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Original article

Does High Self-Control Accelerate Epigenetic Aging in Low-Income Adolescents?

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A B S T R A C T

Purpose: Persistent self-control in the context of upward mobility in low-income adolescents, especially those of color, may have physiological costs, such as greater risks of developing cardiometabolic diseases in young adulthood. One potential mechanism linking self-control to cardiometabolic health is epigenetic age acceleration (EAA). However, little is known regarding the association between high self-control and EAA, as well as what factors may play protective roles. Therefore, we evaluated (1) the association between self-control and EAA and if this association varies by race and ethnicity, and (2) whether neighborhood collective efficacy (NCE) and school connectedness moderate the association in low-income adolescents.
Methods: This study used data from the Future of Families and Child Wellbeing Study. Participants included 772 adolescents with a household income <300% of poverty level (mean age: 15.6 years). Self-control, NCE, and school connectedness were all self-reported. EAA was assessed in saliva and estimated using Horvath, Skin and Blood, and Pediatric-Buccal-Epigenetic clocks. Multiple linear regression and PROCESS analyses were employed.
Results: Higher self-control was positively associated with EAA estimated by the skin and blood clock in low-income adolescents of color. Further, the association of higher self-control with EAA was not significant among low-income adolescents of color with higher NCE. No significant association was found among low-income White adolescents.
Discussion: The results suggest that supportive resources like neighborhood collective efficacy could mitigate adverse associations of high self-control with health in low-income adolescents of color.

IMPLICATIONS AND CONTRIBUTION

This study contributes to the understanding of whether intense and persistent self-control incurs physiological costs within disadvantaged socioeconomic contexts. Findings highlight the association between higher self-control and faster epigenetic aging among low-income adolescents of color, emphasizing the potentially important role of enhancing neighborhood collective efficacy in mitigating this association.

Youth experiencing socioeconomic adversity encounter significant challenges compared to their higher socioeconomic status (SES) counterparts. They are more likely to have academic difficulties, complete fewer years of education, and have a higher prevalence of health problems [1–3]. However, adolescents with high levels of self-control address the challenges and achieve positive outcomes, including better academic performance, fewer depressive symptoms and behavioral problems, and increased likelihood of college graduation, [4] despite adverse environments. Self-control, the capacity to regulate immediate impulses and behaviors, is a robust predictor of favorable life

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outcomes throughout life. However, successes achieved with intense and persistent self-control may have physiological costs [5]. This is part of a phenomenon known as “skin-deep resilience,” where health costs are associated with achieving favorable psychosocial outcomes in disadvantaged socioeconomic conditions [6]. Recent studies support this, showing that these adolescents have greater risks of developing cardiometabolic diseases in young adulthood while achieving upward mobility by overcoming obstacles that accompany socioeconomic adversity [4,7,8]. This phenomenon appears to be more prominent in adolescents of color and less likely in White adolescents [9].

Intense and persistent self-control may influence cardiometabolic health in adolescents facing socioeconomic adversity through DNA methylation-based epigenetic age acceleration (EAA). Research in young adults from low SES backgrounds suggested this mechanism, showing a significant association between a high level of self-control and EAA [5]. EAA has been suggested as a strong predictor of chronic illnesses such as cardiovascular disease, [10,11] and epigenetic clocks have been employed as a promising marker for molecular-level aging. Although the application of epigenetic clocks in the pediatric population is a relatively new approach, they appear to be an effective measure to detect accelerated aging in adolescents. This is because inter-individual variations in estimated DNA methylation-based epigenetic age (epigenetic age) may arise before adulthood. In support of this, Kananen et al. [12] found that the majority of epigenetic age variations were already established at 15 years of age and the estimation of EAA remained relatively stable throughout adulthood.

The impact of self-control on EAA in adolescents experiencing socioeconomic adversity is understudied. Although one study tested associations of self-control assessed during adolescence with EAA, they focused on EAA in young adults, not in adolescents [5]. In addition, a previous study implied that the association between high self-control and health-relevant outcomes in the context of socioeconomic adversity may differ by race and ethnicity, showing that higher rates of metabolic syndrome were associated with college completion among low-SES Black and Hispanic young adults, but not White individuals [9]. Therefore, our study evaluates not only whether high self-control was associated with EAA but also whether this association differed by race and ethnicity.

If high self-control does come at physiological costs, it becomes important to determine whether the toll varies across contexts. The social ecological resilience model emphasizes the impact of social and environmental contexts on health outcomes in the face of significant adversity. When stressors are abnormally high, relational and structural factors, such as supportive networks of community members or teachers, school and community safety, may outweigh individual-level factors in influencing health [13]. Aligned with social ecological resilience, studies hint that for low-income youth, living in a neighborhood with high collective efficacy (defined as the willingness of neighbors to work together for the common good and a sense of belonging within their community [14]) and attending a school high in connectedness may offset health risks. For instance, a study showed that perceived neighborhood collective efficacy (NCE) buffered the negative influence of neighborhood disadvantage on accelerated cardiometabolic aging in African American young adults [15]. Additionally, a meta-analytic review suggested school connectedness as an important protective factor against youth health risk behaviors, [16] with one study linking low school connectedness to increased body mass index in adolescents [17]. Despite the implications from the literature, no known study has investigated the protective roles of NCE and school connectedness in the relationship between self-control and EAA in adolescents.

To address these research gaps, the proposed study aimed to (1) evaluate associations between self-control and EAA, and (2) evaluate the potential moderating effects of NCE and school connectedness on the association between self-control and EAA in low-income adolescents. Specifically, we hypothesized that in low-income adolescents: (1) higher self-control is positively associated with EAA, with a stronger association among adolescents of color than White adolescents; (2) NCE mitigates the association of self-control with EAA; (3) school connectedness mitigates the association of self-control with EAA.

Methods

Study population

We used data from the Future of Families and Child Wellbeing Study (FFCWS), a national longitudinal study comprising 4,898 children born in 20 U.S. cities between 1998 and 2002 [18]. The FFCWS collected data over seven waves, oversampling unmarried families, with a majority identifying as racial and ethnic minorities. The research protocol and consent forms for the FFCWS were approved by the relevant Institutional Review Boards or Human Subjects Committees at each hospital participating in data collection. Since we used publicly available deidentified datasets, separate ethical approval for our analyses was not required. Our study included adolescents whose epigenetic age data were collected during the FFCWS Year 15 wave, from 2014 to 2017.

Out of the 1,120 adolescents with epigenetic age data, 820 were considered low-income participants. We chose to use 300% of the federal poverty threshold as a cutoff for low-income for two reasons: (1) it represents the highest threshold for qualification in welfare programs for low-income households, and (2) it has been used in prior studies [19,20]. As a result, 300 participants were excluded due to missing poverty level data or having a poverty level of 300% or higher. Among low-income adolescents, 48 were excluded for missing main study variables: two due to missing race/ethnicity data and 46 due to incomplete self-control measures. Consequently, a total of 772 adolescents were included in the study.

Measures

Participant race and ethnicity. Adolescents' race and ethnicity were coded into two categories: non-Hispanic White (11.8%) and adolescents of color, which included those who self-reported as non-Hispanic African American (48.3%), other (1.4%), multiracial (6.2%), and Hispanic/Latino (32.3%). This categorization aligns with previous study findings, indicating that the association between effort for upward mobility and subsequent physiological costs was observed in participants of color and not in White participants [9].

Self-control. Self-control was measured using the self-reported modified version of the Engagement, Perseverance, Optimism, Connectedness, and Happiness Measure of Adolescent Well-Being [21]. Among the various aspects of self-control, characteristics such as industriousness and perseverance have been associated with EAA [5]. Therefore, to capture this aspect of self-control, we employed the Perseverance subscale of the Engagement, Perseverance, Optimism, Connectedness, and Happiness, which assesses adolescents' capability to persistently work toward accomplishing their goals, even when faced with obstacles (4 items, e.g., "I finish whatever I begin" and "I am a hard worker"). Each item was scored on a four-point Likert scale (1 = strongly agree to 4 = strongly disagree). All items were reversed coded to compute the mean scores, where higher values indicated greater self-control. Since only a small number of participants (11%; 45 out of 772) had scores below 3, with no participant scoring 1 (see eFigure 1), this distribution may pose potential risks to the linear relationship with the outcome variable. Therefore, for data analysis, we computed quartiles of self-control scores and defined up to the 75th percentile of the mean scores as lower self-control, while the top 25th percentile of the mean scores was defined as higher self-control. In our study, the Cronbach's α for the Perseverance subscale was 0.68.

Epigenetic age acceleration. We used FFCWS's DNA methylation data analyzed with the Illumina Infinium Human Methylation450K or Illumina Infinium Methylation EPIC arrays using saliva samples. EAA was estimated using three epigenetic clocks that have been commonly employed in the pediatric population: [22] Horvath, Skin and Blood, and Pediatric-Buccal-Epigenetic (PedBE) clocks. Horvath clock, [23] the first pan-tissue epigenetic clock, is the most widely accepted method for estimating epigenetic ages across all age groups. The Skin and Blood clock, developed by Horvath et al., [24] is a multitissue epigenetic age predictor, primarily utilizing cells isolated from the skin. Lastly, the PedBE clock is a clock specifically designed for the pediatric population (individuals aged 0–20 years old) [25]. EAA was calculated from the residuals of a linear regression model of each epigenetic age measure and chronological age. An EAA value greater than 0 suggests accelerated epigenetic aging, indicating that the estimated epigenetic age is older than the chronological age of the participant.

Neighborhood collective efficacy. Adolescents completed two sets of items measuring NCE [14]. The first set assessed informal social control (4 items, e.g., "neighborhood would get involved if children were showing disrespect to an adult") and the second set measured the level of cohesion and trust (4 items, e.g., "This is a close-knit neighborhood.") Each item was scored on a four-point Likert scale (1 = very likely to 4 = very unlikely), and we recoded them so that higher scores represented higher levels of NCE. Mean scores for the eight Items were calculated for analysis and Cronbach's α for NCE in this current study was 0.75.

School connectedness. To measure school connectedness, adolescents completed four items complied by Jacquelyn Eccles for the Panel Study of Income Dynamics—Child Development Supplement III. [26] This self-reported questionnaire assessed inclusiveness, closeness, happiness, and safety at school using a four-point Likert scale (1 = strongly agree to 4 = strongly disagree). Item responses were reverse-coded so that higher scores indicated greater levels of school connectedness. Mean scores of the four items were calculated for analysis and in this current study, Cronbach's α for them was 0.72.

Covariates. We included the following multiple covariates: SES (parental cohabitation status at birth and primary caregiver (PCG)'s education), factors associated with EAA (smoking history of both the PCG and participants, participants' sex, body mass index, [27] intake of fruits and vegetables, [28] chronological age, [29] and pubertal status [30]), and technical covariates for processing DNA methylation data (arrays on which the sample was processed and estimated cell-type proportions). More detailed information is in Supplementary Material.

Data analysis

StataCorp Stata/IC 15.1 (College Station, TX) was used for data cleaning and preparation. To minimize losing power from excluding samples, we conducted hot-deck imputation in IBM SPSS v23 (Chicago, IL). More detailed information on the imputation process is in Supplementary Material. Descriptive statistics were generated to describe participants' characteristics. Between-group comparisons were conducted using Welch's t-tests or Chi-square tests. To test our hypotheses, we employed multiple linear regression analysis to determine the association between self-control and EAA independent of the study covariates. In testing hypothesis 1, we initially conducted analyses with all low-income participants and then performed stratified analyses to investigate potential racial and ethnic differences in this relationship. We examined the statistical significance of the association in each racial and ethnic group, using those with significant associations for further hypothesis testing. To test moderation models, we used Model one of the PROCESS macro (version 4.3.1). Prior to analysis, we excluded 16 adolescents who were homeschooled due to the inability to measure their school connectedness, resulting in 746 adolescents included for moderation model analyses.

We conducted several sensitivity and supplemental analyses. For sensitivity analyses testing hypotheses one and two, we restricted the analyses to participants with complete data, ensuring the robustness of results derived from imputed data. Additionally, we conducted another sensitivity analysis categorizing self-control into three groups with consideration of its distribution (low $\leq$ mean scores of 3, middle = 3.25 to 3.75, and high = 4); this analysis was conducted for testing hypothesis one only. The final sensitivity analyses tested hypothesis one by additionally adjusting for the estimated cell-type proportions alongside the study covariates. This was done in two steps: (1) the models were adjusted for the fraction of epithelial cells versus immune cells, and (2) the models were adjusted for the major classes of immune cells, including natural killer cells, B cells, CD4 cells, CD8 cells, and monocytes. As supplemental analyses, we examined the association between self-control and EAA among adolescents with a poverty level of 300% or higher, as well as among three groups of adolescents of color (non-Hispanic African American, Hispanic/Latino, and Other and Multiracial adolescents).

Results

Participant characteristics

As shown in Table 1, the mean chronological age for all participants was 15.55. The majority of participants in both self-control groups were adolescents of color (86.70% for the lower group and 93.60% for the higher group). The mean score for the

Table 1
Descriptive statistics for participants' characteristics by self-control level

Variable	All	Self-control level	
		Lower	Higher
n (%)	772 (100)	600 (77.72)	172 (22.28)
Chronological age, mean (SD)	15.55 (0.62)	15.55 (0.62)	15.53 (0.59)
Sex, n (%)			
Boy	368 (47.67)	281 (46.83)	87 (50.58)
Girl	404 (52.33)	319 (53.17)	85 (49.42)
Pubertal status (physical development), n (%)			
Earlier than most	182 (23.60)	135 (22.50)	47 (27.30)
About the same	445 (57.60)	343 (57.20)	102 (59.30)
Later than most	145 (18.80)	122 (20.30)	23 (13.40)
Smoking history, n (%)			
Yes	53 (6.90)	49 (8.20)	4 (2.30)*
No	719 (93.10)	551 (91.80)	168 (97.70)*
BMI, mean (SD)	24.34 (5.72)	24.43 (5.78)	24.02 (5.50)
Intake of fruits and vegetables, mean (SD)	4.48 (2.09)	4.45 (2.10)	4.62 (2.07)
Race/Ethnicity, n (%)			
Adolescents of color	681 (88.20)	520 (86.70)	161 (93.60)*
Non-Hispanic White	91 (11.80)	80 (13.30)	11 (6.40)*
PCG's education level, n (%)			
Less than high school	176 (22.80)	135 (22.50)	41 (23.80)
≥ Graduated high school	596 (77.20)	465 (77.50)	131 (76.20)
Parental cohabitation at birth, n (%)			
Yes	315 (40.80)	242 (40.30)	73 (42.40)
No	457 (59.20)	358 (59.70)	99 (57.60)
PCG's smoking history, n (%)			
Yes	304 (39.40)	237 (39.50)	67 (39.00)
No	468 (60.60)	363 (60.50)	105 (61.00)
Self-control, mean (SD)	3.42 (0.47)	3.26 (0.41)	4 (0.00)
Range	1.5–4	1.5–3.75	4–4
Epigenetic age acceleration, mean (SD)			
Horvath clock	−0.02 (2.91)	−0.02 (2.97)	−0.01 (2.71)
Skin and blood clock	0.01 (2.29)	−0.06 (2.29)	0.26 (2.29)
PedBE clock	0.07 (2.25)	0.10 (2.23)	−0.03 (2.31)
NCE, mean (SD)[a]	2.80 (0.62)	2.74 (0.60)	3.00 (0.65)
Connectedness at school, mean (SD)[a]	3.40 (0.58)	3.35 (0.59)	3.60 (0.52)*

BMI = body mass index; NCE = neighborhood collective efficacy; PCG = primary caregiver; PedBE = Pediatric-Buccal-Epigenetic; SD = standard deviation.
* $p < .05$ for between-group comparison.
[a] The number of participants differed due to the exclusion of home-schooled participants: total n = 756, n with the lower self-control group = 585, and n with the higher self-control group = 171.

Table 2
Descriptive statistics for participants' characteristics by race/ethnicity

Variable	Race/Ethnicity	
	Adolescents of color (n = 681)	Non-hispanic white (n = 91)
Chronological age, mean (SD)	15.56 (0.63)	15.44 (0.47)*
Sex, n (%)		
Boy	325 (47.70)	43 (47.30)
Girl	356 (52.30)	48 (52.70)
Pubertal status (physical development), n (%)		
Earlier than most	163 (23.90)	19 (20.90)
About the same	390 (57.30)	55 (60.40)
Later than most	128 (18.80)	17 (18.70)*
Smoking history, n (%)		
Yes	37 (5.40)	16 (17.60)*
No	644 (94.60)	75 (82.40)*
BMI, mean (SD)	24.47 (5.81)	23.34 (4.89)
Intake of fruits and vegetables, mean (SD)	4.43 (2.10)	4.86 (1.96)
PCG's education level, n (%)		
Less than high school	161 (23.60)	15 (16.50)
≥ Graduated high school	520 (76.40)	76 (83.50)
Parental cohabitation at birth, n (%)		
Yes	269 (39.50)	46 (50.50)*
No	412 (60.50)	45 (49.50)*
PCG's smoking history, n (%)		
Yes	434 (63.70)	57 (62.60)*
No	247 (36.3)	34 (37.40)*
Self-control, n (%)		
Higher self-control	161 (23.64)	11 (12.09)*
Lower self-control	520 (76.36)	80 (87.91)*
Epigenetic age acceleration, mean (SD)		
Horvath clock	−0.05 (2.91)	0.20 (2.95)
Skin and blood clock	0.03 (2.33)	−0.18 (1.98)*
PedBE clock	0.13 (2.26)	−0.33 (2.06)
NCE, mean (SD)[a]	2.80 (0.63)	2.83 (0.56)*
Connectedness at school, mean (SD)[a]	3.40 (0.59)	3.44 (0.56)

BMI = body mass index; NCE = neighborhood collective efficacy; PCG = primary caregiver; PedBE = Pediatric-Buccal-Epigenetic; SD = standard deviation.
* $p < .05$ for between-group comparison.
[a] The number of participants differed due to the exclusion of home-schooled participants: total n = 756, n with the Adolescents of Color = 672, and n with Non-Hispanic White = 84.

lower self-control group was 3.26 and for the higher self-control, the score was 4. In the higher self-control group, the mean score of EAA estimated by the skin and blood clock was 0.26, indicating accelerated epigenetic age, while it was −0.06 in the lower self-control group.

Table 2 presents participants' characteristics by race/ethnicity. Descriptive statistics for the overall sample and by self-control and race/ethnicity groups for the technical covariates related to processing DNA methylation data are presented in eTable 1.

Associations of self-control with epigenetic age acceleration

Significant associations between self-control and EAA were observed in the models for all participants (coefficient = 0.42, $p = .03$; $R^2 = 0.07$, $F = 4.74$, $p < .001$) and for adolescents of color (Table 3). Among the three epigenetic clocks, only the skin and blood clock showed a significant association with self-control. Specifically, a significant difference in EAA was found between adolescents of color with lower self-control and those with high self-control. Higher self-control was positively associated with EAA (coefficient = 0.50, $p = .02$). The model was statistically significant while controlling for study covariates ($R^2 = 0.08$, $F = 4.97$, $p < .001$). Conversely, among non-Hispanic White adolescents, no multiple regression models were significant.

The results remained consistent in sensitivity analyses (eTables 3, 6, and 7). In the sensitivity analyses involving the three categorizations of self-control, a significant difference in EAA measured by the skin and blood clock was observed only between adolescents of color with low self-control and those with high self-control (coefficient = 0.55, $p = .04$). However, these findings were consistent with the main analyses (eTable 5).

Supplemental analyses found a significant negative association between higher self-control and EAA among adolescents of color with a poverty level of 300% or higher, showing an opposite direction of association compared to the main analysis result (coefficient = −0.77, $p = .03$; eTable 8). Additionally, although the associations were not significant among the three groups of

Table 3
Associations of self-control with EAA

EAA estimator	All (n = 772)		Adolescents of color (n = 681)		White adolescents (n = 91)	
	Coefficient (95% CI)	*p* Value	Coefficient (95% CI)	*p* Value	Coefficient (95% CI)	*p* value
Horvath clock	0.10 (−0.40 to 0.59)	.71	0.18 (−0.34 to 0.70)	.49	−0.63 (−2.61 to 1.34)	.52
Skin and blood clock	0.42 (0.03 to 0.80)	.03*	0.50 (0.10 to 0.90)	.02*	−0.94 (−2.29 to 0.40)	.17
PedBE clock	−0.10 (−0.49 to 0.28)	.60	−0.12 (−0.52 to 0.29)	.57	−0.32 (−1.72 to 1.08)	.65

CI = confidence interval; EAA = epigenetic age acceleration; PedBE = Pediatric-Buccal-Epigenetic.
Models were adjusted for control variables, including parental cohabitation status at birth, PCG's education, smoking history of both the PCG and participants, participants' sex, BMI, intake of fruits and vegetables, chronological age, pubertal status, and the arrays in which the sample was processed.
* $p < .05$.

adolescents of color, the magnitude and direction of the associations among African Americans and Hispanic/Latinos were consistent with the main analyses (eTable 9).

Moderation model testing

Among the moderators, NCE showed significant moderating effects between higher self-control and EAA (Table 4); no moderation models with school connectedness were significant (eTable 2). Among adolescents of color, NCE significantly moderated the positive association of higher self-control with EAA estimated by the Horvath clock (coefficient = −0.98, $p = .02$) and by the skin and blood clock (coefficient = −1.04, $p = .001$), when controlling for study covariates. Simple slope tests showed that adolescents of color with higher self-control exhibited EAA when reporting low levels of NCE (25th percentile), compared to those with lower self-control. On the other hand, higher self-control showed no significant association with EAA when NCE levels were high (75th percentile) (Figure 1).

The sensitivity analyses with participants with complete data yielded similar results (eTable 4).

Discussion

In the present study, we examined the association between self-control and EAA among low-income adolescents and explored whether this association differs by race and ethnicity. Additionally, we investigated the buffering roles of NCE and school connectedness in this association. We found that higher self-control was positively associated with EAA among low-income adolescents of color after adjusting for study covariates. This association was not significant among non-Hispanic White adolescents. This suggests that maintaining high self-control in adolescence incurs physiological costs, particularly among adolescents of color within socioeconomically adverse contexts. Lastly, we observed that NCE significantly moderated the positive association between higher self-control and EAA among low-income adolescents of color, suggesting the potential positive contribution of improving NCE to alleviate the effect of high self-control on EAA in this population.

Our findings align with previous research that observed skin-deep resilience. A previous study found that better self-control in adolescence was associated with faster epigenetic aging among low-SES African American young adults aged 22, while self-

Table 4
Moderating effect of NCE on the associations between self-control and EAA in low-income adolescents of color (n = 672)

Independent variable	EAA estimator						
	Horvath clock						
	Coef.	SE	*p* Value	95% CI		R^2	F (*p* value)
				Lower	Upper		
Self-control						0.04	1.88 (.03*)
Higher self-control	3.11	1.24	.01*	0.68	5.54		
NCE	−0.01	0.21	.98	−0.42	0.41		
Self-control*NCE	−0.98	0.41	.02*	−1.79	−0.17		
			Skin and blood clock				
Self-control						0.10	5.32 (<.001**)
Higher self-control	3.56	0.96	<.001**	1.67	5.44		
NCE	0.10	0.16	.52	−0.21	0.42		
Self-control*NCE	−1.04	0.32	.001**	−1.67	−0.41		
			PedBE clock				
Self-control						0.03	1.28 (.21)
Higher self-control	0.86	0.97	.34	−1.05	2.76		
NCE	−0.09	0.16	.60	−0.41	0.24		
Self-control*NCE	−0.33	0.32	.31	−0.97	0.31		

CI = confidence interval; Coef. = coefficient; EAA = epigenetic age acceleration; NCE = neighborhood collective efficacy; PedBE = Pediatric-Buccal-Epigenetic; SE = standard error.
Models were adjusted for control variables, including parental cohabitation status at birth, PCG's education, smoking history of both the PCG and participants, participants' sex, BMI, intake of fruits and vegetables, chronological age, pubertal status, and the arrays in which the sample was processed.
* $p < .05$.
** $p < .01$.

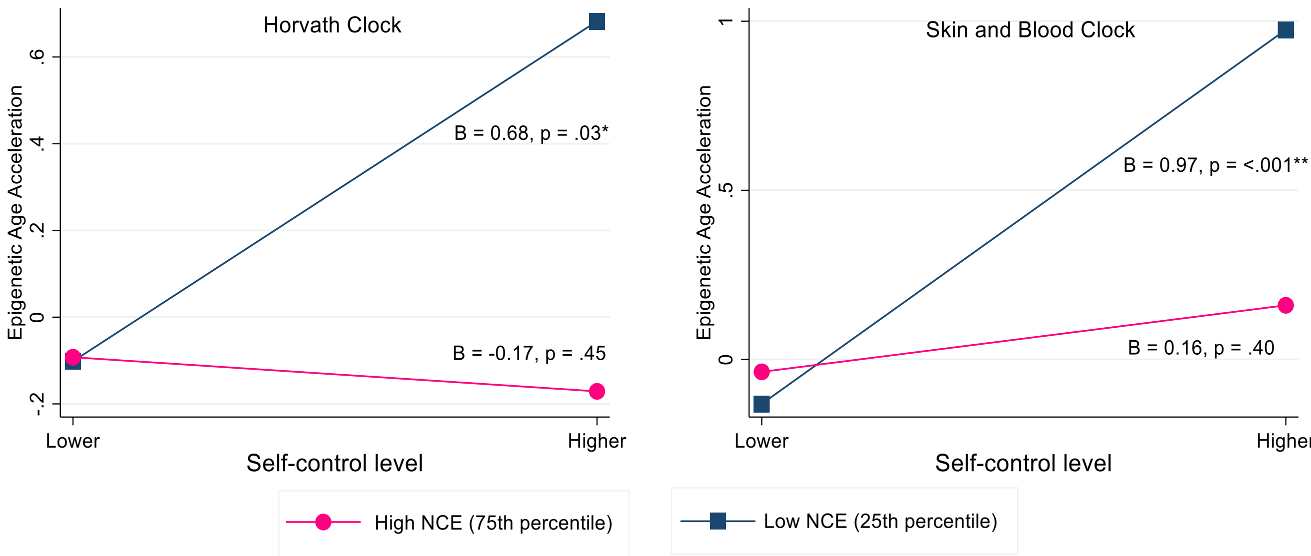

Figure 1. Estimated effect of higher self-control on EAA at different levels of NCE in low-income adolescents of color (n = 672). *$p < .05$, **$p < .001$

control was associated with the deceleration of epigenetic aging among high-SES youth. [5] Furthermore, another study conducted in Black and Latinx children and adolescents aged 8–16 years suggested that health costs associated with skin-deep resilience may present even in childhood. [31] Although epigenetic aging was not their outcome, the authors demonstrated that among children and adolescents with John Henryism high-effort coping (defined as "mental and physical determination, a commitment to hard work, and a single-minded determination to succeed despite challenges,") socioeconomic disadvantage was positively associated with cardiometabolic risk. Taken together, these findings suggest that the association between high self-control and EAA may begin in adolescence or even earlier, potentially linking to increased cardiometabolic risk in childhood. This suggests the potential need for early interventions to mitigate the physical toll of self-control, especially for low-income adolescents of color.

The significant buffering effect of NCE in the association between higher self-control and EAA among low-income adolescents of color, as observed in our study, may inform future interventions to alleviate the physical costs of self-control, offering one possible approach. Although no previous study specifically supports this relationship, prior research has suggested the protective role of NCE on physical health in adverse socioeconomic context across various associations. For instance, NCE was suggested to buffer the negative influences of disadvantaged neighborhood environments on accelerated cardiometabolic aging in young adults (aged 18–29) [15] and on EAA in adults (mean age = 54.0). [32] Additionally, another study showed a buffering effect of NCE on the increase in obesity rates during COVID-19 among racially/ethnically minoritized children and adolescents. [33] Low-income adolescents of color who maintain high self-control may experience persistent activation of stress-response and inflammatory pathways, along with changes in DNA methylation patterns relevant to epigenetic aging. [5,32,34] High NCE, characterized by frequent reciprocal exchanges and cohesive ties, may alleviate this link between stress and EAA by offering emotional support. [35] Taken together, our study findings suggest that improving NCE may be beneficial to mitigate the negative influence of maintaining high self-control on EAA among low-income adolescents of color.

Contrary to our expectations, school connectedness did not buffer the association between higher self-control and EAA among low-income adolescents of color. For these adolescents, school connectedness may be less influential compared to neighborhood factors. A study suggested that neighborhood factors could diminish the relevance of school connectedness for physical health among children from disadvantaged neighborhoods. [36] However, previous research on school connectedness in adolescents has primarily emphasized its influences on psychosocial health, such as depression and health risk behaviors, [16] while rarely including physical health outcomes or epigenetic aging. Moreover, since our study was the first to evaluate the buffering role of school connectedness between higher self-control and EAA, there are no prior study results to validate our findings. Further investigations into the buffering role of school connectedness in the association of high self-control with EAA are warranted.

We noted that most of the significant study findings were observed when estimating EAA using the skin and blood clock. Although we selected three commonly used epigenetic clocks in the pediatric population, [22] the history of using epigenetic clocks in this population is relatively short compared to that in adults, and there is no solid evidence indicating which clock is more powerful in predicting EAA in adolescents. For example, some studies suggested the potential strength of using the PedBE clock in pediatric population, but they did not include the skin and blood clock in their study for comparison. [37,38] Furthermore, no study suggests a specific clock suitable for capturing the association between high self-control and EAA in adolescents due to limited research on this relationship. Therefore, future studies are needed to validate which clock is most effective in capturing this specific phenomenon in this population.

While our study is the first to evaluate the association between self-control and EAA in low-income adolescents and explore the potential protective roles of NCE and school connectedness, there are several limitations. First, due to the cross-sectional design, the long-term effects of self-control on

EAA and the buffering effects of NCE over time remain to be evaluated, limiting our ability to determine causality or directionality. Second, due to its skewed distribution, we implemented binary categorization of self-control in analyses. Although sensitivity analyses supported our findings, future research could improve rigor by using a continuous self-control variable. Moreover, the internal consistency of the self-control measure in our study was slightly low (Cronbach's $\alpha = 0.68$), suggesting the need for measures with better internal consistency to accurately capture the self-control domain and its association with EAA. Furthermore, despite the advantages of using saliva samples in estimating epigenetic aging, uncertainty remains regarding potential variations in the calculation of epigenetic aging across different tissue types in adolescents. [38] Therefore, repeated investigation with different tissue types in evaluating the association between self-control and EAA would be needed. Lastly, in our study, we used self-reported pubertal status as a covariate because of availability in the FFCWS data and this might affect our findings.

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Supplementary Data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jadohealth.2024.10.012

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