 28,* 90–97.

Baker, E., Shelton, K. H., Baibarazova, E., Hay, D. F., & Van Goozen, S. H. M. (2013). Low skin conductance activity in infancy predicts aggression in toddlers 2 years later. *Psychological Science, 24,* 1051–1056.

Barker, E. D., Séguin, J. R., White, H. R., Bates, M. E., Lacourse, É., Carbonneau, R., et al. (2007). Developmental trajectories of male physical violence and theft: Relations to neurocognitive performance. *Archives of General Psychiatry, 64,* 592–599.

Bauer, A. M., Quas, J. A., & Boyce, W. T. (2002). Associations between physiological reactivity and children's behavior: Advantages of a multisystem approach. *Journal of Developmental and Behavioral Pediatrics, 23,* 102–113.

Beauchaine, T. P. (2001). Vagal tone, development, and Gray's motivational theory: Toward an integrated model of autonomic nervous system functioning in psychopathology. *Development and Psychopathology, 13,* 183–214.

Beauchaine, T. P., Gatzke-Kopp, L., & Mead, H. K. (2007). Polyvagal theory and developmental psychopathology: Emotion dysregulation and conduct problems from preschool to adolescence. *Biological Psychology, 74,* 174–184.

Beauchaine, T. P., Hong, J., & Marsh, P. (2008). Sex differences in autonomic correlates of conduct problems and aggression. *Journal of the American Academy of Child and Adolescent Psychiatry, 47,* 788–796.

Beauchaine, T. P., Katkin, E. S., Strassberg, Z., & Snarr, J. (2001). Disinhibitory psychopathology in male adolescents: Discriminating conduct disorder from attention-deficit/hyperactivity disorder through concurrent assessment of multiple autonomic states. *Journal of Abnormal Psychology, 110,* 610–624.

Beauchaine, T. P., & Webb, S. J. (2016). Developmental processes. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (pp. 495–510). Cambridge, UK: Cambridge University Press.

Beck, J. E., & Shaw, D. S. (2005). The influence of perinatal complications and environmental adversity on boys' antisocial behavior. *Journal of Child Psychology and Psychiatry, 46,* 35–46.

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1991). Autonomic determinism: The modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. *Psychological Review, 98,* 459–487.

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1993). Respiratory sinus arrhythmia:

Autonomic origins, physiological mechanisms, and psychophysiological implications. *Psychophysiology, 30,* 183–196.

Blair, R. J. R. (2007). The amygdala and ventromedial prefrontal cortex in morality and psychopathy. *Trends in Cognitive Sciences, 11,* 387–392.

Blascovich, J., & Kelsey, R. M. (1990). Using electrodermal and measures of arousal in social psychological research. *Review of Personality and Social Psychology, 11,* 45–73.

Bongers, I. L., Koot, H. M., van der Ende, J., & Verhulst, F. C. (2004). Developmental trajectories of externalizing behaviors in childhood and adolescence. *Child Development, 75,* 1523–1537.

Boyce, W. T., & Ellis, B. J. (2005). Biological sensitivity to context: I. An evolutionary-developmental theory of the origins and functions of stress reactivity. *Development and Psychopathology, 17,* 271–301.

Boyce, W. T., Quas, J., Alkon, A., Smider, N. A., Essex, M. J., Kupfer, D. J., et al. (2001). Autonomic reactivity and psychopathology in middle childhood. *British Journal of Psychiatry, 179,* 144–150.

Calkins, S. D., & Dedmon, S. E. (2000). Physiological and behavioral regulation in two-year-old children with aggressive/destructive behavior problems. *Journal of Abnormal Child Psychology, 28,* 103–118.

Chrousos, G. P., & Gold, P. W. (1992). The concepts of stress and stress system disorders: Overview of physical and behavioral homeostasis. *Journal of the American Medical Association, 267,* 1244–1252.

Cicchetti, D., & Rogosch, F. A. (2001). The impact of child maltreatment and psychopathology on neuroendocrine functioning. *Development and Psychopathology, 13,* 783–804.

Crick, N. R., & Grotpeter, J. K. (1995). Relational aggression, gender, and social-psychological adjustment. *Child Development, 66,* 710–722.

De Kloet, E. R. (1991). Brain corticosteroid receptor balance and homeostatic control. *Frontiers in Neuroendocrinology, 12,* 95–164.

De Kloet, E. R., Joëls, M., & Holsboer, F. (2005). Stress and the brain: From adaptation to disease. *Nature Reviews Neuroscience, 6,* 463–475.

de Vries-Bouw, M., Jansen, L., Vermeiren, R., Doreleijers, T., van de Ven, P., & Popma, A. (2012). Concurrent attenuated reactivity of alpha-amylase and cortisol is related to disruptive behavior in male adolescents. *Hormones and Behavior, 62,* 77–85.

De Wied, M., van Boxtel, T., Matthys, W., & Meeus, W. (2012). Verbal, facial and autonomic responses to empathy-eliciting film clips by disruptive male adolescents with high versus low callous–unemotional traits. *Journal of Abnormal Child Psychology, 40,* 211–223.

Dierckx, B., Kok, R., Tulen, J. H. M., Jaddoe, V. W., Hofman, A., Verhulst, F. C., et al. (2014). A prospective study of heart rate and externalising behaviours in young children. *Journal of Child Psychology and Psychiatry, 55,* 402–410.

Dodge, K. A., Harnish, J. D., Lochman, J. E., Bates, J. E., & Pettit, G. S. (1997). Reactive and proactive aggression in school children and psychiatrically impaired chronically assaultive youth. *Journal of Abnormal Psychology, 106,* 37–51.

Edwards, S., Clow, A., Evans, P., & Hucklebridge, F. (2001). Exploration of the awakening cortisol response in relation to diurnal cortisol secretory activity. *Life Sciences, 68,* 2093–2103.

Ellis, B. J., & Boyce, W. T. (2008). Biological sensitivity to context. *Current Directions in Psychological Science, 17,* 183–187.

El-Sheikh, M., Hinnant, J. B., & Erath, S. (2011). Developmental trajectories of delinquency symptoms in childhood: The role of marital conflict and autonomic nervous system activity. *Journal of Abnormal Psychology, 120,* 16–32.

Fanti, K. (2016). Understanding heterogeneity in conduct disorder: A review of psychophysiological studies. *Neuroscience and Biobehavioral Reviews.* [Epub ahead of print]

Frick, P. J., Ray, J. V., Thornton, L. C., & Kahn, R. E. (2014). Annual research review: A developmental psychopathology approach to understanding callous–unemotional traits in children and adolescents with serious conduct problems. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 55,* 532–548.

Fries, E., Dettenborn, L., & Kirschbaum, C. (2009). The cortisol awakening response (CAR): Facts and future directions. *International Journal of Psychophysiology, 72,* 67–73.

Fries, E., Hesse, J., Hellhammer, J., & Hellhammer, D. H. (2005). A new view on hypocortisolism. *Psychoneuroendocrinology, 30,* 1010–1016.

Gordis, E. A., Granger, D. A., Susman, E. J., & Trickett, P. K. (2006). Asymmetry between salivary cortisol and α-amylase reactivity to stress: Relation to aggressive behavior in adolescents. *Psychoneuroendocrinology, 31,* 976–987.

Gump, B. B., Matthews, K. A., & Raikkonen, K. (1999). Modeling relationships among socioeconomic status, cardiovascular reactivity and left ventricular mass in African American and white children. *Health Psychology, 18,* 140–150.

Gunnar, M. R., Wewerka, S., Frenn, K., Long, J. D., & Griggs, C. (2009). Developmental changes in hypothalamus–pituitary–adrenal activity over the transition to adolescence: Normative changes and associations with puberty. *Development and Psychopathology, 21,* 69–85.

Hubbard, J. A., Smithmyer, C. M., Ramsden, S. R., Parker, E. H., Flanagan, K. D., Dearing, K. F., et al. (2002). Observational, physiological, and self-report measures of children's anger: Relations to reactive versus proactive aggression. *Child Development, 73,* 1101–1118.

Kahle, S., Miller, J. G., Lopez, M., & Hastings, P. D. (2016). Sympathetic recovery from anger is associated with emotion regulation. *Journal of Experimental Child Psychology, 142,* 359–371.

Kavish, N., Vaughn, M. G., Cho, E., Barth, A., Boutwell, B., Vaughn, S., et al. (2017). Physiological arousal and juvenile psychopathy: Is low resting heart rate associated with affective dimensions? *Psychiatric Quarterly, 88,* 103–114.

Kimonis, E. R., Frick, P. J., & McMahon, R. J. (2014). Conduct and oppositional defiant disorders. In E. J. Mash & R. A. Barkley (Eds.), *Child psychopathology* (3rd ed., pp. 145–179). New York: Guilford Press.

Lopez-Duran, N. L., Hajal, N. J., Olson, S. L., Felt, B., & Vazquez, D. M. (2009). Hypothalamic pituitary adrenal axis functioning in reactive and proactive aggression in children. *Journal of Abnormal Child Psychology, 37,* 169–182.

Lorber, M. F. (2004). Psychophysiology of aggression, psychopathy, and conduct problems: A meta-analysis. *Psychological Bulletin, 130,* 531–552.

Marsman, R., Swinkels, S. H. N., Rosmalen, J. G. M., Oldehinkel, A. J., Ormel, J., & Buitelaar, J. K. (2008). HPA-axis activity and externalizing behavior problems in early adolescents from the general population: The role of comorbidity and gender (the TRAILS study). *Psychoneuroendocrinology, 33,* 789–798.

Mills-Koonce, W. R., Wagner, N. J., Willoughby, M. T., Stifter, C., Blair, C., Granger, D. A., et al. (2015). Greater fear reactivity and psychophysiological hyperactivity among infants with later conduct problems and callous–unemotional traits. *Journal of Child Psychology and Psychiatry, 56,* 147–154.

Moffitt, T. E., Caspi, A., Rutter, M., & Silva, P. A. (2001). *Sex differences in antisocial behaviour: Conduct disorder, delinquency, and violence in the Dunedin Longitudinal Study.* New York: Cambridge University Press.

Mullin, B. C., & Hinshaw, S. P. (2007). Emotion regulation and externalizing disorders in children and adolescents. In J. J. Gross (Ed.), *Handbook of emotion regulation* (pp. 523–541). New York: Guilford Press.

Murray-Close, D., & Crick, N. R. (2007). Gender differences in the association between

cardiovascular reactivity and aggressive conduct. *International Journal of Psychophysiology, 65,* 103–113.

Obradović, J. (2013). How can the study of physiological reactivity contribute to our understanding of adversity and resilience processes in development? *Development and Psychopathology, 24,* 371–387.

Obradović, J., Bush, N. R., & Boyce, W. T. (2011). The interactive effect of marital conflict and stress reactivity on externalizing and internalizing symptoms: The role of laboratory stressors. *Development and Psychopathology, 23,* 101–114.

Ortiz, J., & Raine, A. (2004). Heart rate level and antisocial behavior in children and adolescents: A meta-analysis. *Journal of the American Academy of Child and Adolescent Psychiatry, 43,* 154–162.

Pine, D. S., Shaffer, D., Schonfeld, I. S., & Davies, M. (1997). Minor physical anomalies: Modifiers of environmental risks for psychiatric impairment? *Journal of the American Academy of Child and Adolescent Psychiatry, 36,* 395–403.

Platje, E., Jansen, L. M. C., Raine, A., Branje, T. A. H., Doreleijers, M., de Vries-Bouw, A., et al. (2013). Longitudinal associations in adolescence between cortisol and persistent aggressive or rule-breaking behavior. *Biological Psychology, 93,* 132–137.

Platje, E., Popma, A., Vermeiren, R. R. J. M., Doreleijers, T. A., Meeus, W. H., van Lier, P. A., et al. (2015). Testosterone and cortisol in relation to aggression in a non-clinical sample of boys and girls. *Aggressive Behavior, 41,* 478–487.

Popma, A., Vermeiren, R., Geluk, C. A. M. L., Rinne, T., van den Brink, W., Knol, D. L., et al. (2007). Cortisol moderates the relationship between testosterone and aggression in delinquent male adolescents. *Biological Psychiatry, 61,* 405–411.

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74,* 116–143.

Portnoy, J., & Farrington, D. P. (2015). Resting heart rate and antisocial behavior: An updated systematic review and meta-analysis. *Aggression and Violent Behavior, 22,* 33–45.

Poustka, L., Maras, A., Hohm, E., Fellinger, J., Holtmann, M., Banaschewski, T., et al. (2010). Negative association between plasma cortisol levels and aggression in a high-risk community sample of adolescents. *Journal of Neural Transmission, 117,* 621–627.

Powch, I. G., & Houston, B. K. (1996). Hostility, anger-in, and cardiovascular reactivity in White women. *Health Psychology, 15,* 200–208.

Pruessner, J. C., Wolf, O. T., Hellhammer, D. H., Buske-Kirschbaum, A., von Auer, K., Jobst, S., et al. (1997). Free cortisol levels after awakening: A reliable biological marker for the assessment of adrenocortical activity. *Life Sciences, 61,* 2539–2549.

Raine, A. (1997). Antisocial behavior and psychophysiology: A biosocial perspective and a prefrontal dysfunction hypothesis. In D. Stoff, J. Breiling, & J. D. Maser (Eds.), *Handbook of antisocial behavior* (pp. 289–304). New York: Wiley.

Raine, A. (2002). Biosocial studies of antisocial and violent behavior in children and adults: A review. *Journal of Abnormal Child Psychology, 30,* 311–326.

Raine, A. (2005). The interaction of biological and social measures in the explanation of antisocial and violent behavior. In D. Stoff & E. Susman (Eds.), *Developmental psychobiology of aggression* (pp. 13–42). New York: Cambridge University Press.

Raine, A., Fung, A. L., Portnoy, J., Choy, O., & Spring, V. L. (2014). Low heart rate as a risk factor for child and adolescent proactive aggressive and impulsive psychopathic behavior. *Aggressive Behavior, 40,* 290–299.

Raine, A., Venables, P. H., & Mednick, S. A. (1997). Low resting heart rate at age 3 years predisposes to aggression at age 11 years: Evidence from the Mauritius Child Health Project. *Journal of the American Academy of Child and Adolescent Psychiatry, 36,* 1457–1464.

Rappaport, N., & Thomas, C. (2004). Recent research findings on aggressive and violent behavior in youth: Implications for clinical assessment and intervention. *Journal of Adolescent Health, 35,* 260–277.

Sapolsky, R. M., Romero, L. M., & Munck, A. U. (2000). How do glucocorticoids influence stress responses?: Integrating permissive, suppressive, stimulatory, and preparative actions. *Endocrine Reviews, 21,* 55–89.

Scarpa, A., Chiara Haden, S., & Tanaka, A. (2010). Being hot-tempered: Autonomic, emotional, and behavioral distinctions between childhood reactive and proactive aggression. *Biological Psychology, 84,* 488–496.

Scarpa, A., & Raine, A. (1997). Psychophysiology of anger and violent behavior. *Psychiatric Clinics of North America, 20,* 375–394.

Shirtcliff, E. A., Granger, D. A., Booth, A., & Johnson, D. (2005). Low salivary cortisol and externalizing behavior problems in youth. *Development and Psychopathology, 17,* 167–184.

Shoal, G. D., Giancola, P. R., & Kirillova, G. P. (2003). Salivary cortisol, personality, and aggressive behavior in adolescent boys: A 5-year longitudinal study. *Journal of the American Academy of Child and Adolescent Psychiatry, 42,* 1101–1107.

Sijtsema, J. J., Van Roon, A. M., Groot, P. F. C., & Riese, H. (2015). Early life adversities and adolescent antisocial behavior: The role of cardiac autonomic nervous system reactivity in the TRAILS study. *Biological Psychology, 110,* 24–33.

Sijtsema, J. J., Veenstra, R., Lindenberg, S., van Roon, A. M., Verhulst, F. C., Ormel, J., et al. (2010). Mediation of sensation seeking and behavioral inhibition on the relationship between heart rate and antisocial behavior: The TRAILS study. *Journal of the American Academy of Child and Adolescent Psychiatry, 49,* 493–502.

Skosnik, P. D., Chatterton, R. T., Swisher, T., & Park, S. (2000). Modulation of attentional inhibition by norephinephrine and cortisol after psychological stress. *International Journal of Psychophysiology, 36,* 59–68.

Sondeijker, F. E. P. L., Ferdinand, R. F., Oldehinkel, A. J., Veenstra, R., Tiemeier, H., Ormel, J., et al. (2007). Disruptive behaviors and HPA-axis activity in young adolescent boys and girls from the general population. *Journal of Psychiatric Research, 41,* 570–578.

Stoppelbein, L., Greenig, L., Luebbe, A., Fite, P., & Becker, S. P. (2014). The role of cortisol and psychopathic traits in aggression among at-risk girls: Tests of mediating hypotheses. *Aggressive Behavior, 40,* 263–272.

Tackett, J. L., Reardon, K. W., Herzhoff, K., Page-Gould, E., Harden, K. P., & Josephs, R. A. (2015). Estradiol and cortisol interactions in youth externalizing psychopathology. *Psychoneuroendocrinology, 55,* 146–153.

Terranova, J. I., Song, Z., Larkin, T. E., II, Hardcastle, N., Norvelle, A., Riaz, A, et al. (2016). Serotonin and arginine–vasopressin mediate sex differences in the regulation of dominance and aggression by the social brain. *Proceedings of the National Academy of Sciences of the USA, 113,* 13233–13238.

Tremblay, R. E. (2003). Why socialization fails: The case of chronic physical aggression. In B. B. Lahey, T. E. Moffitt, & A. Caspi (Eds.), *Causes of conduct disorder and juvenile delinquency* (pp. 182–224). New York: Guilford Press.

Tremblay, R. E. (2010). Developmental origins of disruptive behaviour problems: The "original sin" hypothesis, epigenetics and their consequences for prevention. *Journal of Child Psychology and Psychiatry, 51,* 341–367.

van Bokhoven, I., Van Goozen, S. H. M., van Engeland, H., Schaal, B., Arseneault, L., Séguin, J. R., et al. (2005). Salivary cortisol and aggression in a population-based longitudinal study of adolescent males. *Journal of Neural Transmission, 112,* 1083–1096.

van der Graaff, J., Meeus, W., De Wied, M., Van Boxtel, A., Van Lier, P., & Branje, S. (2016). Respiratory sinus arrhythmia moderates the relation between parent–adolescent relationship quality and adolescents' social adjustment. *Journal of Abnormal Child Psychology, 44,* 269–281.

Van Goozen, S. H. M., Fairchild, G., Snoek, H., & Harold, G. T. (2007). The evidence for

a neurobiological model of childhood antisocial behavior. *Psychological Bulletin, 133,* 149–182.

van Honk, J., Harmon-Jones, E., Morgan, B. E., & Schutter, D. J. L. G. (2010). Socially explosive minds: The triple imbalance hypothesis of reactive aggression. *Journal of Personality, 78,* 67–94.

van Stegeren, A., Rohleder, N., Everaerd, W., & Wolf, O. T. (2006). Salivary alpha amylase as marker for adrenergic activity during stress: Effect of betablockade. *Psychoneuroendocrinology, 31,* 137–141.

Vazquez, D. M. (1998). Stress and the developing limbic–hypothalamic–pituitary–adrenal axis. *Psychoneuroendocrinology, 23,* 663–700.

Vitiello, B., & Stoff, D. M. (1997). Subtypes of aggression and their relevance to child psychiatry. *Journal of the American Academy of Child and Adolescent Psychiatry, 36,* 307–315.

Voors, A. W., Webber, L. S., & Berenson, G. S. (1982). Resting heart rate and pressure-rate product of children in a total biracial community. *American Journal of Epidemiology, 16,* 276–286.

Wagner, N., Mills-Koonce, R., Willoughby, M., Propper, C., Rehder, P., & Gueron-Sela, N. (2017). Respiratory sinus arrhythmia and heart period in infancy as correlates of later oppositional defiant and callous–unemotional behaviors. *International Journal of Behavioral Development, 41,* 127–135.

Wilson, B. J., & Gottman, J. M. (1996). Attention: The shuttle between emotion and cognition: Risk, resiliency, and physiological bases. In E. M. Hetherington & E. A. Blechman (Eds.), *Stress, coping and resiliency in children and families* (pp. 189–228). Mahwah, NJ: Erlbaum.

Wilson, L. C., & Scarpa, A. (2014). Aggressive behavior: An alternative model of resting heart rate and sensation seeking. *Aggressive Behavior, 40,* 91–98.

Yu, R., Nieuwenhuis, J., Meeus, W., Hooimeijer, P., Koot, H. M., & Branje, S. J. T. (2016). Biological sensitivity to context: Cortisol awakening response moderates the effects of neighbourhood density on the development of adolescent externalizing problem behaviors. *Biological Psychology, 120,* 96–107.

Zuckerman, M. (1979). *Sensation seeking: Beyond the optimum level of arousal.* Hillsdale, NJ: Erlbaum.