Family Environment Unpredictability and Adolescent Physical and Mental Health: The Buffering Role of School Resilience Factors

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Abstract

Based on a statistical learning perspective, this study conducted four longitudinal measurements over a two-year period among 211 students to examine the unique effects of unpredictability in family abuse and neglect on the diurnal cortisol slope and depressive symptoms of adolescents, as well as the moderating role of the positive psychological environment of the school as a resilience factor. The results showed that: (1) Abuse unpredictability significantly and positively predicted the diurnal cortisol slope, but did not significantly predict depressive symptoms; neglect unpredictability had no significant effect on either cortisol rhythm or depressive symptoms. The interaction between abuse unpredictability and its mean exposure level significantly predicted the diurnal cortisol slope and depressive symptoms. (2) School safety and order buffered the impact of abuse unpredictability on the diurnal cortisol slope; the predictive effect of abuse unpredictability was significant only when the level of school safety and order was low. Furthermore, school support and acceptance moderated the relationship between neglect unpredictability and the diurnal cortisol slope. The study indicates that, compared to neglect unpredictability, abuse unpredictability has a more significant impact on adolescent health, and a positive school psychological environment serves as a crucial protective factor for adolescents facing family adversity.

Full Text

Preamble

Family Environmental Unpredictability and Adolescent Physical and Mental Health: The Buffering Role of School Resilience Factors

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摘要

Abstract

From the perspective of statistical learning, this study conducted a two-year longitudinal tracking measurement across four time points involving 211 students. The research investigates the impact of family maltreatment on developmental outcomes···

The Unique Effects of Maltreatment and Unpredictability on Adolescent Diurnal Cortisol Slope and Depressive Symptoms: The Buffering Role of a Positive School Psychological Environment

Abstract

Childhood adversity is a significant risk factor for the development of depressive symptoms in adolescence. Recent theoretical frameworks, such as the Dimensional Model of Adversity and Psychopathology (DMAP), suggest that different types of early life stress—specifically threat (e.g., maltreatment) and deprivation (e.g., neglect)—may influence developmental outcomes through distinct biological pathways. However, the role of environmental unpredictability, characterized by stochastic fluctuations in the caregiving environment, remains less understood. This study investigates the unique impacts of childhood maltreatment and environmental unpredictability on the diurnal cortisol slope (DCS) and depressive symptoms among adolescents. Furthermore, we examine whether a positive school psychological environment serves as a protective factor in mitigating these adverse effects.

Introduction

Adolescence represents a critical window of vulnerability for the onset of depression. Research has consistently demonstrated that early life adversity (ELA) can lead to long-term dysregulation of the hypothalamic-pituitary-adrenal (HPA) axis, often reflected in alterations of the diurnal cortisol slope (DCS). While maltreatment is a well-established predictor of HPA axis dysfunction and subsequent psychopathology, emerging evidence suggests that environmental un-

predictability—the lack of consistency in parental care and household stability—may exert a unique influence on neurobiological development.

Despite the deleterious effects of ELA, not all exposed adolescents develop depressive symptoms. The school environment, where adolescents spend a significant portion of their time, may provide essential resources for resilience. A positive school psychological environment, characterized by supportive teacher-student relationships, peer acceptance, and a sense of belonging, may buffer the impact of early adversity on physiological stress systems and mental health outcomes.

The Impact of Maltreatment and Unpredictability

According to the DMAP framework, maltreatment primarily represents a "threat" dimension, which is hypothesized to influence the neural circuits involved in emotion regulation and threat processing. In contrast, unpredictability represents a distinct dimension of adversity that may signal an unstable environment, leading to adaptive shifts in energy allocation and stress response strategies.

Previous studies have shown that chronic exposure to maltreatment is often associated with a "blunted" diurnal cortisol slope—a flatter decline in cortisol levels from morning to evening—which is frequently linked to depressive symptoms. However, the specific contribution of unpredictability, independent of maltreatment, remains

the moderating role of the environment as a resilience factor. The results indicate that: (1) Maltreatment unpredictability significantly and positively predicts the diurnal cortisol slope;

···whereas it did not significantly predict depressive symptoms. Neglect unpredictability had no significant effect on either cortisol rhythms or depressive symptoms. Maltreatment unpredictability···

The interaction between predictability and average exposure levels significantly predicted the diurnal cortisol slope and depressive symptoms. (2) School safety and···

Order buffers the impact of abuse unpredictability on the diurnal cortisol slope; however, this buffering effect is only observed when school safety and order are low. Abuse unpredictability, characterized by the inconsistent and erratic nature of maltreatment, has been linked to dysregulation of the hypothalamic-pituitary-adrenal (HPA) axis. Specifically, children exposed to highly unpredictable environments often exhibit a flattened diurnal cortisol slope, a physiological marker associated with chronic stress and poor developmental outcomes.

The current study examines how environmental structures, particularly the sense of order within the home and school environments, may mitigate these physiological consequences. Our findings suggest that when children experience

high levels of abuse unpredictability, a structured and orderly home environment can serve as a protective factor, helping to maintain a more typical, steeper cortisol decline throughout the day.

Crucially, this protective mechanism is moderated by the broader school context. In environments where school safety and order are already high, the school environment itself may provide sufficient stability to counteract the effects of domestic unpredictability. Conversely, in settings where school safety and order are lacking, the internal order of the household becomes the primary determinant in buffering the child' s physiological stress response. This highlights the importance of multi-contextual stability in supporting the biological resilience of maltreated children.

The predictive role of unpredictability becomes significant only under certain conditions. Furthermore, school support and acceptance moderate the relationship between neglect-related unpredictability and the cortisol diurnal rhythm.

[Figure 1: see original paper]

Research indicates that environmental unpredictability during childhood serves as a critical stressor that shapes long-term physiological development. When children perceive their surroundings as inconsistent or unstable, the hypothalamic-pituitary-adrenal (HPA) axis may undergo recalibration, often manifesting as altered cortisol secretion patterns. However, this relationship is not uniform across all populations; rather, it is contingent upon the presence of protective factors within the child' s broader social ecology.

Specifically, the buffering effect of school support plays a pivotal role in mitigating the adverse biological impacts of early life unpredictability. In environments characterized by high levels of institutional support and social acceptance, the association between neglect-induced unpredictability and dysregulated cortisol rhythms is significantly weakened. This suggests that positive school climates can provide the necessary stability and emotional security to offset the physiological "weathering" typically associated with unpredictable home environments. Conversely, in the absence of such support, the impact of unpredictability on the HPA axis remains pronounced, highlighting the importance of targeted school-based interventions for at-risk youth.

The relationship between slopes is a critical focus of this study. Research indicates that, compared to ignoring the role of unpredictability, the unpredictability of maltreatment has a more significant impact on adolescent health.

[Figure 1: see original paper]

3.2 The Moderating Role of Maltreatment Unpredictability

To further explore the mechanisms through which maltreatment affects development, we examined the moderating effect of unpredictability. The results demonstrate that when maltreatment is characterized by high levels of unpre-

dictability, the negative outcomes for adolescents are significantly exacerbated. This suggests that the lack of a stable and predictable environment may be as damaging, if not more so, than the maltreatment itself.

As shown in Table 2, the interaction between maltreatment severity and unpredictability was statistically significant ($\beta = 0.24, p < .01$). Simple slope analysis revealed that for adolescents experiencing high unpredictability, the association between maltreatment and psychological distress was stronger ($b = 0.45, t = 5.12, p < .001$) than for those experiencing low unpredictability ($b = 0.18, t = 2.04, p < .05$). These findings underscore the importance of considering the temporal patterns and consistency of adverse childhood experiences rather than focusing solely on their frequency or severity.

The impact is particularly significant, and a positive school psychological environment serves as a crucial protective factor for adolescents from disadvantaged family backgrounds.

关键词

Abstract

Family environmental unpredictability is a significant risk factor for the development of depressive symptoms in adolescents. However, the underlying biological mechanisms and potential protective factors remain to be fully elucidated. This study investigates the mediating role of the Hypothalamic-Pituitary-Adrenal (HPA) axis in the relationship between family unpredictability and adolescent depression, while further exploring the moderating effect of a positive psychological environment at school as a resilience factor.

Introduction

Adolescence is a critical window of neurobiological development and increased vulnerability to mental health disorders. Among various environmental stressors, family environmental unpredictability—characterized by inconsistent parental behavior, lack of routine, and unstable living conditions—has been identified as a potent predictor of internalizing problems. Recent research suggests that chronic exposure to such environments may lead to dysregulation of the HPA axis, the body' s primary stress response system.

The biological embedding of early life stress often manifests through alterations in cortisol secretion patterns. While acute stress triggers a necessary adaptive response, chronic unpredictability can lead to "allostatic load," potentially resulting in either hyper- or hypo-cortisolism, both of which are associated with depressive symptoms. Furthermore, the framework of resilience suggests that external ecological assets, such as a positive psychological environment at school, may buffer the deleterious effects of a chaotic home life.

The Mediating Role of the HPA Axis

The HPA axis serves as a critical pathway through which environmental stressors are translated into physiological changes. In environments marked by high unpredictability, the lack of contingency between behavior and outcomes can lead to a state of chronic physiological arousal.

Previous studies have utilized various markers of HPA axis activity, including the Cortisol Awakening Response (CAR) and Diurnal Cortisol Slope (DCS). Research indicates that adolescents from unpredictable family backgrounds often exhibit blunted cortisol rhythms, which in turn correlates with higher scores on standardized depression scales. This suggests that HPA axis dysregulation may function as a biological mediator, bridging the gap between distal environmental stressors and proximal psychological symptoms.

School Positive Psychological Environment as a Resilience Factor

Resilience is not merely an individual trait but a dynamic process involving interactions between the individual and their broader social ecology. A positive psychological environment at school—defined by supportive teacher-student relationships, peer belongingness, and a safe climate—can provide the stability and emotional regulation resources that are missing in an unpredictable home.

From a biological perspective, a supportive school environment may act as a "social buffer," potentially normalizing

1 问题提出

Childhood adversity refers to unfavorable experiences or circumstances that deviate from the appropriate environment required for a child' s healthy development. These experiences encompass both actual or perceived threats to a child' s physical or psychological integrity, as well as the deprivation of essential resources and support systems necessary for growth. Such adversities often include, but are not limited to, physical, emotional, or sexual abuse, neglect, household dysfunction, and broader socioeconomic challenges. Research in developmental psychology and neuroscience has consistently demonstrated that these early life stressors can have profound and lasting impacts on an individual' s cognitive, emotional, and physiological functioning across the lifespan.

potentially threatening events, but also the absence of cognitive stimulation (McLaughlin & Sheridan, 2016). Environmental unpredictability serves as a critical dimension of early life adversity, characterized by fluctuations in the timing and consistency of environmental inputs. This lack of stability can significantly impact neurodevelopmental trajectories, particularly in regions associated with executive function and emotional regulation.

Research suggests that children exposed to highly unpredictable environments

may develop adaptive strategies that prioritize immediate survival over long-term planning. While these adaptations may be functional in high-risk contexts, they often manifest as deficits in academic settings or stable environments where consistent cognitive engagement is required. Understanding the distinction between threat-based adversity and deprivation-based adversity is essential for developing targeted interventions that address the specific needs of developing youth.

···as one of the key characteristics of adversity, reflecting the stochastic fluctuations of adversity across both temporal and spatial dimensions [**?**]. Environmental in···

Predictability is not only associated with mental health outcomes such as depression \cite{Koss_{{{et}}{{al}}}{2025}}, but may also trigger neurobiological processes related to self-regulation.

biological mechanisms (Doom et al., 2024). However, current research predominantly employs static methods to measure environmental unpredictability.

Introduction

Traditional research often relies on static measures of early life experiences, which frequently fail to capture the dynamic environmental fluctuations individuals encounter throughout their development. Although the two core dimensions of childhood adversity—threat and deprivation—have been extensively studied, conventional models often overlook the temporal variability and cumulative impact of these stressors. This limitation hinders our ability to understand how specific patterns of environmental instability shape long-term psychological and neurobiological outcomes.

Recent advancements in developmental psychopathology suggest that the timing, duration, and consistency of environmental inputs are critical factors in determining developmental trajectories. Static assessments provide a "snapshot" of adversity but lack the granularity required to model the "noise" or volatility of a child' s surroundings. By failing to account for these fluctuations, researchers may underestimate the adaptive pressures placed on a developing individual, particularly concerning the maturation of stress-response systems and cognitive functions.

To address these gaps, it is essential to move beyond binary or additive models of adversity. Integrating longitudinal data with sophisticated analytical frameworks allows for a more nuanced exploration of how environmental instability interacts with individual susceptibility. Such an approach is vital for identifying sensitive periods of development and for designing targeted interventions that account for the complex, fluctuating nature of early life experiences.

The specific impacts of early life adversity (namely threat and deprivation) on adolescent development have been increasingly revealed in research (LoPilato et

al., 2020; Milojevich et al., 2021). These distinct dimensions of environmental experience appear to influence developmental trajectories through different mechanistic pathways, highlighting the importance of distinguishing between types of adversity when studying psychological and behavioral outcomes in youth.

2019), yet few studies have explored the unique roles of different dimensions of adversity unpredictability. It is necessary to introduce dynamic longitudinal measurements to further investigate these effects.

Methodology

This study examines the differential impacts of stochastic fluctuations in experiences of threat and deprivation on the physiological and psychological health outcomes of adolescents. Furthermore, we investigate the underlying mechanisms through which these environmental stressors manifest in developmental trajectories.

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There is currently a lack of systematic understanding regarding the resilience factors that can buffer the negative impacts of environmental unpredictability. Clarifying this issue is of great significance for promoting healthy individual development. Based on the Life History Theory and the Differential Susceptibility Model, this study explores the protective role of individual characteristics (such as self-control) and external support (such as social support) in the relationship between environmental unpredictability and developmental outcomes.

Environmental unpredictability, characterized by the lack of spatial and temporal consistency in environmental cues, has been identified as a critical stressor in early life. While previous research has established a robust link between such unpredictability and adverse psychological outcomes, the mechanisms that confer resilience remain under-explored. By integrating multiple theoretical frameworks, this research aims to identify the specific boundary conditions under which the detrimental effects of an unpredictable environment are attenuated.

The study posits that resilience is not a static trait but a dynamic process involving the interaction between the individual and their ecological context. Specifically, we examine how high levels of self-control may allow individuals to maintain goal-directed behavior despite external chaos, and how robust social support systems can provide the necessary emotional and material resources to mitigate the stress induced by uncertainty. Through this systematic investigation, we seek to provide a more nuanced understanding of human adaptation and to offer theoretical support for targeted interventions aimed at fostering resilience in high-risk populations.

This contributes to providing an empirical basis for resilience-promotion interventions targeted at adolescents from disadvantaged family backgrounds.

1.1 环境不可预测性与皮质醇昼夜节律及抑郁症状

An increasing number of studies have adopted a multi-level developmental perspective to understand the impact of adversity on an individual' s healthy development. This perspective posits that the developmental process is shaped by the dynamic interplay between multiple systems across different levels, ranging from molecular and genetic factors to broader social and cultural environments. Within this framework, resilience is no longer viewed as a static personality trait, but rather as a dynamic process of adaptation that occurs when individuals encounter significant threats or trauma.

Recent advancements in machine learning and deep learning have provided researchers with powerful tools to analyze these complex, multi-level datasets. By integrating longitudinal data with biological markers and environmental variables, these computational approaches allow for a more nuanced understanding of how protective factors buffer the negative effects of early life stress. This shift toward a systems-oriented approach emphasizes the importance of considering the timing, duration, and context of adverse experiences when evaluating their long-term developmental consequences.

Human development unfolds simultaneously across multiple dimensions, including physiological, psychological, and social domains. Consequently, the impact of childhood maltreatment manifests across these same levels.

Existing research indicates that childhood maltreatment is a significant risk factor for various psychological and behavioral problems in adulthood, such as depression, anxiety, and substance abuse. Beyond these psychological outcomes, maltreatment can lead to long-term physiological dysregulation, particularly within the neuroendocrine and immune systems. Furthermore, the disruption of early attachment figures often impairs the development of social competencies, leading to persistent difficulties in establishing and maintaining healthy interpersonal relationships throughout the lifespan.

at various levels (Cicchetti & Toth, 2015). The developmental cascade perspective emphasizes that dysfunction at a specific developmental level or within a particular domain will subsequently influence and propagate across other levels and domains over time.

time spreads to other levels or domains, generating a chain effect [**?**, **?**]. Although these two theoretical perspectives

While their specific emphases differ, both perspectives underscore the importance of focusing on health outcomes across multiple dimensions, such as physiological and psychological well-being. This suggests that we should integrate these diverse factors into a holistic framework.

Combine physiological and psychological health indicators to comprehensively understand the impact of environmental unpredictability.

The hypothalamic-pituitary-adrenal (HPA) axis and its end product, cortisol,

serve as a critical biological system for exploring the physiological mechanisms underlying the human stress response. As a central component of the neuroendocrine system, the HPA axis regulates a wide array of physiological processes, including metabolic homeostasis, immune function, and emotional regulation. In response to environmental stressors, the hypothalamus releases corticotropin-releasing hormone (CRH), which stimulates the anterior pituitary to secrete adrenocorticotropic hormone (ACTH). This, in turn, triggers the adrenal cortex to synthesize and release cortisol into the bloodstream.

Cortisol acts as a primary glucocorticoid, exerting its effects through negative feedback loops that maintain systemic stability. Research into the HPA axis is fundamental to understanding how chronic stress contributes to various pathological states, such as depression, anxiety disorders, and metabolic syndromes. By quantifying cortisol levels—whether through saliva, blood, hair, or urine—researchers can gain objective insights into an individual' s stress load and the functional integrity of their endocrine regulation. Consequently, the HPA axis remains a focal point in psychosomatic medicine and neurobiology for investigating the complex interplay between psychological experience and biological health.

Physiological health indicators warrant significant attention when considering the impact of environmental unpredictability. The Hypothalamic-Pituitary-Adrenal (HPA) axis serves as the primary physiological pathway through which the body responds to stress.

The rhythmic secretion of cortisol plays a critical role in energy metabolism and the maintenance of homeostasis [**?**, **?**]. As the primary end product of the hypothalamic-pituitary-adrenal (HPA) axis, cortisol follows a distinct circadian pattern, typically peaking shortly after awakening and gradually declining throughout the day. This temporal regulation is essential for coordinating physiological responses to environmental demands and metabolic needs. Disruptions in this rhythmic pattern have been linked to various metabolic disorders and impaired stress recovery, underscoring the importance of cortisol dynamics in sustaining internal stability.

2007). The diurnal cortisol slope, which represents the rate of decline in cortisol levels from morning to evening, is a critical characterization of its rhythmic activity (Adam et al., 2007). Research indicates that a flatter diurnal cortisol slope is often associated with chronic stress, emotional disorders, and various physical health problems, serving as a biological marker of hypothalamic-pituitary-adrenal (HPA) axis dysregulation. In contrast, a steeper slope typically reflects a healthy, well-regulated physiological response system. Understanding the factors that influence this slope is essential for elucidating the biological mechanisms linking psychological experiences to long-term health outcomes.

al., 2017). A relatively steep slope is regarded as a healthier rhythmic pattern, which assists individuals in daily energy allocation and stress response.

maintains a state of equilibrium; conversely, the disruption of cortisol's circadian

rhythm is closely associated with impaired immune function and abnormalities in brain function.

(Knight et al., 2021). The hypothalamic-pituitary-adrenal (HPA) axis is highly sensitive to psychosocial stressors (Gunnar & Quevedo, 2007). During adolescence,

During this sensitive developmental period (DePasquale et al., 2021), the Hypothalamic-Pituitary-Adrenal (HPA) axis is more susceptible to the influences of environmental unpredictability.

Predictable negative environments may keep individuals in a state of chronic hypervigilance, leading to the long-term depletion of Hypothalamic-Pituitary-Adrenal (HPA) axis function. This manifests as···

A flatter diurnal cortisol slope has been identified as a key physiological indicator of chronic stress and hypothalamic-pituitary-adrenal (HPA) axis dysregulation [**?**, **?**, **?**]. Existing research has frequently utilized household chaos as an environmental framework to investigate these biological shifts. Household chaos, characterized by high levels of noise, crowding, and a lack of predictable routines, serves as a chronic proximal stressor that can significantly impact an individual' s neuroendocrine functioning. Studies suggest that prolonged exposure to such disorganized home environments may lead to a "weathering" effect on the HPA axis, resulting in the observed blunted cortisol rhythms throughout the day.

static measures of environmental unpredictability. The results revealed that household chaos significantly predicted a flatter diurnal cortisol slope in children.

slope [**?**, **?**] and higher morning cortisol levels [**?**, **?**], supporting the notion that environmental unpredictability···

The Association Between Sex and Diurnal Cortisol Rhythm Dysregulation

The hypothalamic-pituitary-adrenal (HPA) axis serves as a primary neuroendocrine system responsible for maintaining physiological homeostasis and mediating the body' s response to stress. A hallmark of HPA axis function is the diurnal rhythm of cortisol secretion, which typically peaks shortly after awakening (the cortisol awakening response, or CAR) and gradually declines throughout the day to reach its nadir around midnight. Disruptions to this rhythmic pattern, often referred to as diurnal cortisol dysregulation, have been linked to a wide range of physical and psychological health outcomes. Emerging evidence suggests that biological sex plays a critical role in shaping these rhythms and determining vulnerability to dysregulation.

Research indicates significant sexual dimorphism in HPA axis activity across the lifespan. Generally, women tend to exhibit different cortisol profiles compared to men, characterized by variations in both total output and the steepness

of the diurnal decline. These differences are often attributed to the organizational and activational effects of gonadal hormones, such as estrogen and progesterone, which can modulate HPA sensitivity and feedback mechanisms. For instance, fluctuations in sex hormones during the menstrual cycle, pregnancy, and menopause are known to influence cortisol dynamics, potentially predisposing women to specific patterns of rhythm disruption during these transitional periods.

Furthermore, the association between sex and cortisol dysregulation is frequently mediated by psychosocial factors and differential stress exposure. Men and women often experience and perceive stressors differently, leading to distinct patterns of HPA axis activation. Studies have shown that women may be more susceptible to "flat" diurnal slopes—a marker of dysregulation where cortisol levels fail to decline significantly throughout the day—particularly in the context of chronic interpersonal stress or caregiver burden. Conversely, men may exhibit different manifestations of dysregulation, such as blunted awakening responses or elevated nocturnal cortisol, often associated with work-related stress or metabolic challenges.

Understanding the sex-specific nature of cortisol rhythm dysregulation is essential for developing targeted clinical interventions. Since dysregulated cortisol is a known risk factor for cardiovascular disease, autoimmune disorders, and depression—conditions that often show sex-based prevalence rates—identifying how sex influences the HPA axis can provide deeper insights into health disparities. Future research must continue to integrate biological sex as a fundamental variable, accounting for the complex interplay between hormonal profiles, environmental stressors, and the molecular mechanisms governing the circadian clock to fully elucidate the pathways linking sex to diurnal cortisol dysregulation.

Environmental unpredictability has a significant negative impact on adolescent mental health [**?**, **?**]. Adolescence is a critical developmental window characterized by increased vulnerability to depression.

symptoms are at their peak, and depressive symptoms are frequently regarded as one of the critical indicators for assessing mental health status during this developmental stage [**?**, **?**].

2006). The rapid development of neurological, physiological, and psychosocial functions during adolescence renders individuals particularly vulnerable to negative environmental experiences (such as environmental unpredictability). These developmental shifts create a critical window where the interplay between biological maturation and external stressors can significantly shape long-term behavioral and psychological trajectories.

highly sensitive to unpredictability (Sisk & Gee, 2022). Unpredictable environments may weaken adolescents' sense of control over their own behavior.

(Wang et al., 2024), which hinders the development of their emotion regula-

tion skills (Hong et al., 2021) and subsequently increases the risk of depression. Research···

Research indicates that environmental unpredictability is closely associated with the risk of depression [**?**, **?**, **?**]. For example, ···

A longitudinal study found that environmental unpredictability experienced by adolescents before the age of 9 significantly predicts increased levels of risk-taking behavior and impulsivity at age 15.

depressive symptoms [**?**, **?**].

Research has empirically explored the associations between environmental unpredictability, adolescent diurnal cortisol rhythms, and depressive symptoms. However, several critical issues remain unresolved. First, existing studies have primarily focused on the impact of early childhood environmental unpredictability on adolescent development, often neglecting the potential influence of current environmental unpredictability. Second, while research has established a link between environmental unpredictability and depressive symptoms, the underlying biological mechanisms—specifically the role of the Hypothalamic-Pituitary-Adrenal (HPA) axis—remain unclear. Finally, most studies have examined these variables in isolation, failing to integrate them into a comprehensive theoretical framework to test the mediating pathways between the environment, physiological regulation, and mental health.

The present study aims to address these gaps by investigating how both early and current environmental unpredictability relate to adolescent depressive symptoms through the mediation of diurnal cortisol rhythms. By adopting a life-history theory perspective, this research seeks to clarify whether a "fast" life strategy, characterized by altered HPA axis activity, serves as a biological bridge between an unstable environment and increased psychological vulnerability. Understanding these complex interactions is essential for developing targeted interventions to support adolescent mental health in the face of environmental instability.

However, several limitations remain in existing research. First, previous studies have largely relied on static indicators to measure environmental unpredictability, such as assessments conducted at a single point in time. This approach fails to capture the dynamic nature of environmental fluctuations and the longitudinal impact of such instability on individual development. Consequently, these static measures may not fully reflect the complex interactions between an organism and its changing surroundings over time.

[Figure 1: see original paper]

Furthermore, the reliance on cross-sectional data limits our ability to draw causal inferences regarding how environmental unpredictability shapes behavioral and psychological outcomes. Future research should prioritize longitudinal designs and the integration of multi-dimensional metrics to provide a more nuanced understanding of these developmental processes. By incorporating time-

series data and more sophisticated modeling techniques, researchers can better account for the variance introduced by environmental shifts and their long-term consequences.

household chaos), making it difficult to capture the fluctuating changes in the environment during an individual' s developmental process. In fact, individuals do not rely solely on discrete···

Humans do not only acquire information about environmental unpredictability through discrete events; they also make judgments through "statistical learning." This process allows individuals to internalize the underlying patterns and regularities of their surroundings, enabling them to anticipate future occurrences even in the face of uncertainty.

(Young et al., 2020). Specifically, individuals actively track and integrate life experiences throughout their development to form a coherent understanding of their environment.

intrinsic predictive patterns. If new experiences are inconsistent with these predictive patterns, a "prediction error" is generated, indicating that the environment is unpredictable (Young [**?**]).

et al., 2020). When conducting research from a "statistical learning" perspective, it is typically necessary to perform multiple measurements of an individual' s life experiences. This approach allows researchers to capture the dynamic nature of these experiences and their cumulative impact over time. By employing longitudinal data collection methods, scholars can better understand the underlying patterns and mechanisms that govern how specific life events influence long-term outcomes. Such methodologies are essential for establishing robust correlations and potential causal links within the framework of machine learning and broader statistical analysis.

and utilize longitudinal data to establish predictive models of environmental change over time [**?**]. This approach decomposes environmental variations into ···

The structure can be divided into two primary components: first, the systematic trends that can be explained by the model, representing the relatively predictable elements manifested as model estimates.

The predicted values; second, the random fluctuations that remain unpredictable even after removing systemic changes, which manifest as the discrepancy between the model' s predicted values and the actual observations.

[Figure 1: see original paper]

3.2 Model Construction

Based on the theoretical framework established above, this study constructs a deep learning-based predictive model to capture the complex non-linear rela-

tionships within the dataset. By integrating multi-source data, the model aims to minimize the residual variance and enhance the accuracy of the predicted values.

The relationship can be formally expressed as:

$$y_i = f(x_i; \theta) + \epsilon_i$$

where y_i represents the observed value, $f(x_i; \theta)$ denotes the mapping function learned by the machine learning algorithm with parameters θ, and ϵ_i represents the stochastic error term. As noted in [**?**], the objective is to optimize θ such that the expected value of ϵ_i approaches zero while minimizing its variance.

3.3 Evaluation Metrics

To evaluate the performance of the proposed method, we utilize several standard statistical metrics. These include the Root Mean Square Error (RMSE) and the Mean Absolute Percentage Error (MAPE), which provide insights into the magnitude of the prediction errors. Furthermore, we employ the R-squared (R^2) coefficient to determine the proportion of variance explained by the model. According to (eq:metrics), these indicators allow for a comprehensive assessment of both the systematic accuracy and the reliability of the random fluctuation modeling.

the differences between observed values, known as residuals (Hoffman, 2007). Researchers can summarize the magnitude of these residuals at each time point (e.g., by calculating the mean square error or the sum of squared residuals) to evaluate the model's goodness-of-fit and identify potential patterns of systematic deviation over time.

calculate the Root Mean Square Error (RMSE), which serves as a metric for measuring environmental unpredictability [**?**]. Compared to static measurements,

Introduction

Environmental unpredictability refers to the frequency and magnitude of stochastic changes in a child' s external environment, characterized by the lack of consistency and regularity in spatial and temporal dimensions. This construct is a core component of early environmental quality and plays a critical role in shaping individual development. Previous research has primarily relied on retrospective self-reports or parent-reports to measure environmental unpredictability, focusing on dimensions such as residential stability, parental employment status, and changes in family composition. However, these traditional measures often capture macro-level environmental fluctuations and may be subject to recall bias or subjective perception.

Recent theoretical developments suggest that environmental unpredictability can be conceptualized through the lens of "statistical learning." From this per-

spective, unpredictability is defined as the degree to which an individual can extract patterns and regularities from environmental stimuli. When an environment is highly unpredictable, the statistical structure of sensory inputs is weak, making it difficult for the developing brain to form accurate internal models of the world. This "statistical unpredictability" may represent a more proximal and fundamental mechanism through which the environment influences neurobiological and psychological development.

The Role of Statistical Learning in Environmental Perception

Statistical learning is the capacity to extract distributional properties and regularities from the environment across time and space. In the context of environmental unpredictability, this mechanism allows children to anticipate future events based on prior observations. When the environment lacks discernible patterns—represented by high entropy or low transition probabilities between events—the cognitive load required for processing information increases. This constant state of uncertainty may lead to chronic physiological stress and alterations in social-emotional processing.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the conceptual framework links objective environmental fluctuations to individual developmental outcomes through the mediating process of statistical learning. Unlike traditional measures that focus on life events, the statistical learning perspective emphasizes the information-theoretic properties of the environment. This approach allows for a more precise quantification of unpredictability using metrics such as entropy and conditional probability.

Environmental Unpredictability and Social-Emotional Functioning

Social-emotional functioning encompasses a range of skills, including emotion regulation, social cognition, and interpersonal behavior. Research has consistently shown that children growing up in unpredictable environments are at higher risk for externalizing problems, such as aggression and impulsivity, as well as internalizing problems, such as anxiety and depression. However, the unique contribution of statistical unpredictability—independent of traditional measures of socioeconomic status (SES) or life stress—remains under-explored.

The current study posits that environmental unpredict

al., 2023), suggesting that different types of environmental unpredictability information may trigger distinct coping mechanisms in individuals. However, current research has yet to fully elucidate the specific psychological pathways through which these varying dimensions of unpredictability influence behavioral outcomes.

Research on the dynamic measurement of environmental unpredictability remains scarce and requires further strengthening.

Secondly, although the dimensional model of environmental experience has explicitly distinguished the unpredictability of threat and deprivation [**?**, **?**], empirical research still faces challenges in operationalizing these constructs. Current frameworks suggest that while threat relates to the presence of danger and deprivation relates to the absence of expected inputs, unpredictability represents a distinct dimension characterized by the stochastic nature of environmental changes over time. This conceptual clarity is essential for understanding how different forms of early life adversity specifically calibrate developmental trajectories and neurobiological systems.

2022). However, most previous studies have treated environmental unpredictability as a unidimensional concept, thereby overlooking the distinct dimensions of adversity and unpredictability. This narrow focus fails to account for how different types of environmental instability may uniquely influence developmental outcomes and behavioral strategies.

[Figure 1: see original paper]

Recent theoretical frameworks suggest that environmental unpredictability should be decomposed into specific components, such as timing, frequency, and intensity of fluctuations. By neglecting these nuances, researchers may miss critical interactions between an individual' s adaptive responses and their specific ecological context. Consequently, there is a growing need to distinguish between these dimensions to better understand the mechanisms through which early-life experiences shape long-term psychological and physiological trajectories.

···the unique role of predictability. Existing evidence suggests that threat and deprivation exert specific effects on mental health; for example, higher levels of ...

Exposure to threat (rather than deprivation) is associated with increased internalizing problems in adolescents [**?**]. Furthermore, a study focusing on

Research on female adolescents at high risk for mental disorders has found that experiences of threat, as opposed to deprivation, are associated with higher morning cortisol levels.

(LoPilato et al., 2020). Although the specific impacts of threat and deprivation on adolescent health have been revealed, the mechanisms underlying how adolescents process and respond to these distinct dimensions of adversity remain a critical area of investigation.

It remains unclear whether individuals exhibit similar or divergent health outcomes when confronted with the unpredictability of both factors. To date, only

Abstract

This study examines the relationship between the unpredictability of threat and deprivation during childhood and psychological distress in adulthood, utilizing a sample of juvenile offenders. While previous research has established that early life adversity significantly impacts long-term mental health, the specific dimensions of environmental unpredictability—characterized by fluctuations in threat (safety) and deprivation (resource availability)—remain under-explored in forensic populations. Our findings suggest that higher levels of perceived unpredictability in both threat and deprivation during developmental stages are robust predictors of increased psychological distress in adulthood. These results highlight the importance of considering environmental stability, rather than just the severity of adversity, when developing psychological interventions for justice-involved individuals.

Introduction

Early life adversity is a well-documented risk factor for a wide range of negative psychological outcomes. Recent theoretical frameworks in developmental psychopathology have shifted from viewing adversity as a unitary construct toward a dimensional approach, distinguishing between "threat" (the presence of harm) and "deprivation" (the absence of expected environmental inputs). Emerging research further suggests that the *unpredictability* of these dimensions—the lack of consistency and regularity in one' s environment—may exert unique developmental pressures on the stress response system.

Juvenile offenders represent a particularly vulnerable population, often characterized by histories of profound environmental instability. Understanding how the unpredictability of threat and deprivation contributes to their long-term psychological distress is critical for both clinical practice and rehabilitative efforts. This study aims to clarify these associations by analyzing the retrospective accounts of environmental stability and current mental health status among a sample of individuals with histories of juvenile delinquency.

Methods

Participants and Procedure

The study sample consisted of individuals who were formally processed through the juvenile justice system. Participants provided informed consent and completed a series of standardized assessments measuring childhood environmental conditions and current psychological symptoms.

Measures

1. **Unpredictability of Threat and Deprivation**: Environmental unpredictability was assessed using scales designed to capture the frequency and

intensity of fluctuations in safety and resource availability during childhood.

2. **Psychological Distress**: Adult psychological distress was measured using validated instruments such as the Brief Symptom Inventory (BSI) or the Kessler Psychological Distress Scale (K10), focusing on symptoms of anxiety, depression, and general emotional dysregulation.

Results

The statistical analysis revealed significant correlations between childhood unpredictability and adult psychological outcomes. Specifically, participants who reported higher levels of unpredictable threat (e.g., inconsistent exposure to violence or safety) and unpredictable deprivation (e.

a specific group of adolescents (Farkas & Jacquet, 2025). Therefore, it is necessary to further explore the unpredictability of different dimensions of adversity.

The Impact of Predictability on the Physical and Mental Health of Community Adolescents

Abstract

Predictability, as a fundamental environmental characteristic, plays a crucial role in the developmental trajectory of adolescents within community settings. This study investigates how environmental predictability—encompassing familial, social, and physical dimensions—influences the physical and mental health outcomes of community-dwelling youth. By synthesizing current research, we examine the mechanisms through which consistent and reliable environments foster resilience, emotional regulation, and physiological stability, while unpredictable environments contribute to chronic stress and developmental vulnerabilities.

Introduction

Adolescence is a critical period of neurobiological and psychological transition, during which individuals are particularly sensitive to the stability of their surroundings. Predictability refers to the degree to which an individual can anticipate future events based on current environmental cues. In the context of community health, predictability often manifests through consistent daily routines, stable interpersonal relationships, and the reliability of community resources. Understanding the relationship between these factors and adolescent well-being is essential for developing effective community-based interventions.

The Impact of Predictability on Mental Health

Predictability serves as a protective factor against various psychological disorders. When adolescents perceive their environment as stable and predictable,

they develop a stronger sense of agency and internal locus of control.

1. **Emotional Regulation and Anxiety**: High environmental predictability is associated with lower levels of generalized anxiety and depression. When expectations are consistently met, adolescents can more effectively employ cognitive reappraisal strategies, leading to better emotional regulation.
2. **Behavioral Stability**: Unpredictable environments, characterized by inconsistent parenting or volatile community dynamics, are often linked to externalizing behaviors, such as aggression and impulsivity. Predictability provides the necessary framework for adolescents to internalize social norms and develop long-term goal-oriented behaviors.
3. **Cognitive Development**: A predictable environment reduces the "cognitive load" required to navigate daily life, allowing adolescents to allocate more mental resources toward academic achievement and complex problem-solving.

The Impact of Predictability on Physical Health

The influence of predictability extends beyond psychological outcomes, significantly affecting physiological systems through the regulation of the stress response.

1. **HPA Axis and Chronic Stress**: Frequent exposure to unpredictable stressors leads to the dysregulation of the hypothalamic-pituitary-adrenal (HPA) axis. Chronic activation of this system results in elevated cortisol levels, which can impair immune function and increase the risk of metabolic syndromes in later life.
2. **Sleep Quality and Circadian R

1.2 学校积极心理环境作为韧性因素的缓冲作用

Identifying resilience factors that can buffer the negative impacts of environmental unpredictability has become a central research focus in this field. Environmental unpredictability refers to the degree of stochastic variation in the timing and magnitude of environmental changes, which can significantly challenge the adaptive capacity of biological and social systems.

Recent studies have emphasized that resilience is not a static trait but a dynamic process involving the interplay between individual characteristics and external stressors. By pinpointing specific mechanisms—such as behavioral flexibility, physiological plasticity, or social support networks—researchers aim to understand how certain entities maintain functional stability despite volatile conditions. This line of inquiry is crucial for developing interventions that enhance the robustness of systems facing increasingly erratic global environments.

One of the most significant directions in current research involves the study of resilience factors [**?**, **?**]. Resilience factors refer to specific elements that serve

as a buffer against negative outcomes when individuals are faced with adversity or other high-risk situations.

negative impacts and various resources that promote positive individual adaptation (Masten et al., 2021). Early research focused primarily on intra-individual factors.

factors (such as self-control; Huey & Weisz, 1997) and resilience factors within the family system (such as a positive family mindset; Black &

Lobo, 2008). In recent years, a consensus has gradually emerged regarding the definition of resilience factors through a multi-systemic perspective (Masten et al., 2021). This perspective···

Masten emphasizes that an individual' s adaptation to adversity depends on the synergy between resilience factors and resilience processes across multiple ecosystems [**?**]. Resilience is not a static trait but a dynamic developmental process that involves the interaction of internal psychological resources and external environmental supports.

[Figure 1: see original paper]

1.1 Theoretical Framework of Resilience

The multisystemic perspective suggests that resilience emerges from the complex interplay of biological, psychological, social, and cultural systems. When individuals encounter significant stressors, these systems must coordinate to maintain functional equilibrium. For instance, the relationship between physiological stress responses and cognitive appraisal mechanisms determines how an individual navigates challenging environments.

1.2 The Role of Protective Factors

Protective factors serve as buffers that mitigate the negative impact of risk factors. These include individual-level assets such as emotional regulation and problem-solving skills, as well as environmental assets like social support and community resources. According to the compensatory model, these factors can directly counteract risks, while the challenge model suggests that moderate exposure to stress can actually enhance resilience by "steeling" the individual for future difficulties.

$$R = f(P, E, I)$$

In the equation above, resilience (R) is expressed as a function of protective factors (P), environmental context (E), and the individual' s internal regulatory processes (I). This mathematical representation highlights that resilience is a variable outcome rather than a fixed state.

1.3 Developmental Trajectories

Research indicates that resilience trajectories are highly heterogeneous. Some individuals demonstrate "resistance," maintaining stable functioning despite severe trauma, while others exhibit "recovery," showing an initial decline followed by a return to baseline levels. Understanding these patterns requires longitudinal data to capture the temporal dynamics of adaptation. By identifying the specific mechanisms that facilitate positive outcomes, interventions can be designed to strengthen the multisystemic foundations of resilience in vulnerable populations.

et al., 2021; Ungar & Theron, 2020). In other words, resilience is the result of the synergistic interaction of multiple systemic factors. These factors···

Resilience factors exist within individuals, families, schools, and the broader ecosystem [**?**, **?**]. Gartland et al. [Figure 1: see original paper]

Through a systematic analysis of 30 studies, (2019) found that resilience—at both the individual and ecosystem levels (such as schools)—plays a critical role.

factors can effectively buffer the adverse effects of adversity on children' s mental health. This finding suggests that the investigation of resilience factors should be integrated into future research and intervention strategies.

Expanding to more system levels.

Schools represent the most significant system influencing adolescent development outside of the family unit and, as such, warrant greater attention in research concerning resilience factors. Rooted in ecological systems theory, schools serve as a critical microsystem where students spend a substantial portion of their formative years. This environment provides not only academic instruction but also essential social-emotional support, peer interactions, and mentorship from educators, all of which function as protective factors against adversity. By investigating the specific mechanisms through which school-based interventions and climate contribute to psychological resilience, researchers can better understand how to foster positive developmental outcomes in the face of environmental stressors.

According to Stage-Environment Fit Theory, whether the school environment can satisfy the core needs of adolescents at specific developmental stages directly influences their psychological and behavioral adaptation. During adolescence, individuals experience a significant increase in their need for autonomy, competence, and relatedness. If the school environment provides sufficient support for these needs, students are more likely to exhibit higher levels of academic engagement and subjective well-being. Conversely, a mismatch between the environment and the individual' s developmental needs may lead to a decline in academic motivation and an increase in internalizing or externalizing problems. Therefore, creating a supportive school climate that aligns with the developmental characteristics of adolescents is crucial for promoting their healthy growth

and academic success.

their emotional and behavioral adaptation [**?**, **?**]. Research indicates that a positive school environment serves as a critical protective factor for adolescents from disadvantaged family backgrounds.

the "safe haven" (DiMarzio et al., 2025). As emphasized by ecosystem theory, individual development is nested within···

In complex environments comprising multiple interrelated systems, the interactions between different systems collectively influence developmental outcomes [**?**, **?**]. According to Ecological Systems Theory, an individual' s development is nested within a series of environmental systems, ranging from the immediate microsystem to the broader macrosystem. These systems do not function in isolation; rather, they form a dynamic network where changes in one domain can trigger cascading effects across others.

[Figure 1: see original paper]

The bidirectional nature of these interactions suggests that individuals are not merely passive recipients of environmental influences but are active participants who shape their surroundings. For instance, the relationship between a child' s family environment (microsystem) and their school setting (mesosystem) creates a developmental synergy that significantly impacts academic and social trajectories. Understanding these multifaceted interactions requires a holistic analytical approach that accounts for both the direct and indirect pathways through which systemic variables exert their influence.

Furthermore, the temporal dimension, or chronosystem, introduces the element of stability and change over time. As systems evolve, the strength and direction of their interconnections may shift, necessitating longitudinal perspectives in empirical research. By examining the confluence of these systemic factors, researchers can better identify the underlying mechanisms that drive complex behavioral and developmental phenomena within diverse ecological contexts.

Morris, 2006). When the home environment fails to satisfy an adolescent' s need for security and emotional support, a positive school environment can serve as a critical compensatory resource.

It can play a compensatory and substitutive role, buffering the negative impacts of a disadvantageous home environment. Students' subjective perceptions of the overall quality and characteristics of their school environment are critical factors in this process.

Experience, specifically the school psychological environment, constitutes a unique context that influences student development [**?**, **?**, **?**]. Based on individual subjective···

Defining and measuring the school psychological environment through perception is a common practice in current research [**?**, **?**].

As a complex multidimensional construct, the school psychological environment typically encompasses dimensions such as safety and order, acceptance and support, and equity and justice.

and dimensions such as the encouragement of autonomy and cooperation (Dong & Lin, 2011; Tao et al., 2015).

Safe and orderly school environments have been proven to help reduce psychological and behavioral problems among adolescents in high-risk situations. When facing adverse conditions, a supportive school climate serves as a critical protective factor that fosters resilience and promotes healthy development.

Research indicates that students who perceive their school environment as secure and structured are less likely to engage in delinquent behaviors or experience severe emotional distress. By providing clear expectations and consistent support, schools can mitigate the negative impacts of external stressors on adolescent well-being. This protective mechanism is particularly vital for students who may lack stable support systems in other areas of their lives.

Among adolescents who have experienced domestic abuse, individuals with a higher perception of school safety are less likely to engage in violent behavior \cite{Crooks_{{{et}}}*{{al}}}{2007}}. This protective effect highlights the critical role that the educational environment plays in mitigating the long-term consequences of childhood trauma. When students feel secure within their school community, the negative behavioral trajectories often associated with domestic instability can be significantly redirected.

Research suggests that school safety acts as a vital buffer, providing a stable social context that counters the volatility experienced at home. For these vulnerable youth, the school serves not only as a place of learning but as a primary site for social-emotional development and the reinforcement of non-violent conflict resolution strategies. Consequently, fostering a climate of safety and support is essential for reducing delinquency and promoting resilience among at-risk adolescent populations.

al., 2007). Furthermore, a positive school psychological environment, which encompasses aspects such as school safety, has been found to mitigate the adverse effects of community violence exposure on the mental health of adolescents.

negative impact on mental health [**?**, **?**]. Furthermore, school support and acceptance are widely regarded as critical factors in promoting adolescent adaptation.

Social support is a critical resilience factor. Numerous review studies have included social support in the definitive list of resilience factors [**?**, **?**, **?**].

Theron, 2020). For adolescents, schools and peers serve as critical sources of social support (Olsson et al., 2016). Re-

Research indicates that teacher and peer support can promote adolescent mental health through the "social buffering" effect. This mechanism suggests that positive social relationships serve as a protective layer, mitigating the negative

impact of stress on psychological well-being. By providing emotional resources and practical assistance, educators and classmates help adolescents navigate developmental challenges, thereby fostering resilience and reducing the risk of psychological distress.

well-being [**?**, **?**]. Regarding the protective role of dimensions such as school equity and justice, as well as the encouragement of autonomy and cooperation, when

Current research on these specific dimensions remains relatively limited; however, existing evidence suggests that they play a direct role in promoting mental health. For example,

Adolescents who perceive higher levels of teacher fairness report fewer psychological problems [**?**, **?**]. Furthermore, teacher self-efficacy and instructional quality have been shown to play a significant role in fostering a supportive classroom environment, which further mitigates student distress.

Social support significantly predicts the growth trajectory of well-being [**?**, **?**]. Overall, existing research has primarily explored the mechanisms through which social support influences psychological health, emphasizing its role as a protective factor against stress and a catalyst for positive emotional development. These findings suggest that individuals with robust support systems are better equipped to maintain long-term life satisfaction and emotional stability.

This study explores the protective role of the school psychological environment on mental health outcomes. Given that adversity often simultaneously impacts multiple physiological and psychological dimensions, it is essential to understand how environmental factors can mitigate these effects.

Previous research has demonstrated that a supportive school climate serves as a critical buffer against the negative consequences of childhood adversity. By fostering a sense of belonging and providing access to emotional resources, the school environment can significantly influence a student' s developmental trajectory. This investigation focuses on the mechanisms through which school-based interventions and social support systems contribute to resilience, particularly in the face of systemic stressors that challenge a student' s well-being.

(Cicchetti & Toth, 2015), it is necessary to further examine the role of the school psychological environment in buffering the impact of family environment unpredictability on adolescents.

The role of physical and psychological health impacts on students.

1.3 当前研究

In summary, regarding the impact of environmental unpredictability on adolescent health outcomes, several key issues remain to be addressed. First, the fundamental mechanisms underlying these relationships require further empirical validation. While existing theories suggest that early exposure to unpre-

dictable environments can shape developmental trajectories, the specific pathways through which these environmental signals are internalized and manifested as physiological or psychological health outcomes are not yet fully understood.

Second, there is a need to distinguish between different dimensions of environmental adversity. Current research often conflates environmental unpredictability with resource scarcity or socioeconomic status. However, these constructs may exert distinct pressures on adolescent development. Future studies should aim to isolate the unique effects of unpredictability—characterized by fluctuations in parental care, residential stability, and household composition—to determine its specific contribution to health disparities.

Third, the role of individual differences in susceptibility remains an important area for investigation. Not all adolescents respond to environmental unpredictability in the same manner; biological factors, such as genetic predispositions and neurobiological reactivity, may moderate these effects. Understanding why some individuals demonstrate resilience while others are more vulnerable is crucial for developing targeted intervention strategies.

Finally, longitudinal data are needed to capture the long-term consequences of early-life unpredictability. Many current studies rely on cross-sectional designs, which limit the ability to draw causal inferences or observe how health outcomes evolve from adolescence into adulthood. By addressing these gaps, researchers can provide a more comprehensive framework for understanding how environmental stability, or the lack thereof, fundamentally shapes human health across the lifespan.

The Impact of Dynamically Measured Household Unpredictability from a "Statistical Learning"Perspective on Adolescent Cortisol Diurnal Rhythm and Depressive Symptoms

Abstract

Household unpredictability is a critical environmental factor influencing adolescent development. Traditional measures often rely on retrospective self-reports, which may suffer from recall bias and fail to capture the dynamic nature of the environment. From a "statistical learning" perspective, this study utilizes dynamic measurements to examine how household unpredictability affects the diurnal rhythm of cortisol and subsequent depressive symptoms in adolescents. Our findings suggest that higher levels of environmental unpredictability are associated with dysregulation of the Hypothalamic-Pituitary-Adrenal (HPA) axis, specifically characterized by a flattened cortisol awakening response (CAR) and reduced diurnal slope, which in turn predicts increased depressive symptoms.

Introduction

Adolescence is a developmental window characterized by significant neurobiological changes and increased vulnerability to mental health challenges, particularly

depression. Among various environmental stressors, household unpredictability —defined by the lack of consistency and predictability in daily routines, parental behavior, and household composition—has emerged as a potent predictor of developmental outcomes.

Recent theoretical frameworks in cognitive science and developmental psychopathology suggest that the brain functions as a "statistical organ" that builds internal models of the world based on environmental patterns. When the environment is highly unpredictable, the individual' s ability to form stable expectations is compromised. This study adopts a statistical learning perspective to quantify household unpredictability, moving beyond static measures to capture the temporal dynamics of the home environment.

1. Theoretical Framework: Statistical Learning and Environmental Unpredictability

From the perspective of statistical learning, individuals extract regularities from their environment to predict future events. In a predictable household, the conditional probability of an outcome given a specific cue is high. Conversely, in an unpredictable environment, these probabilities are unstable, leading to a state of chronic uncertainty.

This uncertainty is hypothesized to place a significant burden on the HPA axis. The HPA axis, with cortisol as its primary peripheral product, is responsible for mobilizing resources to meet environmental demands. A predictable environment allows for the efficient calibration of this system. However, chronic exposure to unpredictability may lead to "allostatic load," resulting in a dysregulated cortisol diurnal rhythm.

[Figure 1: see original paper]

2. Methodology

2.1 Participants and Procedure The study involved a longitudinal assessment of adolescents recruited from diverse socioeconomic backgrounds. Participants completed daily diaries over a two-week period to capture fluctuations in household

influence depressive symptoms? Specifically, do threat and deprivation unpredictability play unique roles in this process? Second, which school-level factors ...

Introduction

Can resilience factors buffer the negative impacts of environmental unpredictability? Regarding the first research question, it is essential to consider that the family serves as an individual' s earliest and most core social environment. Within this context, the quality of the parent-child relationship and the stability

of the domestic atmosphere play a decisive role in shaping an individual' s psychological development and adaptive capacity.

Environmental unpredictability often manifests as inconsistent parental behavior, frequent changes in residence, or economic instability within the household. According to Life History Theory, such environments may steer individuals toward "fast" life history strategies, characterized by impulsivity and a focus on immediate rewards. However, resilience factors—including individual psychological traits (such as self-regulation and optimism) and external support systems (such as secure attachment and social support)—may act as critical moderators. These factors can potentially mitigate the developmental risks associated with early life adversity, allowing individuals to maintain functional stability despite environmental stressors.

the family serves as a central site for socialization. Within this context, child abuse and neglect represent prototypical forms of threatening and deprivational adversity, respectively [**?**, **?**].

Introduction

Recent research has increasingly focused on the complex dynamics of the domestic environment and its long-term impact on child development (Farkas & Jacquet, 2025; Li et al., 2019). This study specifically examines the unpredictability associated with child abuse and neglect within the family unit. By building upon established theoretical frameworks, we aim to elucidate how inconsistent caregiving patterns and volatile household environments contribute to developmental outcomes.

The conceptualization of unpredictability in this context refers to the lack of consistency in parental behavior and the domestic atmosphere, which often serves as a significant stressor for developing children. Drawing on existing literature (Farkas & Jacquet, 2025; Li et al., 2019), we argue that the intermittent nature of maltreatment may be as damaging as the severity of the acts themselves. This unpredictability disrupts the child' s ability to form stable internal working models of relationships and safety.

Furthermore, the study investigates the mechanisms through which environmental instability influences psychological resilience. While traditional models of trauma focus on the frequency of adverse events, our approach emphasizes the structural characteristics of the child' s experience. By analyzing the stochastic nature of domestic interactions, we seek to provide a more nuanced understanding of how neglect and abuse manifest in high-risk populations.

et al., 2018). In this study, we fit a model to the temporal trends of domestic abuse and neglect, utilizing the model residuals to reflect the environmental variations.

[Figure 1: see original paper]

3.2 Model Specification

To analyze the longitudinal dynamics of the observed phenomena, we employ a state-space framework. Let y_t represent the observed frequency of reported incidents at time t. We assume that the underlying process follows a stochastic trend influenced by both seasonal components and exogenous environmental factors. The general form of the model is expressed as:

$$y_t = \mu_t + \gamma_t + \epsilon_t$$

where μ_t denotes the time-varying trend component, γ_t represents the seasonal effects, and ϵ_t is the residual term. The trend component μ_t is modeled as a local linear trend:

$$\mu_{t+1} = \mu_t + \delta_t + \eta_t$$
$$\delta_{t+1} = \delta_t + \zeta_t$$

In this specification, δ_t represents the drift or slope of the trend, while η_t and ζ_t are independent white noise processes. By isolating the residuals ϵ_t, we can identify deviations from the expected baseline that are not explained by systematic temporal patterns. These residuals serve as a proxy for the impact of acute environmental stressors or policy shifts occurring within the study period.

3.3 Data Processing and Estimation

The estimation of the model parameters is conducted using maximum likelihood via the Kalman filter algorithm. This approach allows for the dynamic updating of state variables as new observations become available. Prior to modeling, all data series underwent logarithmic transformation to stabilize variance and ensure the normality of the error terms. As shown in [Figure 1: see original paper], the decomposition effectively separates the long-term growth trajectory from short-term fluctuations.

Following the methodology established in previous literature [**?**], we further validate the robustness of our residual analysis by comparing it against alternative specifications, including autoregressive integrated moving average (ARIMA) models. The results indicate that the state-space formulation provides a superior fit for capturing the non-stationary nature of the domestic abuse datasets used in this research.

Introduction

Existing theories suggest that environmental unpredictability plays a critical role in developmental outcomes. Building upon this foundation, the present study aims to investigate the specific impact of unpredictability within the context of child maltreatment, specifically focusing on the unique effects of unpredictability in domestic abuse and neglect.

The Role of Environmental Unpredictability

Current theoretical frameworks posit that environmental unpredictability—characterized by inconsistent parental behavior and unstable living conditions—serves as a primary stressor that shapes cognitive and emotional development. While the severity and frequency of maltreatment are well-documented, recent research suggests that the lack of predictability in these experiences may be equally detrimental. By isolating the dimensions of unpredictability, we can better understand how children adapt to volatile environments and the long-term consequences for their psychological well-being.

[Figure 1: see original paper]

Distinguishing Abuse and Neglect

It is essential to distinguish between the direct harm caused by abuse and the systemic instability associated with neglect. Although these experiences often co-occur, they may exert distinct influences on a child' s developmental trajectory. This study explores how the unpredictable nature of these experiences—rather than just their occurrence—contributes to specific behavioral outcomes. By analyzing these factors independently, we aim to clarify the mechanisms through which domestic instability affects child development and to identify potential points of intervention for at-risk families.

The impact of predictability depends not only on its own level but may also be influenced by the current degree of adversity exposure [**?**, **?**]. According to the "match-mismatch"hypothesis, individuals who experience high levels of adversity in early life may develop phenotypes that are better adapted to high-adversity environments in adulthood. Conversely, if there is a mismatch between the early-life environment and the adult environment, the risk of developing psychological and behavioral problems increases [**?**, **?**].

[Figure 1: see original paper]

Recent studies have further refined this perspective, suggesting that the influence of environmental predictability on individual development is moderated by the overall severity of environmental stressors. Specifically, in environments characterized by extreme deprivation or high threat, the protective effects of predictability may be attenuated. As shown in , the interaction between predictability and adversity exposure significantly predicts long-term developmental outcomes, particularly in the domains of executive function and emotional regulation.

Furthermore, the biological embedding of these environmental signals often occurs during sensitive periods of development. When early environmental cues reliably predict future conditions, the organism can calibrate its physiological systems—such as the HPA axis—to optimize fitness. However, as noted by [**?**, **?**], if the current environment deviates significantly from the predicted state, these previously adaptive responses may become maladaptive, leading to increased

vulnerability to metabolic and mental health disorders. This underscores the importance of considering both historical and proximal environmental factors when assessing the role of predictability in human development.

2024; Ellis et al., 2022). However, relevant empirical research remains relatively limited, and findings have yet to reach a consensus (Doom et al., 2016;

(Farkas & Jacquet, 2025; Li et al., 2018). In the present study, the degree of adversity exposure was operationalized as the cumulative frequency and severity of maltreatment and neglect across multiple measurement points.

average levels of exposure, and explore the interaction between the unpredictability of domestic abuse/neglect and its average exposure levels, with the aim of deepening our understanding of these dynamics.

To gain a deeper understanding of the impact of environmental unpredictability, this study addresses the second research question by examining whether the various dimensions of a positive school psychological environment play a significant role.

can buffer the impact of family environmental unpredictability. This study proposes the following hypotheses: (1) Maltreatment and neglect unpredictability will···

significantly predicted a flatter diurnal cortisol slope and higher levels of depressive symptoms in adolescents; however, maltreatment/neglect was not a significant predictor.

Regarding the interaction between individual characteristics and their average exposure levels, this study does not presuppose any specific functional form or direction for these effects. (2) School positive psychological environment···

Various dimensions can buffer the adverse effects of family environment unpredictability on adolescent health outcomes.

2.1 被试

This study recruited students from two schools in Anhui Province, China, as research participants. A four-wave longitudinal questionnaire survey was conducted over a two-year period, with data collection occurring in December 2019 (T1),

December 2020 (T2), June 2021 (T3), and December 2021 (T4). At the

T4 assessment, 216 students were randomly selected to participate in a three-day consecutive saliva sample collection. Five students were excluded from the analysis due to their failure to participate in the baseline questionnaire

survey, resulting in a final analytical sample of 211 students. At baseline, the participants' ages

ranged from 9 to 13 years, with a mean age of 10.82 years ($SD = 0.85$). The sample consisted of 138 boys (65.4%) and 73 girls (34.6%).

2.2 程序

This study was reviewed and approved by the Academic Ethics Committee of Beijing Normal University (Approval No. 201912210084).

The research was formally conducted after obtaining informed consent from both the participants and their parents. The questionnaire survey was administered on a class-by-class basis, with participating students completing the forms simultaneously during self-study periods.

Each class was assigned at least one examiner, and all examiners underwent standardized training prior to each round of investigation.

Before administration, the examiners provided students with a detailed explanation regarding the purpose and significance of the study, instructions for answering the questions, and the principles of confidentiality and voluntary participation. During the session, examiners monitored the students' progress and addressed any queries.

Upon completion of the session, the examiners verified each questionnaire for completeness. The total time required to complete the questionnaire was approximately 45 minutes.

Saliva collection was scheduled from Monday to Wednesday during the same week as the fourth round of the questionnaire survey. Researchers explained the necessary precautions to the students one day in advance and provided an on-site demonstration of the collection procedure.

The collection steps were as follows: participants placed a sterile cotton swab from a specialized saliva collection tube into their mouths, sucked on it for approximately 2 minutes, and then spat it back into the collection tube.

Participants were instructed to avoid manual contact with the swab to prevent contamination. Subsequently, the collection tubes were sealed, labeled with the participant' s identification number, and stored in a freezer at -25°C.

The collection for boarding students was completed with the assistance of the research team, while the collection for commuting students was assisted by their parents.

Collection materials for commuting students were distributed one day in advance for them to take home.

On the day of sampling, all participants were required to complete a daily log recording their wake-up time and whether they had taken any medication that day.

2.3.1 家庭虐待与忽视

The Childhood Trauma Questionnaire-Short Form (CTQ-SF), originally developed by Bernstein et al. (2003) and revised by Zhao et al. (2005), was utilized across four

time points to assess participants' experiences of maltreatment and neglect within the family, specifically covering physical abuse, emotional abuse, physical neglect, and emotional neglect.

All items were rated on a 5-point Likert scale, ranging from 1 ("never") to 5 ("always"). To determine the levels of maltreatment and neglect, the mean scores of the physical and

emotional abuse items were calculated as the family abuse score, while the mean scores of the physical and emotional neglect items were calculated as the family neglect

score. Higher scores indicate a greater degree of family abuse or neglect experienced by the individual. This scale has demonstrated good reliability and validity among adolescent populations (Hagborg et al., 2022).

Across the four measurements in this study, the internal consistency coefficients (Cronbach' s α) for family abuse were 0.88, 0.77, 0.85, and 0.83, respectively.

For family neglect, the internal consistency coefficients were 0.76, 0.76, 0.83, and 0.85, respectively.

2.3.2 学校积极心理环境

The school positive psychological environment was assessed using the School Positive Psychological Environment Questionnaire, developed by the National Project Group of Psychological Development Characteristics of Chinese Children and Adolescents.

This instrument evaluates adolescents' psychological experiences regarding the quality of their school environment [**?**, **?**, **?**, **?**]. The questionnaire consists of 21

items categorized into four dimensions: safety and order, acceptance and support, fairness and justice, and encouragement of autonomy and cooperation. All

items are rated on a 4-point Likert scale, ranging from 1 (never) to 4 (always). Longitudinal invariance testing indicated that

each dimension of the school positive psychological environment supported partial strong invariance. Scores for each dimension were calculated by averaging the corresponding items. This questionnaire was administered during the first, second, and

fourth waves of the survey. To maximize data utilization and provide a more comprehensive reflection of adolescents' psychological experiences of the school

environment throughout the tracking period,

this study averaged the scores from each measurement point to serve as the final indicators for each dimension. The questionnaire is well-suited to Chinese socio-cultural

characteristics and has been widely applied in research involving Chinese adolescents [**?**, **?**]. Across the three measurements in this study,

the internal consistency coefficients for the total scale were 0.89, 0.92, and 0.93, respectively, while the internal consistency coefficients for each dimension ranged from 0.72 to 0.87.

2.3.3 抑郁症状

During the first and fourth waves of the survey, depressive symptoms experienced by participants over the past week were measured using the Center for Epidemiologic Studies Depression Scale (CES-D). This scale was originally developed by Radloff (1977) and subsequently simplified by Andresen et al. (1994).

The scale consists of 13 items, each rated on a 4-point Likert scale ranging from 0 ("rarely or none of the time") to 3 ("most or all of the time").

The average score across all items was calculated, with higher scores indicating higher levels of depression.

This scale has demonstrated robust psychometric properties within Chinese adolescent samples [**?**, **?**].

In the present study, the internal consistency coefficients (Cronbach' s α) for the scale across the two measurement points were 0.80 and 0.90, respectively.

2.3.4 唾液皮质醇的采集与分析

Salivary cortisol was measured during the fourth survey. Participants were required to collect saliva samples at three fixed time points over three consecutive days: immediately upon waking, 30 minutes after waking, and at bedtime. To ensure the accuracy of the samples, participants were instructed to refrain from eating, drinking caffeine, or brushing their teeth for 30 minutes prior to collection. The samples were then analyzed using enzyme-linked immunosorbent assay (ELISA) to determine cortisol concentrations. This multi-day, multi-point sampling protocol was designed to capture the diurnal rhythm of cortisol secretion and minimize the impact of daily fluctuations on the results.

Saliva samples were collected at nine specific time points, including 30 minutes after waking and immediately before bedtime. All samples were collected using Salivette® sampling devices manufactured by Sarstedt AG & Co. (Nümbrecht, Germany).

Saliva samples were collected using specialized Salivette centrifuge tubes, with approximately 2 ml obtained per session. To prevent sample contamination, participants were required to abstain from eating, drinking, or smoking for at least 30 minutes prior to the sampling procedure.

Do not eat, drink, or brush your teeth. The collected samples were transported to BGI Proteomics (Beijing, China) and processed using a German-manufactured instrument.

The Enzyme-Linked Immunosorbent Assay (ELISA) kits produced by DRG International, Inc. were utilized to determine the levels of cortisol (COR) and adrenocorticotropic hormone (ACTH) in the serum. All experimental procedures were conducted in strict accordance with the manufacturer' s provided instructions.

The fundamental principle of this assay is based on the competitive binding method. Within the system, an unknown amount of antigen present in the sample competes with a fixed amount of enzyme-labeled antigen for binding sites on a limited quantity of specific antibodies immobilized on the solid-phase microplate. After the competitive reaction reaches equilibrium, the unbound components are removed through a washing process. Subsequently, a substrate solution is added to the wells; the resulting color intensity is inversely proportional to the concentration of the target hormone in the sample. The reaction is terminated by the addition of a stop solution, and the optical density (OD) is measured at the specified wavelength using a microplate reader. The final concentrations of COR and ACTH are then calculated by comparing the OD values of the samples against a standard curve generated from known concentrations.

The cortisol concentration was measured in units of ng/mL. Prior to the assay, samples were centrifuged at $3000g$ for 10 minutes at 4°C, after which the supernatant was collected for analysis.

The cortisol levels were measured accordingly. The minimum detectable concentration of cortisol was less than 0.537 ng/mL, and both intra-assay and inter-assay coefficients of variation were less than 15%.

A total of 211 participants provided 1,840 valid samples. Among these, 88.6% ($n = 187$) of the participants provided all 9 samples.

A total of samples were collected. Prior to data analysis, the dataset underwent rigorous cleaning and treatment for extreme values. Among these, 33 were morning samples (defined as the first sample collected immediately upon waking).

If the collection time exceeds the specified duration by more than 10 minutes, the sample is regarded as invalid and is treated as a missing value [**?**, **?**].

2009). Considering that cortisol data typically exhibit a positively skewed distribution, a base-10 logarithmic transformation was applied to the cortisol concentration values.

Furthermore, 16 samples were identified with concentration values exceeding the range of the mean plus or minus three standard deviations; these outliers were addressed using the winsorization method.

Finally, the daily

Note: Figure translations are in progress. See original paper for figures.