Examining the relationship between resting heart rate and callous-unemotional traits in juvenile delinquency

Palix, J.; Habersaat, S.; Boonmann, C.; Nauta-Jansen, L.; Schmeck, K.; Fegert, J.M.; ... ; Urben, S.

Journal of Criminal Justice 88 (2023) 102112

Contents lists available at ScienceDirect

Journal of Criminal Justice

journal homepage: www.elsevier.com/locate/jcrimjus

Examining the relationship between resting heart rate and callous-unemotional traits in juvenile delinquency

Julie Palix [a,b,*], Stéphanie Habersaat [a], Cyril Boonmann [a,c,d], Lucres Nauta-Jansen [e], Klaus Schmeck [a], Joerg M. Fegert [f], Marc Schmid [a,1], Sébastien Urben [g,1]

[a] Research Department of Child and Adolescent Psychiatry, Psychiatric University Hospitals, University of Basel, Basel, Switzerland
[b] Research Unit of Legal Psychiatry and Psychology, University Hospital of Lausanne, Lausanne, Switzerland
[c] Department of Forensic Child and Adolescent Psychiatry, Psychiatric University Hospitals, University of Basel, Basel, Switzerland
[d] Curium LUMC, Department of Child and Adolescent Psychiatry, Leiden University Medical Center, Leiden, the Netherlands
[e] Department of Child and Adolescent Psychiatry, Amsterdam University Medical Centers, Amsterdam, the Netherlands
[f] Department of Child and Adolescent Psychiatry and Psychotherapy, University Hospital of Ulm, Ulm, Germany
[g] Division of Child and Adolescent Psychiatry, University Hospital of Lausanne, Lausanne, Switzerland

ARTICLE INFO

Keywords:
Heart rate
Callous-unemotional traits
Offending youth
Adolescence
Development

ABSTRACT

Purpose: Both the resting heart rate (RHR) and the callous-unemotional (CU) traits have been associated with juvenile delinquency, however the effect of their interaction is not yet clear.
Methods: Four hundred and twenty-three institutionalized adolescents divided into early adolescents (10–14 years, $n = 133$), late adolescents (15–17 years, $n = 286$), and young adults (18–22 years, $n = 136$) participated in the study. RHR was measured using a wristband, and CU traits and delinquency history were assessed using self-reported questionnaires. Moderation analysis was performed to understand how the combination between RHR and CU is associated to offending.
Results: CU traits were associated with offending at all ages. The interactions between RHR and CU traits were significantly related to the likelihood of offending in the early and the late adolescent. The highest likelihood of offending is related to high CU traits combined with low RHR in early adolescents and with high RHR in late adolescents.
Conclusions: These findings provide further insight in the relationship between psychopathic traits and bio-physiological maturation in explaining juvenile delinquency.

1. Introduction

There is strong evidence that childhood and adolescence are key life course periods for the development of delinquent behaviors, with involvement and frequency of offending generally peaking between mid-adolescence and young adulthood (Farrington, Piquero, Jennings, and Jolliffe, 2023; Loeber and Farrington, 2012; Piquero, Farrington, and Blumstein, 2007). Emotional coldness and autonomic hypoactivity have been described as important risk factors for an early onset of antisocial behavior (De Looff et al., 2022; Frick, Ray, Thornton, and Kahn, 2014), but the relationship between the two factors has yet to be determined. This is the purpose of the present study.

The human cardiovascular system operates in a dynamic mode that favors rapid and efficient adaptation to changing environments (Pieper, Warren, and Pickering, 1993; Sterling and Eyer, 1988). The maintenance of this flexibility is made possible by complex regulation involving multiple biological mechanisms at different levels, from molecular to organ level (Rushmer, 1989). Autonomic nervous system responses are part of this regulation through the activity of two antagonistic pathways, one mediating aggressive, dominant and competitive behaviors (i.e., sympathetic branch, increased heart rate and rapid blood flow to muscles and brain) and the other maintaining calm, subordinate and fearful postures (i.e., parasympathetic branch, decreased heart rate and increased behavioral inhibition; Guyll and Contrada, 1998; Newton and Bane, 2001; Rosenman and Friedman, 1974; Suls and Wan, 1993). These dynamic physiological capacities have been described as particularly

* Corresponding author at: Forensic Psychiatry Institute, University Hospital of Lausanne, Cery Road 1, CH-1008 Prilly, Switzerland.
E-mail address: julie.palix@chuv.ch (J. Palix).
[1] Both co-authors shared senior authorships.

https://doi.org/10.1016/j.jcrimjus.2023.102112
Received 17 July 2023; Received in revised form 5 September 2023; Accepted 5 September 2023
Available online 11 September 2023

informative about the adaptability and responsiveness of the organism to internal and external (Camm et al., 1996), organic and socio-emotional demands (Kamarck, Annunziato, and Amateau, 1995).

During resting state, the balance between these two antagonistic pathways may already show singularities for certain groups of individuals, as for example in connection with aggressive and antisocial behaviors (for review and meta-analyses see De Looff et al., 2022; Ortiz and Raine, 2004; Portnoy and Farrington, 2015). Thus, low resting heart rate (RHR) is recognized as one of the most robust and replicated biological markers of delinquent behavior in children and adolescents (Lorber, 2004; Ortiz and Raine, 2004), and is now listed in the Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM-5, The American Psychiatric Association, 2013) as a physiological risk factor for conduct disorder. This physiological under-arousal is thought to be unpleasant and needs to be overstimulated to achieve a satisfactory level of comfort (see the *low arousal hypothesis*; Eysenck, 1979; Eysenck, 1997; Zuckerman, Eysenck, and Eysenck, 1978). Therefore, under-aroused individuals could be in need of more stimulation leading to sensation-seeking and risk-taking behaviors (Beauchaine, Gatzke-Kopp, and Mead, 2007; De Vries-Bouw et al., 2011; Mezzacappa et al., 1997; Patrick, 2014; Zuckerman, 2014), also underestimating the severity of punishment and consequences of their actions (Armstrong and Boutwell, 2012).

The evidence of low rather than high resting heart activity as being related to antisocial behaviors opened the door to the possible association of this under-aroused physiological state with emotional coldness and socio-emotional distancing, also closely related to delinquency (Frick and Dickens, 2006; Frick and White, 2008). In fact, 25–30% of youth with important conduct problems showed elevated callous-unemotional (CU) traits (i.e., lack of empathy and guilt, reduced attachment), and the presence of CU traits in children and adolescents either co-occurs with or predicts serious antisocial and aggressive behavior (Kahn, Byrd, and Pardini, 2013). Reflecting this evidence, a CU-based specifier has recently been added to diagnose conduct and oppositional defiant disorders (DSM-5, APA, 2013; Colins, Fanti, and Andershed, 2021; ICD-11, Reed et al., 2019). Theoretical interpretation suggests that emotional coldness may result from exposure to recurrent negative emotions in daily life, and that children, by learning to distance themselves and inhibit certain behaviors, condition themselves to avoid certain experiences in order to reduce negative arousal (Blair, Colledge, Murray, and Mitchell, 2001; Frick and Kemp, 2021; Kahn et al., 2013; Kochanska, 1991). Similar mechanisms are attributed to blunted autonomic functioning (e.g., low cortisol, low heart rate, reduced heart-rate reactivity) when confronted during development with early social adversity (Fagan, Zhang, and Gao, 2017; Graziano and Derefinko, 2013; Krenichyn, Saegert, and Evans, 2001; Lovallo, Farag, Sorocco, Cohoon, and Vincent, 2012; Miskovic, Schmidt, Georgiades, Boyle, and MacMillan, 2009; Scarpa and Ollendick, 2003).

Thus, a low RHR, but also high CU traits, seem to be closely related to juvenile delinquency; however, their relationship across development is not clear yet. In community children of 12 years old, low RHR was observed to be related to high CU traits, but with no assumed link to delinquency (Kavish et al., 2017). However, some other authors found no difference in RHR between two groups of adolescents (12 to 15 years old) with disruptive behavior problems, one with low and the other with high CU traits (de Wied, van Boxtel, Matthys, and Meeus, 2012). Noteworthy, in a large epidemiological study of over 14,000 community adults aged between 24 and 34 years old (Kavish, Fu, Vaughn, Qian, and Boutwell, 2019), no significant relationship between RHR and cold-heartedness in relation to antisocial behaviors was found. However, in a study including only children from low-income families (Galán, Choe, Forbes, and Shaw, 2017), low levels of RHR were associated with low levels of empathy (and thus related to high callousness-unemotionality) at 12 years of age and predicted delinquency and arrests at 17 and 20 years of age.

1.1. The current study

Overall, it appears that the putative relationship between RHR and CU traits in explaining delinquency is not consistent across age, sample types (i.e., healthy adolescents, high-risk adolescents, general population adults), and dimensions of the antisocial spectrum considered (De Looff et al., 2022; Lorber, 2004). This suggests that the role of RHR and CU traits in juvenile offending may evolve across development.

The present study aims to better understand the relationship between low resting physiological arousal (i.e., low RHR) and high CU traits, from early adolescence to early adulthood, in high-risk youth living in institutions. The common characteristics of these institutionalized youth are disruption of their social and family environments, a high propensity for callousness and externalizing symptoms (Seker et al., 2021; Urben et al., 2022). Derived from the literature, we hypothesized that RHR would be lower and CU traits higher for youth with an history of delinquency than for those without. This point would confirm the presence of both mechanisms in offending and will provide physiological and emotional support for the *low arousal theory* (Eysenck, 1997; Zuckerman, Buchsbaum, and Murphy, 1980). We also anticipate, based on previous research, that the association of the two mechanisms in explaining offending occurrence would not be constant from pre-adolescence to young adulthood. We speculate that the association between low RHR and high CU traits will be associated with a higher likelihood of delinquent behavior, earlier in adolescence. This proposal arises from the evidence that the autonomic nervous system matures significantly during this period (i.e., myelination, recalibration), as indicated by the slowing of heart rate (Fleming et al., 2011; Wallis, Healy, Undy, and Maconochie, 2005) and the refinement of parasympathetic inhibitory pathways (Simmonds, Hallquist, Asato, and Luna, 2014; Thayer and Lane, 2009). Accordingly, a stronger psychophysiological association with delinquency can be expected at an earlier age compared to young adulthood because the parasympathetic nervous system pathway, a highly myelinated pathway that acts as a brake on the impulsive sympathetic nervous system and promotes emotion regulation and social cognition, is not fully developed (Armstrong, 2011; Beauchaine et al., 2007).

2. Method

2.1. Sample

A total of 592 individuals aged between 5 and 27 participated in the study. To be consistent with the age ranges of interest, we selected individuals from 10 to 22 years of age. A total of 555 juveniles (33% girls; mean age = 15.9 years old, SD = 2.3), mostly Swiss nationals (75%; n = 417), were included in this study.

Participants were divided into three age groups: early adolescence (10–14 y.o.), late adolescence (15–17 y.o.) and young adulthood (18–22 y.o.). Most participants were late adolescents (51%, n = 286, 42% girls), about one-quarter were early adolescents (24%, n = 133, 28% girls) and one-quarter were young adults (25%; n = 136, 18% girls). These three categories were defined to be as representative as possible of developmental stages of young people (10 to 24 years, World Health Organization) and to the different educational levels in Switzerland (primary school, secondary school, and beyond).

The institutions included in the study were those acknowledged by the Federal Justice Office in Switzerland. The placement of one individual in a specific institution depends on his/her age and his/her reasons for placement (criminal vs civil law). Institutions are relatively different from one another in terms of size and services (workshops, psychological and somatic support, professional training, etc.), although they all must respect criteria defined by the law to obtain federal accreditation. Placement for civil reasons (e.g., dysfunctional family environment) was 61% for early adolescents (n = 81/133), 60% for late adolescents (n = 173/286), and 29% for young adults (n = 40/136). This

decrease may be explained by the age of legal majority being at 18 years old in Switzerland. Placement by criminal law represents 9% of cases in early adolescence ($n = 12/133$), 19% in late adolescence ($n = 53/286$), and 51% in young adulthood ($n = 70/136$). Voluntary placement accounted for approximately 20% of the sample in each age group ($n =$ 34, 52, and 25, respectively). We have no information about placement reasons for 15 participants.

2.2. Procedure

The data used in this study come from a countrywide research project conducted between 2007 and 2011 in Switzerland that aimed to better understand the psychological and behavioral issues of the children and young people placed in Swiss justice or residential welfare institutions (Modellversuch zur Abklärung und Zielerreichung in stationären Massnahmen MAZ; Schmid, Kölch, Fegert, and Schmeck, 2011). The research team contacted all institutions accredited by the Ministry of Justice, and 64 institutions were willing to participate. The eligibility criteria for study participation encompassed all children, adolescents and young adults who had been living for at least one month prior to the study in one of those institutions and spoke one of the three main national languages (German, French, or Italian) sufficiently well to answer the questionnaires. All participants (including their legal representatives if they were younger than 18 years), as well as their social caseworkers in the institutions, received oral and written information about the study. Informed consent was obtained from the children, adolescents, and their legal representatives, as well as young adults, who were willing to participate. Participation was voluntary, but the participants were offered a debriefing by one of the psychologists regarding their possible needs and difficulties. The procedure was approved by the Ethics Committees on Research Involving Humans of Basel and of Vaud states in Switzerland and by the Institutional Review Board at the University of Ulm in Germany.

2.3. Measures

2.3.1. Heart rate

We measured physiological arousal using heart rate obtained with a digital wrist blood pressure monitor (Omron R 6, Henrotech, Belgium). This device uses the automatic inflation of a pump in the wrist cuff to record heart rate by oscillometry and provides average pulse signal values over one minute. The pulses must be between 40 and 180 beats per minute (bpm) with an accuracy of ±5% to be displayed on the digital display. In the event of a measurement failure (e.g., weak pulses, movement during measurement, and accuracy >5%), the one-minute procedure was restarted by the experimenter. This method of heart rate measurement has been described as highly correlated with resting electrocardiogram values (Iyriboz, Powers, Morrow, Ayers, and Landry, 1991). Measurements were taken twice at 10-min intervals in the middle of the structural interview. The interviews lasted an average of 2.5–3 h, depending on the participant. Because the clinician structured the interviews, the first mid-interview measurement was administered at approximately the same time (number of questions and content) for each participant. Both measures of RHR were found to be highly correlated ($r = 0.677, p < .01$), without any interaction with age categories or offense history ($ps > .310$). The individual means of both RHR measurements were used for all subsequent analyses.

2.3.2. Callous-unemotional traits

CU traits were measured using the affective scale of the YPI, a 50-item self-reported questionnaire for children and adolescents assessing the core personality traits of psychopathy (Andershed, Kerr, Stattin, and Levander, 2002). The affective scale is composed of 3 subscales (callousness, unemotionality and remorselessness), which are composed of five items each. Each item is rated on a 4-point Likert-type scale (1 = "*does not apply at all*", 2 = "*does not apply well*", 3 = "*applies fairly well*", and 4 = "*applies very well*"). The German (Köhler, Kuska, Schmeck, Hinrichs, and Fegert, 2010), Italian (Fossati et al., 2016), and French (Pihet, Suter, Meylan, and Schmid, 2014) versions were used for this study. For the current study, the Cronbach's α was 0.651 for early adolescence, 0.729 for late adolescence, and 0.805 for young adulthood.

2.3.3. Delinquency - offending history

Severity of delinquent behavior was measured using a self-report, computer-administered questionnaire adapted from the Crime Questionnaire developed in the Münster Longitudinal Study (Boers and Reinecke, 2007). This 41-item instrument assesses past delinquency. Participants had to answer "yes" or "no" to questions such as: *"Have you ever broken into a car to steal something (e.g. radio, money, cell phone, etc.)?", "Have you ever attacked or tried to attack and injure someone with an object (e.g. stick) or a weapon (e.g. knife or tear gas)?",* or *"Have you ever forced another person of the same age, older or younger (less than two years) to have sex by threatening violence?"* The Munster Longitudinal Study records three main categories of crime (property, interpersonal, sexual) and uses latent class analysis to identify four groups according to the severity of their offenses. The first group committed no offenses. The low severity of offending group consisted of individuals who committed at least one of the following offenses: spray-painting or graffiti on public or private property without permission, defacing public or private property, shoplifting, theft (e.g., from coat check), or watching pornographic videos. The moderate severity of offending group was composed of individuals who committed at least one of the following offenses: physical aggression causing injury (not using a weapon), receiving stolen property, bicycle theft, or threats and sexual coercion (older or <2 years younger victim). Finally, the high severity of offending group was composed of individuals who committed at least one of the following offenses: theft of money by damaging an ATM, theft of a motorized vehicle, breaking and entering to commit a theft, robbery, assault with a weapon, sexual harassment, downloading a pornographic video, and sexual assault (including underage victims). In the present study, the last two categories, moderate and high severity of offending, were combined to form a group of high severity offenders (hereafter referred to as offenders), while the others were referred to as non-offenders.

Additionally to RHR, CU traits and offending history, Raven's standard progressive matrices (Raven, 2003) or the Culture Fair Intelligence Test (Cattell, 1963) was measured to test the utility of using nonverbal reasoning as a control variable. Both measures are accepted as valid and independent of language proficiency (Engle, Tuholski, Laughlin, and Conway, 1999).

2.4. Data analyses

First, we performed chi-squares to examine the weight of gender and the proportion of offenders on RHR and CU traits by age group. Then, differences in RHR and CU were compared by age group and prior offending behavior (ANOVA). Moderation analyses were computed using PROCESS for SPSS (v3.4.2; Hayes, 2017) to assess the effects of RHR and CU and their interaction on offending (Yes/No), for each age groups (i.e., early and late adolescents, early adulthood). As the moderators are included in the statistical models as an interaction term that can vary with the values of the third variable, this type of analysis will help us to answer the question "at what level of RHR are CU traits most at risk" and vice versa. Prototypical graphs were created using the PROCESS analysis to illustrate the effects of the moderators on the outcome of offending. The PROCESS macro also provides the significance of the focal predictor at the 16th and 84th percentiles for each moderator and calculates the Johnson-Neyman significance region. This last calculation is a technique that allows for the precise determination of boundary values at which the moderator produces statistically significant slopes (Hayes, 2017; Lazar and Zerbe, 2011).

Missing data were excluded from the calculations. One hundred and thirty-two data points were missing for RHR (23.8%), mainly due to the

lack of a wrist pulse band at the site or refusal of the participants to wear it. The missing physiological data were evenly distributed across the age categories: 21 in early adolescence (15.8%), 72 in late adolescence (25.2%), and 39 in young adulthood (28.7%) ($F(2,552) = 2.97$; $p = .052$). Subjects without RHR measurements were not characterized by their CU scores ($p = .131$) or offending history ($p = .347$) and were equally distributed between females and males ($p = .327$). Therefore, a total sample of 423 subjects with RHR measurements was retained for all analyses involving RHR, 151 non-offenders and 272 offenders, distributed as 112 early adolescents, 214 late adolescents, and 97 young adults.

There were also 52 (9.4%) missing data on CU scores, of which 19 were participants with RHR measures. Subjects without CU scores were not characterized by their RHR mean ($p < .07$), offending history ($p < .76$) or gender ($p < .64$) and were evenly distributed across the three age categories (16 early adolescents and thus 12%, 24 late adolescents and thus 8.4%, 12 young adults and thus 8.8%; $F(2,552) = 1.31$; $p = .37$).

3. Results

3.1. Control variables: nonverbal reasoning and gender

The nonverbal reasoning score for the entire sample was 96 (SD = 14) and did not differ between the age groups (M = 96, SD = 12; M = 96, SD = 14; and M = 98, SD = 17, respectively). Therefore, we decided not to keep this variable as a control variable. The mean RHR for the entire sample was 75.1 bpm (SD = 10.6) and was higher in females than in males ($p < .01$, Cohen's d = 0.31; females: M = 77.6 bpm, SD = 10.9; and males: M = 74.0 bpm, SD = 10.2), which is in line with standards from previous studies (Wallis et al., 2005). The CU traits were higher for males (M = 2.28, SD = 0.53) than females (M = 1.95, SD = 0.40; $F(1,501) = 50.03$; $p < .001$) with no interaction with age group ($p = .503$). Therefore, we decided to include gender as a control variable in all inferential analyses and results described below.

3.2. Descriptive & developmental trends

The offender group accounted for 66% ($n = 363$) of the total sample. Forty-three percent of offenders committed only property offenses, 42% committed interpersonal violence, and 15% committed sexual violence, according to the self-report questionnaire. The proportion of juveniles who committed an offense was 53% for early adolescents, 66% for adolescents, and 77% for young adults, with a significant increase across the age categories ($\chi^2(2) = 17.98$, $p < .001$), which may be related to placement for criminal reasons, which also increased.

Descriptive statistics of the RHR and CU scores for the total sample and for the three respective age range groups (early adolescents 10–14 years, late adolescents 15–17 years, and young adults 18–22 years) based on their offending history (No/Yes) are presented in Table 1.

The RHR decreases significantly with age ($r = -0.145$; $p < .01$); this relationship remains marginal when comparing the age groups ($F(2,421) = 2.48$; $p = .08$). The offenders do not differ from non-offenders on RHR ($F(1,422 = 0.02$; $p > .88$); no interaction by age group ($F(2,417) = 0.59$; $p = .55$; Fig. 1A).

CU scores did not vary with age ($F(2,501) = 0.15$; $p = .86$) but were significantly higher for offenders (Mean = 2.23, SD = 0.53) than for non-offenders youth (Mean = 2.05, SD = 0.46; $F(1,502) = 17.98$; $p < .01$; Fig. 1B); no interaction by age group ($F(2,496) = 0.99$; $p = .37$).

3.3. Moderation models assessing the role of RHR and CU traits in explaining offending (adjusted for sex)

3.3.1. Early adolescence (10–14 yo)

Results indicated that the entire moderation model was significant (Fig. 2A; $\chi^2(4) = 18.02$, $p = .001$, Nagelkerke's $R^2 = 0.219$), and related to both main effects, RHR (B = 0.29; $p = .037$) and CU traits (B = 11.88; $p = .015$), and their interaction (B = .-0.137; $p = .027$; Effect size of moderation χ^2 change: $\chi^2(1) = 5.51$; $p = .019$). The conditional effects of the focal predictors to explain offending likelihood concerned CU traits combined with low RHR (16th percentile mean centering = 66.7 bpm; $p = .005$). The Johnson-Neyman region of significance for RHR was 77.8 bpm, below which 60.4% of the sample fell.

3.3.2. Late adolescence (15–17 yo)

Results indicated that the entire moderation model was significant (Fig. 2B; $\chi^2(4) = 12.53$, $p = .014$, Nagelkerke's $R^2 = 0.080$), and related in a marginal way to RHR (B = −0.136; $p = .051$), to CU traits (B = −5.40; $p = .026$), as to their interaction (B = 0.07; $p = .026$; Effect size of moderation χ^2 change: $\chi^2(1) = 5.57$; $p = .018$). The conditional effects of the focal predictors to explain offending probability concerned RHR combined with high CU traits (84th percentile mean centering = 2.67 points; $p = .014$). The Johnson-Neyman region of significance for CU traits was the score of 2.28, below which 64.6% of the sample fell.

3.3.3. Young adulthood (18–22 yo)

The model of moderation did not explain a significant part of the variance ($\chi^2(4) = 7.97$, $p = .09$, Nagelkerke's $R^2 = 0.12$).

4. Discussion

Results of this study showed that low RHR combined with high CU traits explained offending in early adolescence, and high RHR combined with high CU traits explained offending in late adolescence.

4.1. How the relation between RHR and CU traits may trigger offending

Our results partially confirm our main hypothesis, but only in early adolescence: a combination of low RHR and high CU traits is a risk factor for juvenile delinquency. Indeed, the effect of low RHR on offending is strong in early adolescence (10–14 years) but does not seem to persist later in our sample. Therefore, the relationship between RHR and CU traits in explaining offending appears to vary across developmental stages, clarifying previous discrepancies between studies in this area (Kavish et al., 2019; Lorber, 2004).

The present findings regarding early adolescence can be understood in light of the *low arousal theory* (Eysenck, 1997; Zuckerman et al., 1980). Indeed, this theory suggests that a state of unpleasant physiological under-arousal is thought to encourage activities that provide sensations to increase excitement to a more pleasurable level (Zuckerman, 2014), explaining the interest in off-limits behaviors (Armstrong, Keller, Franklin, and Macmillan, 2009; Raine, Fung, Portnoy, Choy, and

Table 1
Descriptive statistics for RHR and CU scores for the three age groups, non-offenders, and offenders.

	Early adolescence (n = 133, 24%)			Late adolescence (n = 286, 51.5%)			Young adulthood (n = 136, 24.5%)		
Offending	No ($n = 63$, 47%)	Yes (n = 70, 53%)	P-Value[a]	No ($n = 98$, 34%)	Yes ($n = 188$, 66%)	P-Value[a]	No ($n = 31$, 23%)	Yes ($n = 105$, 77%)	P-Value[a]
RHR (SD)	77.66 (11.35)	76.12 (9.56)	0.438	74.13 (11.5)	75.24 (10.7)	0.483	75.24 (10.7)	74.07 (9.22)	0.675
CU* (SD)	2.00 (0.35)	2.26 (0.48)	**0.002**	2.10 (0.50)	2.21 (0.52)	0.097	2.21 (0.52)	2.25 (0.57)	**0.046**

Note. Data expressed as Mean (Standard deviation). RHR: resting heart rate in beats per minute (bpm); CU: callous-unemotional scores.
[a] Results of Student's *t*-test.

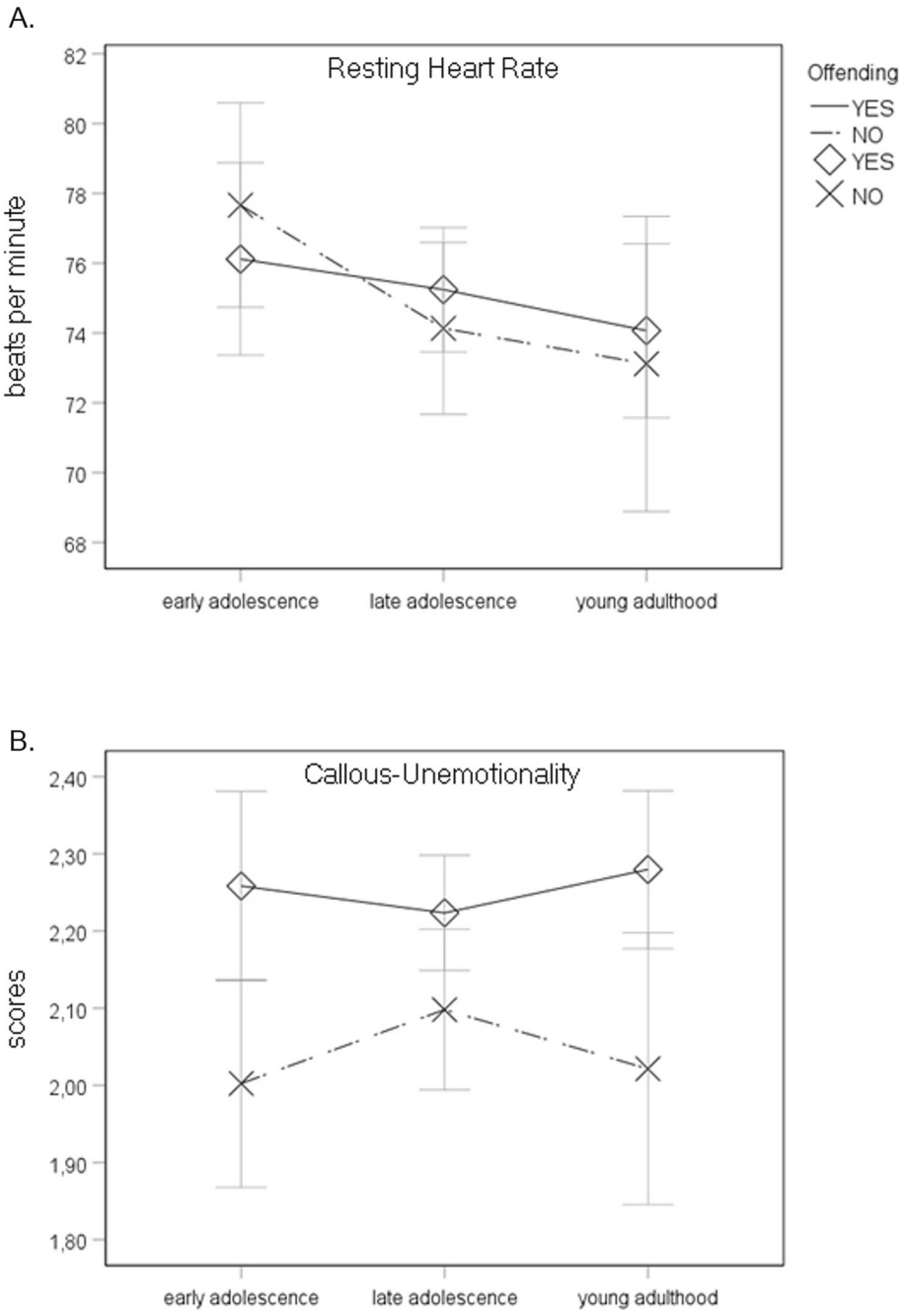

Fig. 1. Resting heart rate (RHR, Panel A) and callous-unemotional traits (CU, Panel B) plotted by age group.
A. RHR did not discriminate between offending and non-offending youth. A significant decrease with age was observed ($r = -0.145$; $p < .01$). B. CU scores were higher for offending than for non-offending youth ($p < .01$). Mean scores were stable across age categories.
Note. Marks indicate estimated marginal means (adjusted for sex). Shaded bars represent ±2 standard errors of the means.

Spring, 2014). However, in view of our findings, this explanation alone does not seem to be complete. In fact, low RHR during preadolescence seems to be risky only when combined with high CU traits. This would imply that under-aroused adolescents may need more stimulation, but also that they may be less constrained by empathic concerns, leading to an increased likelihood of offending. This pattern is consistent with the high levels of callousness and lack of emotion that have been associated with violent and antisocial conduct (Abu-Akel and Abushua'leh, 2004; Blair, 2005; Jolliffe and Farrington, 2006; Miller and Eisenberg, 1988), and with the protective effects of empathy on delinquency suggested by earlier findings (Feshbach and Feshbach, 1982; Jolliffe and Farrington, 2004; Miller and Eisenberg, 1988; Nasaescu, Zych, Ortega-Ruiz, Farrington, and Llorent, 2021).

Also noteworthy for both prevention and intervention is the fact that in the early adolescent's group, low RHR, when associated with low CU traits, results in the lowest probability of offending (28%). Under these conditions, a low RHR would no longer be considered a risk associated with criminality (Armstrong et al., 2009; Raine et al., 2014), but could regain its original cardiac designation reducing adverse outcomes, cardiovascular disease and early mortality (Jensen, 2019; Verrier and Tan, 2009). For the subsequent 15–17 age group, the interaction between RHR and CU traits still exists, but the relationship between the two moderators in explaining the likelihood of delinquency changes, with high CU traits becoming the dominant conditional predictor. The highest probability is measured for its association with high RHR, inversely to the preadolescent period described above.

In our view, this reversal in psychophysiological pairing associated with delinquency could be relied primarily by the maturation and reorganization of physiological functions that occur at this age range. Indeed, puberty reopens a window for recalibration of the hypothalamic-pituitary-adrenal stress axis (Gunnar, DePasquale, Reid, Donzella, and Miller, 2019), with increased myelination of bottom-up

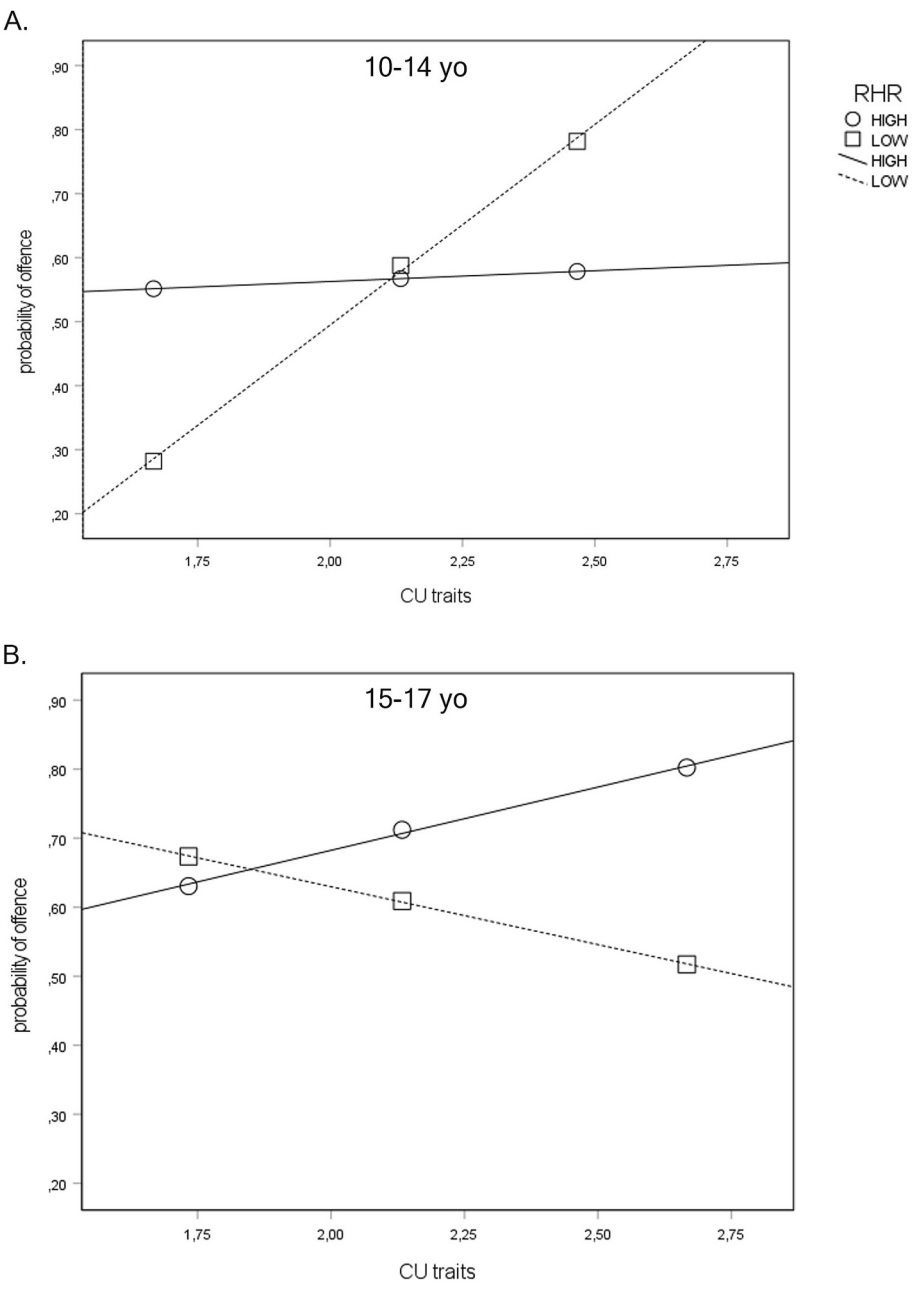

Fig. 2. Moderation plots of Resting Heart Rate (RHR) by Callous-Unemotional (CU) traits related to the likelihood of offending in early (Panel A) and late adolescence (Panel B).
A. The interaction of RHR x CU traits was significantly associated to the likelihood of offending (p = .027). Significant factors were low RHR (square marks: p = .005) combined with CU traits. B. The interaction of RHR x CU traits was significantly related to the likelihood of offending (p = .026). Significant factors were RHR combined with high CU traits (p = .014).
Note. For 10–14 age group, High RHR (84th centile): 86 bpm; Low RHR (16th centile): 67 bpm. For 15–17 age group, High RHR (84th centile): 82 bpm; Low RHR (16th centile): 62 bpm.

and top-down fronto-limbic pathways (Porges, 1995, 2003; Simmonds et al., 2014; Thayer and Lane, 2009). The overall processes may lead to a sympathetic fight-or-flight hyperactivity in late adolescence related to criminality and callousness, reflecting in high heart rate at rest (Grassi et al., 1998). This may be consequent to impaired deployment of parasympathetic regulatory and inhibitory pathways in association to delinquency (Fanti et al., 2019; Palix, Gillespie, Abbiati, and Abu-Akel, 2022; Porges, 2007; Roos et al., 2017), which appears to be consistent with reduced white matter integrity described in youth aged 10–17 years with conduct disorder and CU traits (Breeden, Cardinale, Lozier, VanMeter, and Marsh, 2015). This also fits well with the efficacy of cognitive-behavioral interventions, which benefit high RHR children more than low (Stadler et al., 2008). Thus, even if this hypothesis needs to be confirmed, it deserves attention, especially because the RHR should decrease during development in association with the strengthening of the parasympathetic pathways of the autonomic nervous system (Thayer and Lane, 2009), and that the present high-risk RHR (combined with high CU traits) was 82 bpm, some ten points above the expected norm (Wallis et al., 2005). This suggestion should be supported by future longitudinal studies of a smaller decline in RHR in juvenile delinquency.

In young adults, the association between RHR and CU traits in the likelihood of offending was not found. It is likely that other parameters such as health behaviors and physical fitness (weight gain, diet, sleep, exercise) may be more heterogeneous in young adults (Sallis, 2000) and confound this direct association.

Finally, it is important to remember that the early and late adolescents in our study were represented by different samples. The late adolescent group included more offenders (two-thirds) than the early adolescent group (one-half), probably related to the number of placements following a criminal sentence, which also increased. Consequently, it is also possible that these late adolescents experienced more harsh and inadequate living conditions prior to their institutionalization, leading to a more self-protective, fight-or-flight-driven function of

the cardiovagal balance, and thus higher RHR associated with higher CU traits. In this regard, future studies on that topic should take into account the living environment prior to institutionalization, the length of stay in institution, and the stress experienced by adolescents prior and in the institution, whether using subjective or neuroendocrine data. While awaiting support on this issue, we can argue that the means of the RHR and CU traits do not differ between these two age groups, and thus the idea that it is the association between RHR and CU that changes from early to late adolescence, as well as the increased occurrence of delinquency, seems to us to be the main actual rationale.

4.2. Callous-unemotionality predominance in high-risk juveniles

Knowing that CU traits are a recognized antecedent of adult psychopathy (Viding and McCrory, 2018), the predominance of high CU traits in the propensity to offend in our samples of institutionalized youth should be retained as a hook for intervention and care provided by institutions. Indeed, in our results, low CU traits were not predictive of offending, whether or not associated with low or high RHR, whereas high CU traits were systematically related to offending throughout the entire adolescent period. The etiology of CU traits, defined by low empathy and shallow affect, has been described as rooted in childhood and stable across developmental stages (Lynam et al., 2009; Obradovic, Pardini, Long, and Loeber, 2007), thus qualifying it as a trait. Nonetheless, Frick and colleagues offer a perspective, finding that reductions in CU traits are consistently associated with the quality of child socialization (i.e., socioeconomic status and parenting quality) (Frick and Morris, 2004; Frick and White, 2008). In addition, CU traits have been shown to be strongly mediated by environmental factors such as parental warmth or harshness (Tomlinson, Hyde, Dotterer, Klump, and Burt, 2022). Thus, by focusing on samples of institutionalized youth, our study promotes a better understanding of their "high-risk" classification and highlights the implementation of reducing CU traits as a focus for preventing juvenile delinquency (e.g., through improved socialization and parenting).

4.3. Limitations

Some limitations to these findings should be noted. The cross-sectional nature of the study prevented the possibility of assessing predictive models or causality. Further studies using a longitudinal design may be helpful to clarify the validity of these associations in predicting future offending behavior. In addition, RHR was assessed at discrete time points in the middle of a clinical interview, so these measurement conditions may not be strictly representative of a neutral resting physiological state. These findings will therefore require replication to be confirmed. In addition, we did not control for the use of cardiac stimulants such as nicotine and caffeine. Thus, it cannot be excluded that the proportion of users increases with age and differs in the offender sample from the non-offender sample. It should be noted, however, that the effects of these substances on the autonomic nervous system in young and healthy regular users have been found to be minimal (Perkins, Epstein, Stiller, Marks, and Jacob, 1989; Rauh, Burkert, Siepmann, and Mueck-Weymann, 2006). In addition, although the participants were offered a break during the protocol during which they had the opportunity to smoke and/or drink coffee, this break never occurred near the time of RHR recording. With regard to medication, it is recognized that most psychoactive drugs are not associated with systematic effects on cardiac activity (Alber et al., 2010; Mujica-Parodi, Yeragani, and Malaspina, 2005; and review by Mick, McManus, and Goldberg, 2013 for central nervous system stimulants in the treatment of attention deficit hyperactivity disorder). We also note that delinquency was assessed using a self-report measure that categorizes individuals according to their most severe behaviors. Including the frequency of offending behaviors and adding external sources of information, such as police or court records, would have provided a more accurate measure of offending. Finally, we should mention that the decision to divide our sample into three age-group probably resulted in a reduction of statistical power. However, the three groups were formed in order to compare our results to previous studies using the same groups and to match traditionally recognized age-related developmental stages.

4.4. Conclusions and perspectives

In summary, the interaction between RHR and CU traits on offending varies across development. The developmental mechanisms that account for these variations have been hypothesized as a dysfunction or delay in the maturation of the parasympathetic pathway in offending adolescents. Therefore, strengthening the functioning of the parasympathetic pathway of the autonomic nervous system (and its balance with the central nervous system) through heart rate variability biofeedback may be relevant for intervention (Favrod et al., 2015; Jansen, 2022; Lehrer and Gevirtz, 2014), especially at an early age (Raine et al., 2001). This type of intervention is likely to be more effective if it is accompanied by the targeting of CU traits, which, like other mental disorders, should be assessed early in development by forensic practitioners in juvenile cases, which is not yet systematically done (Palix et al., 2022). Recent meta-analyses and reviews show that treatments focused on child disruptive behavior (Perlstein, Fair, Hong, & Waller, 2023), parent-child interactions and home warmth (Fleming, 2023; Sadri, Alizadeh, Pezehsk, and Asgari, 2022) can be effective in reducing CU traits and should be implemented as early as possible alongside programs in institutional settings.

Fundings

This study was funded by the Ministry of Justice of Switzerland. Open access funding was provided by the University of Lausanne.

Declaration of Competing Interest

The authors declared no potential conflicts of interest regarding research, authorship, or publication of this article.

References

Abu-Akel, A., & Abushua'leh, K. (2004). Theory of mind'in violent and nonviolent patients with paranoid schizophrenia. *Schizophrenia Research, 69*(1), 45–53.

Alber, H., Dromigny, E., Le Hazif, L., Nedelec, M., Perrus-Lesquibe, C., & Burgot, G. (2010). Les troubles du rythme cardiaque liés à la prise de médicaments psychotropes. *Journal de Pharmacie Clinique, 29*(4), 183–209.

Andershed, H. A., Kerr, M., Stattin, H., & Levander, S. (2002). Psychopathic traits in non-referred youths: A new assessment tool. In L. S. Eric Blaauw (Ed.), *Psychopaths: Current International Perspectives* (2002 ed., pp. 131–158). Elsevier.

APA, The American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.). American Psychiatric Publishing.

Armstrong, T. A. (2011). The relationship between low resting heart rate and antisocial behavior: Correlation or causation? In Walsh (Ed.), *The Ashgate Research Companion to Biosocial Theories of Crime* (1st Edition ed., pp. 45–68). Routledge.

Armstrong, T. A., & Boutwell, B. B. (2012). Low resting heart rate and rational choice: Integrating biological correlates of crime in criminological theories. *Journal of Criminal Justice, 40*(1), 31–39. https://doi.org/10.1016/j.jcrimjus.2011.11.001

Armstrong, T. A., Keller, S., Franklin, T. W., & Macmillan, S. N. (2009). Low resting heart rate and antisocial behavior: A brief review of evidence and preliminary results from a new test. *Criminal Justice and Behavior, 36*(11), 1125–1140. https://doi.org/10.1177/0093854809342855

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*(2), 174–184. https://doi.org/10.1016/j.biopsycho.2005.08.008

Blair, R. J., Colledge, E., Murray, L., & Mitchell, D. (2001). A selective impairment in the processing of sad and fearful expressions in children with psychopathic tendencies. *Journal of Abnormal Child Psychology, 29*, 491–498.

Blair, R. J. R. (2005). Responding to the emotions of others: Dissociating forms of empathy through the study of typical and psychiatric populations. *Consciousness and Cognition, 14*(4), 698–718.

Boers, K., & Reinecke, J. (2007). Delinquenz im Jugendalter. *JERO, 3*(1), 259–263.

Breeden, A., Cardinale, E., Lozier, L., VanMeter, J., & Marsh, A. (2015). Callous-unemotional traits drive reduced white-matter integrity in youths with conduct problems. *Psychological Medicine, 45*(14), 3033–3046.

Camm, A. J., Malik, M., Bigger, J. T., Breithardt, G., Cerutti, S., Cohen, R. J., … Kleiger, R. E. (1996). Heart rate variability: Standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Circulation, 93*(5), 1043–1065.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Education & Psychology, 54*, 1–22. https://doi.org/10.1037/h0046743

Colins, O. F., Fanti, K. A., & Andershed, H. (2021). The DSM-5 limited prosocial emotions specifier for conduct disorder: Comorbid problems, prognosis, and antecedents. *Journal of the American Academy of Child & Adolescent, 60*(8), 1020–1029.

De Looff, P. C., Cornet, L. J., De Kogel, C. H., Fernández-Castilla, B., Embregts, P. J., Didden, R., & Nijman, H. L. (2022). Heart rate and skin conductance associations with physical aggression, psychopathy, antisocial personality disorder and conduct disorder: An updated meta-analysis. *Neuroscience and Biobehavioral Reviews, 132*, 553–582.

De Vries-Bouw, M., Popma, A., Vermeiren, R., Doreleijers, T. A. H., Van De Ven, P. M., & Jansen, L. M. C. (2011). The predictive value of low heart rate and heart rate variability during stress for reoffending in delinquent male adolescents. *Psychophysiology, 48*(11), 1597–1604. https://doi.org/10.1111/j.1469-8986.2011.01233.x

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology, 128*, 309–331. https://doi.org/10.1037/0096-3445.128.3.309

Eysenck, H. J. (1979). Crime and personality. *The Medico-Legal Journal, 47*(1), 18–32. https://doi.org/10.1177/002581727904700104

Eysenck, H. J. (1997). Personality and the biosocial model of anti-social and criminal behaviour. In *, Vol. 292. Biosocial Bases of Violence* (pp. 21–37). Springer.

Fagan, S. E., Zhang, W., & Gao, Y. (2017). Social adversity and antisocial behavior: Mediating effects of autonomic nervous system activity. *Journal of Abnormal Child Psychology, 45*, 1553–1564.

Fanti, K. A., Eisenbarth, H., Goble, P., Demetriou, C., Kyranides, M. N., Goodwin, D., … Cortese, S. (2019). Psychophysiological activity and reactivity in children and adolescents with conduct problems: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews, 100*, 98–107. https://doi.org/10.1016/j.neubiorev.2019.02.016

Farrington, D. P., Piquero, A. R., Jennings, W. G., & Jolliffe, D. (2023). *Offending from Childhood to Late Middle Age: Recent Results from the Cambridge Study in Delinquent Development* (p. 80). NY: Springer New York.

Favrod, J., Brana, A., Gavillet, A., Akselrod, M., Nguyen, A., & Palix, J. (2015). Entraînement à faire face au stress professionnel pour les personnes avec un retard intellectuel: une étude pilote. *Journal de Thérapie Comportementale et Cognitive, 25*(3), 132–141.

Feshbach, N. D., & Feshbach, S. (1982). Empathy training and the regulation of aggression: Potentialities and limitations. *Academic Psychology Bulletin, 4*, 399–413.

Fleming, G. E. (2023). Commentary: Optimism and guidance for improving treatment effects among children with callous-unemotional traits–reflections on Perlstein et al. (2023). *Journal of Child Psychology and Psychiatry, 64*(9), 1388–1392.

Fleming, S., Thompson, M., Stevens, R., Heneghan, C., Pluddemann, A., Maconochie, I., … Mant, D. (2011). Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: A systematic review of observational studies. *Lancet, 377*(9770), 1011–1018. https://doi.org/10.1016/S0140-6736(10)62226-X

Fossati, A., Somma, A., Borroni, S., Frera, F., Maffei, C., & Andershed, H. (2016). The factor structure and construct validity of the short version of the youth psychopathic traits inventory in two independent samples of nonreferred adolescents. *Assessment, 23*(6), 683–697. https://doi.org/10.1177/1073191115593628

Frick, P. J., & Dickens, C. (2006). Current perspectives on conduct disorder. *Current Psychiatry Reports, 8*(1), 59–72.

Frick, P. J., & Kemp, E. C. (2021). Conduct disorders and empathy development. *Annual Review of Clinical Psychology, 17*, 391–416.

Frick, P. J., & Morris, A. S. (2004). Temperament and developmental pathways to conduct problems. *Journal of Clinical Child and Adolescent Psychology, 33*(1), 54–68.

Frick, P. J., Ray, J. V., Thornton, L. C., & Kahn, R. E. (2014). Can callous-unemotional traits enhance the understanding, diagnosis, and treatment of serious conduct problems in children and adolescents? A comprehensive review. *Psychological Bulletin, 140*(1), 1.

Frick, P. J., & White, S. F. (2008). Research review: The importance of callous-unemotional traits for developmental models of aggressive and antisocial behavior. *Journal of Child Psychology and Psychiatry, 49*(4), 359–375.

Galán, C. A., Choe, D. E., Forbes, E. E., & Shaw, D. S. (2017). Interactions between empathy and resting heart rate in early adolescence predict violent behavior in late adolescence and early adulthood. *Journal of Child Psychology and Psychiatry, 58*(12), 1370–1380.

Grassi, G., Vailati, S., Bertinieri, G., Seravalle, G., Stella, M. L., Dell'Oro, R., & Mancia, G. (1998). Heart rate as marker of sympathetic activity. *Journal of Hypertension, 16*(11), 1635–1639.

Graziano, P., & Derefinko, K. (2013). Cardiac vagal control and children's adaptive functioning: A meta-analysis. *Biological Psychology, 94*(1), 22–37.

Gunnar, M. R., DePasquale, C. E., Reid, B. M., Donzella, B., & Miller, B. S. (2019). Pubertal stress recalibration reverses the effects of early life stress in postinstitutionalized children. *Proceedings of the National Academy of Sciences of the United States of America, 116*(48), 23984–23988. https://doi.org/10.1073/pnas.1909699116

Guyll, M., & Contrada, R. J. (1998). Trait hostility and ambulatory cardiovascular activity: Responses to social interaction. *Health Psychology, 17*(1), 30.

Hayes, A. F. (2017). *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach*. Guilford Publications.

Iyriboz, Y., Powers, S., Morrow, J., Ayers, D., & Landry, G. (1991). Accuracy of pulse oximeters in estimating heart rate at rest and during exercise. *British Journal of Sports Medicine, 25*(3), 162–164.

Jansen, L. M. (2022). The neurobiology of antisocial behavior in adolescence current knowledge and relevance for youth forensic clinical practice. *Current Opinion in Psychology, 101356*.

Jensen, M. T. (2019). Resting heart rate and relation to disease and longevity: Past, present and future. *Scandinavian Journal of Clinical and Laboratory Investigation, 79*(1–2), 108–116.

Jolliffe, D., & Farrington, D. P. (2004). Empathy and offending: A systematic review and meta-analysis. *Aggression and Violent Behavior, 9*(5), 441–476.

Jolliffe, D., & Farrington, D. P. (2006). Examining the relationship between low empathy and bullying. *Aggressive Behavior, 32*(6), 540–550.

Kahn, R. E., Byrd, A. L., & Pardini, D. A. (2013). Callous-unemotional traits robustly predict future criminal offending in young men. *Law and Human Behavior, 37*(2), 87.

Kahn, R. E., Frick, P. J., Youngstrom, E. A., Kogos Youngstrom, J., Feeny, N. C., & Findling, R. L. (2013). Distinguishing primary and secondary variants of callous-unemotional traits among adolescents in a clinic-referred sample. *Psychological Assessment, 25*(3), 966.

Kamarck, T. W., Annunziato, B., & Amateau, L. M. (1995). Affiliation moderates the effects of social threat on stress-related cardiovascular responses: Boundary conditions for a laboratory model of social support. *Psychosomatic Medicine, 57*(2), 183–194.

Kavish, N., Fu, Q. J., Vaughn, M. G., Qian, Z., & Boutwell, B. B. (2019). Resting heart rate and psychopathy revisited: Findings from the add health survey. *International Journal of Offender Therapy and Comparative Criminology, 63*(4), 543–557. https://doi.org/10.1177/0306624X18806748

Kavish, N., Vaughn, M. G., Cho, E., Barth, A., Boutwell, B., Vaughn, S., … Martinez, L. (2017). Physiological arousal and juvenile psychopathy: Is low resting heart rate associated with affective dimensions? *The Psychiatric Quarterly, 88*(1), 103–114. https://link.springer.com/content/pdf/10.1007%2Fs11126-016-9437-z.pdf.

Kochanska, G. (1991). Socialization and temperament in the development of guilt and conscience. *Child Development, 62*(6), 1379–1392.

Köhler, D., Kuska, S., Schmeck, K., Hinrichs, G., & Fegert, J. (2010). In Hogrefe (Ed.), *Deutsche Version des Youth-Psychopathic-Traits-Inventory (YPI)*.

Krenichyn, K., Saegert, S., & Evans, G. W. (2001). Parents as moderators of psychological and physiological correlates of inner-city children's exposure to violence. *Journal of Applied Developmental Psychology, 22*(6), 581–602.

Lazar, A. A., & Zerbe, G. O. (2011). Solutions for determining the significance region using the Johnson-Neyman type procedure in generalized linear (mixed) models. *Journal of Educational and Behavioral Statistics, 36*(6), 699–719. https://doi.org/10.3102/1076998610396889

Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: How and why does it work? *Frontiers in Psychology, 5*, 756.

Loeber, R., & Farrington, D. P. (2012). *From Juvenile Delinquency to Adult Crime: Criminal Careers, Justice Policy and Prevention*. Oxford University Press.

Lorber, M. F. (2004). Psychophysiology of aggression, psychopathy, and conduct problems: A meta-analysis. *Psychological Bulletin, 130*(4), 531–552. https://doi.org/10.1037/0033-2909.130.4.531

Lovallo, W. R., Farag, N. H., Sorocco, K. H., Cohoon, A. J., & Vincent, A. S. (2012). Lifetime adversity leads to blunted stress axis reactivity: Studies from the Oklahoma Family Health Patterns Project. *Biological Psychiatry, 71*(4), 344–349.

Lynam, D. R., Charnigo, R., Moffitt, T. E., Raine, A., Loeber, R., & Stouthamer-Loeber, M. (2009). The stability of psychopathy across adolescence. *Development and Psychopathology, 21*(4), 1133–1153. https://doi.org/10.1017/S0954579409990083

Mezzacappa, E., Tremblay, R. E., Kindlon, D., Saul, J. P., Arseneault, L., Seguin, J., … Earls, F. (1997). Anxiety, antisocial behavior, and heart rate regulation in adolescent males. *Journal of Child Psychology and Psychiatry, 38*(4), 457–469. https://doi.org/10.1111/j.1469-7610.1997.tb01531.x

Mick, E., McManus, D. D., & Goldberg, R. J. (2013). Meta-analysis of increased heart rate and blood pressure associated with CNS stimulant treatment of ADHD in adults. *European Neuropsychopharmacology, 23*(6), 534–541. https://doi.org/10.1016/j.euroneuro.2012.06.011

Miller, P. A., & Eisenberg, N. (1988). The relation of empathy to aggressive and externalizing/antisocial behavior. *Psychological Bulletin, 103*(3), 324.

Miskovic, V., Schmidt, L. A., Georgiades, K., Boyle, M., & MacMillan, H. L. (2009). Stability of resting frontal electroencephalogram (EEG) asymmetry and cardiac vagal tone in adolescent females exposed to child maltreatment. *Developmental Psychobiology, 51*(6), 474–487.

Mujica-Parodi, L., Yeragani, V., & Malaspina, D. (2005). Nonlinear complexity and spectral analyses of heart rate variability in medicated and unmedicated patients with schizophrenia1. *Neuropsychobiology, 51*(1), 10–15.

Nasaescu, E., Zych, I., Ortega-Ruiz, R., Farrington, D. P., & Llorent, V. J. (2021). Stability and change in longitudinal patterns of antisocial behaviors: The role of social and emotional competencies, empathy, and morality. *Current Psychology*, 1–15.

Newton, T. L., & Bane, C. M. (2001). Cardiovascular correlates of behavioral dominance and hostility during dyadic interaction. *International Journal of Psychophysiology, 40*(1), 33–46.

Obradovic, J., Pardini, D. A., Long, J. D., & Loeber, R. (2007). Measuring interpersonal callousness in boys from childhood to adolescence: An examination of longitudinal invariance and temporal stability. *Journal of Clinical Child and Adolescent Psychology, 36*(3), 276–292. https://doi.org/10.1080/15374410701441633

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*(2), 154–162. https://doi.org/10.1097/00004583-200402000-00010

Palix, J., Abbiati, M., Wouters, E., Seker, S., Aebi, M., & Boonmann, C. (2022). Pratique expertale et mineurs: résultats d'une enquête nationale. *Jusletter.*. https://doi.org/10.38023/9b117b67-1c28-4278-b6f7-cc050fae3b16

Palix, J., Gillespie, S. M., Abbiati, M., & Abu-Akel, A. (2022). Dynamics of parasympathetic activity in violent incarcerated offenders before, during, and in recovery from an emotional inhibition task. *Scientific Reports, 12*(1), 7126.

Patrick, C. J. (2014). Physiological correlates of psychopathy, antisocial personality disorder, habitual aggression, and violence. In *Electrophysiology and Psychophysiology in Psychiatry and Psychopharmacology* (pp. 197–227). Springer.

Perkins, K. A., Epstein, L. H., Stiller, R. L., Marks, B. L., & Jacob, R. G. (1989). Chronic and acute tolerance to the heart rate effects of nicotine. *Psychopharmacology, 97*(4), 529–534. https://doi.org/10.1007/BF00439559

Perlstein, S., Fair, M., Hong, E., & Waller, R. (2023). Treatment of childhood disruptive behavior disorders and callous-unemotional traits: A systematic review and two multilevel meta-analyses. *Journal of Child Psychology and Psychiatry*.

Pieper, C., Warren, K., & Pickering, T. G. (1993). A comparison of ambulatory blood pressure and heart rate at home and work on work and non-work days. *Journal of Hypertension, 11*(2), 177–183.

Pihet, S., Suter, M., Meylan, N., & Schmid, M. (2014). Factor structure of the youth psychopathic traits inventory: Using the total score, three scale scores, and/or 10 subscale scores. *Criminal Justice and Behavior, 41*(10), 1214–1231. https://doi.org/10.1177/0093854814540287

Piquero, A. R., Farrington, D. P., & Blumstein, A. (2007). *Key Issues in Criminal Career Research: New Analyses of the Cambridge Study in Delinquent Development.* Cambridge University Press.

Porges, S. W. (1995). Orienting in a defensive world: Mammalian modifications of our evolutionary heritage. A Polyvagal Theory. *Psychophysiology, 32*(4), 301–318. https://doi.org/10.1111/j.1469-8986.1995.tb01213.x

Porges, S. W. (2003). The Polyvagal Theory: Phylogenetic contributions to social behavior [Research Support, U.S. Gov't, P.H.S.Review]. *Physiology & Behavior, 79*(3), 503–513. https://doi.org/10.1016/s0031-9384(03)00156-2

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*(2), 116–143. https://doi.org/10.1016/j.biopsycho.2006.06.009

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. https://doi.org/10.1016/j.avb.2015.02.004

Raine, A., Fung, A. L. C., 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*(4), 290–299. https://doi.org/10.1002/ab.21523

Raine, A., Venables, P. H., Dalais, C., Mellingen, K., Reynolds, C., & Mednick, S. A. (2001). Early educational and health enrichment at age 3–5 years is associated with increased autonomic and central nervous system arousal and orienting at age 11 years: Evidence from the Mauritius Child Health Project. *Psychophysiology, 38*(2), 254–266.

Rauh, R., Burkert, M., Siepmann, M., & Mueck-Weymann, M. (2006). Acute effects of caffeine on heart rate variability in habitual caffeine consumers. *Clinical Physiology and Functional Imaging, 26*(3), 163–166. https://doi.org/10.1111/j.1475-097X.2006.00663.x

Raven, J. (2003). Raven progressive matrices. In R. S. McCallum (Ed.), *Handbook of Nonverbal Assessment* (pp. 223–237). Springer US. https://doi.org/10.1007/978-1-4615-0153-4_11.

Reed, G. M., First, M. B., Kogan, C. S., Hyman, S. E., Gureje, O., Gaebel, W., … Tyrer, P. (2019). Innovations and changes in the ICD-11 classification of mental, behavioural and neurodevelopmental disorders. *World Psychiatry, 18*(1), 3–19.

Roos, L. E., Knight, E. L., Beauchamp, K. G., Berkman, E. T., Faraday, K., Hyslop, K., & Fisher, P. A. (2017). Acute stress impairs inhibitory control based on individual differences in parasympathetic nervous system activity. *Biological Psychology, 125*, 58–63. https://doi.org/10.1016/j.biopsycho.2017.03.004

Rosenman, R. H., & Friedman, M. (1974). Neurogenic factors in pathogenesis of coronary heart disease. *Medical Clinics of North America, 58*(2), 269–279.

Rushmer, R. F. (1989). Structure and function of the cardiovascular system. In *Handbook of Research Methods in Cardiovascular Behavioral Medicine* (pp. 5–22).

Sadri, S., Alizadeh, H., Pezehsk, S., & Asgari, M. (2022). Evaluation of the effectiveness of psychological interventions on callous-unemotional traits of children with conduct problems: A systematic review. *Journal of Child and Adolescent Mental Health, 9*(3), 30–46.

Sallis, J. F. (2000). Age-related decline in physical activity: A synthesis of human and animal studies. *Medicine and Science in Sports and Exercise, 32*(9), 1598–1600.

Scarpa, A., & Ollendick, T. H. (2003). Community violence exposure in a young adult sample: III. Psychophysiology and victimization interact to affect risk for aggression. *Journal of Community Psychology, 31*(4), 321–338.

Schmid, M., Kölch, M., Fegert, J., & Schmeck, K. (2011). Abschlussbericht für den Fachausschuss für die Modellversuche und das Bundesamt für. In *Justiz Zusammenfassung der wichtigsten Ergebnisse und Erkenntnisse des Modellversuchs Abklärung und Zielerreichung in stationären Maßnahmen (MAZ). In*. Basel: Universitäre Psychiatrische Kliniken.

Seker, S., Habersaat, S., Boonmann, C., Palix, J., Jenkel, N., Fischer, S., … Schmid, M. (2021). Substance-use disorders among child welfare and juvenile justice adolescents in residential care: The role of childhood adversities and impulsive behavior. *Children and Youth Services Review, 121*, Article 105825.

Simmonds, D. J., Hallquist, M. N., Asato, M., & Luna, B. (2014). Developmental stages and sex differences of white matter and behavioral development through adolescence: A longitudinal diffusion tensor imaging (DTI) study. *Neuroimage, 92*, 356–368.

Stadler, C., Grasmann, D., Fegert, J. M., Holtmann, M., Poustka, F., & Schmeck, K. (2008). Heart rate and treatment effect in children with disruptive behavior disorders. *Child Psychiatry and Human Development, 39*, 299–309.

Sterling, P., & Eyer, J. (1988). Allostasis: A new paradigm to explain arousal pathology. In S. Fisher, & J. Reason (Eds.), *Handbook of Life Stress, Cognition and Health* (pp. 629–649). New York: J. Wiley and Sons.

Suls, J., & Wan, C. K. (1993). The relationship between trait hostility and cardiovascular reactivity: A quantitative review and analysis. *Psychophysiology, 30*(6), 615–626.

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews, 33*(2), 81–88.

Tomlinson, R. C., Hyde, L. W., Dotterer, H. L., Klump, K. L., & Burt, S. A. (2022). Parenting moderates the etiology of callous-unemotional traits in middle childhood. *Journal of Child Psychology and Psychiatry, 63*(8), 912–920.

Urben, S., Habersaat, S., Palix, J., Fegert, J. M., Schmeck, K., Bürgin, D., … Schmid, M. (2022). Examination of the importance of anger/irritability and limited prosocial emotion/callous-unemotional traits to understand externalizing symptoms and adjustment problems in adolescence: A 10-year longitudinal study. *Frontiers in Psychiatry, 13*, Article 939603.

Verrier, R. L., & Tan, A. (2009). Heart rate, autonomic markers, and cardiac mortality. *Heart Rhythm, 6*(11), S68–S75.

Viding, E., & McCrory, E. J. (2018). Understanding the development of psychopathy: Progress and challenges. *Psychological Medicine, 48*(4), 566–577.

Wallis, L. A., Healy, M., Undy, M. B., & Maconochie, I. (2005). Age related reference ranges for respiration rate and heart rate from 4 to 16 years. *Archives of Disease in Childhood, 90*(11), 1117–1121. https://doi.org/10.1136/adc.2004.068718

de Wied, M., van Boxtel, A., 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.

Zuckerman, M. (2014). *Sensation Seeking: Beyond the Optimal Level of Arousal* (Routledge ed.). Psychology Press.

Zuckerman, M., Buchsbaum, M. S., & Murphy, D. L. (1980). Sensation seeking and its biological correlates. *Psychological Bulletin, 88*(1), 187–214. https://doi.org/10.1037/0033-2909.88.1.187

Zuckerman, M., Eysenck, S., & Eysenck, H. J. (1978). Sensation seeking in England and America: Cross-cultural, age, and sex comparisons. *Journal of Consulting and Clinical Psychology, 46*(1), 139–149. https://doi.org/10.1037//0022-006x.46.1.139