

Article

Population Diversity Matters: Heterogeneity of Biopsychosocial Pathways from Socioeconomic Status to Tobacco Use via Cerebral Cortical Volume in the ABCD Study

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Abstract:

Background: Most neuroscience research has predominantly focused on White, middle-class populations, leading to gaps in understanding how socioeconomic status (SES) influences brain development and health behaviors in racially diverse groups. Tobacco use, a major public health concern, is influenced by both family and neighborhood SES, with early initiation during adolescence predicting long-term health outcomes. The Adolescent Brain Cognitive Development (ABCD) study provides a unique opportunity to examine racial disparities in the pathways from SES to brain development and behavior, especially through the lens of Marginalization-Related Diminished Returns (MDRs), where the effects of SES are attenuated for minority groups. **Objective:** This study investigates racial variation in the associations between SES, cerebral cortical volume, and tobacco use initiation, comparing Black and White youth over 4-6 years of follow-up. **Methods:** Data from the ABCD study were analyzed to assess pathways from family income to adolescents' cortical volume via the needs-to-income ratio, and from cortical volume to tobacco use initiation. Structural equation modeling was used to evaluate these pathways, stratified by race, with a focus on comparing Black and White participants. Covariates included family and neighborhood SES, demographic factors, and baseline behavioral measures. **Results:** We found that the positive association between income (via the needs-to-income ratio) and total cortical volume was significantly weaker for Black youth compared to White youth. Additionally, the link between larger total cortical volume and reduced risk of tobacco initiation was also weaker in Black adolescents. These findings were consistent over 4-6 years of follow-up, suggesting that Black youth experience diminished returns from higher SES in terms of brain development and behavioral outcomes. **Conclusions:** Our findings highlight significant racial disparities in the pathways from SES to brain development and tobacco use initiation, supporting the Marginalization-Related Diminished Returns (MDRs) framework. While higher SES is associated with larger cortical volumes and lower tobacco use risk in White youth, these associations are attenuated in Black adolescents.

Keywords: Racial Disparities, Socioeconomic Status, Cortical Volume, Tobacco Use, Adolescent Brain Development, Marginalization-Related Diminished Returns, ABCD Study

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1. Introduction

Socioeconomic status (SES) significantly impacts brain development, which in turn influences behaviors such as tobacco use [1-6]. Higher SES [7-10] is typically associated with better access to resources, nutrition, educational opportunities, and lower stress, [11-20], all of which contribute to increased cortical volume [21-28]. In addition to its correlation with SES, larger cortical volume is linked to enhanced cognitive functions such as emotion regulation, decision-making, planning, and inhibitory control, which are critical for avoiding risk behaviors like tobacco use during adolescence.

However, most neuroscience research has predominantly focused on individuals racialized as White, primarily from middle-class populations. This narrow focus leaves substantial gaps in understanding how the pathways from social environments to brain development and behavior vary across racially diverse and historically marginalized groups who have experienced different social and economic conditions. The lack of diversity in research limits the generalizability of findings, particularly regarding how SES interacts with brain development and health behaviors in underrepresented populations. Addressing these gaps is crucial for informing interventions and policies aimed at reducing health disparities.

The Adolescent Brain Cognitive Development (ABCD) study [29-34] offers an unprecedented opportunity to explore these variations, as it includes a diverse dataset with comprehensive social, behavioral, and neurobiological measures. This rich data enables a thorough analysis of the pathways from SES to brain structure—specifically total cortical volume—and how these pathways relate to behaviors such as tobacco use initiation across different racial and ethnic groups.

An increasing body of research suggests that the associations between SES, brain structure, and behavior differ across racial and ethnic lines [35-40]. A key aspect of brain development influenced by SES is cerebral cortical volume, which is associated with cognitive functions crucial for self-regulation. Higher SES is linked to larger cortical volumes, which in turn support better emotion regulation, decision-making, and inhibitory control—skills essential for reducing the likelihood of engaging in risky behaviors like tobacco use. Adolescence is a particularly critical period for brain development, as early tobacco use during this stage often predicts long-term negative health outcomes.

For minoritized and racialized youth, particularly Black adolescents, the relationship between SES and health-related outcomes may be attenuated, a phenomenon described as Marginalization-Related Diminished Returns (MDRs) [41-52]. This framework posits that due to systemic inequalities, chronic social stressors, and historical marginalization, the benefits of higher SES on brain development and health behaviors are often weaker for racialized and minoritized groups compared to their socially privileged White counterparts [38,53-58].

Tobacco use among adolescents is strongly shaped by social factors, particularly family and neighborhood SES [59-61]. Adolescents from lower SES backgrounds or disadvantaged neighborhoods are at higher risk of initiating tobacco use, underscoring the importance of understanding how these social determinants vary by race and ethnicity. Emerging evidence suggests that the strength of these pathways is not uniform across populations.

In this paper, we leverage data from the ABCD [29-34] study to examine how the pathways from family and neighborhood SES to tobacco use via cerebral cortical volume differ across groups defined by racialization. Specifically, we hypothesize that the positive associations between SES and cortical volume, as well as the protective associations between total cortical volume and tobacco initiation, will be weaker for adolescents racialized as Black compared to those racialized as White, who have historically retained social privilege. Importantly, this weakened association is not rooted in biological

differences but in the sociology of race, reflecting historical, social, and contextual factors such as trauma and systemic inequality. This study aims to elucidate the complex interplay between social factors, brain development, and health behaviors, while addressing critical gaps in understanding population diversity and the impacts of racialization on these processes.

2. Methods

2.1. Settings and Design

This study utilized data from the Adolescent Brain Cognitive Development (ABCD) Study, a large-scale, longitudinal research initiative designed to examine brain development and child health in the United States. The ABCD study recruited over 11,000 children aged 9-10 years from 21 sites across the country, using a multi-stage probability sampling method to ensure a diverse and representative sample. Data collection involved a combination of neuroimaging, behavioral assessments, and questionnaires completed by both children and their parents. The current analysis leverages cross-sectional baseline data from the ABCD study, focusing on brain structure, socioeconomic factors, and demographic variables.

2.2. Sample and Sampling

The initial sample for the ABCD study included 11,878 children. For this analysis, we restricted the sample to children identified by their parents as either Black or White, consistent with our focus on racial disparities. To ensure reliable estimates of brain structure, children with missing or poor-quality neuroimaging data were excluded from the sample.

2.3. Eligibility for the Current Analysis

Eligibility for inclusion in the current analysis required that children meet the following criteria: (1) aged 9-10 years at baseline, (2) identified as Black or White, (3) completed parental questionnaires on socioeconomic factors, and (4) had complete neuroimaging data for total cortical volume. Children with missing key demographic or socioeconomic data (e.g. race) were excluded from the analysis.

2.4. Measures

Mediator (Total Cortical Volume): The primary outcome of interest was total cortical volume, measured using MRI data collected as part of the ABCD study's neuroimaging protocol. Cortical volume was calculated by summing the volumes of cortical gray matter across both hemispheres, using FreeSurfer software for brain image processing.

Predictor (Family Income to Needs Ratio): The key independent variable was family **income to needs ratio**, measured at the level of family, considering household income and family size, and poverty ration. This was treated as a continuous variable, representing higher SES.

Outcome (Tobacco Use Initiation): Tobacco use initiation was defined as the first reported use of any tobacco product, including cigarettes, e-cigarettes, and other tobacco-related products, at any follow-up assessment during the study period.

2.5. Covariates

We controlled for several demographic variables that could influence brain development, including the child's age, sex, and parental marital status. Marital status was categorized as married or not married. Age and sex were included to account for normal developmental differences in cortical volume across children.

2.6. Statistical Analysis

We employed Structural Equation Modeling (SEM) to test the associations between family SES (income to needs ratio) and tobacco initiation, with total cortical volume as a potential mediator and race as a moderator. Our analyses were conducted using SEM in Stata, and we used maximum likelihood estimation to account for missing data. Model fit was assessed using standard indices such as the Comparative Fit Index (CFI) and Root Mean Square Error of Approximation (RMSEA). Significance was evaluated at $p < .05$.

2.7. Ethics

The ABCD study received approval from the Institutional Review Boards (IRBs) at each of the 21 data collection sites. Informed consent was obtained from all parents or legal guardians, and assent was obtained from children before participation. This study's secondary analysis of de-identified ABCD data was exempted from a full IRB review by the Charles R. Drew University of Medicine and Science.

3. Results

3.1. Descriptive Data

Table 1 provides the descriptive statistics for the key study variables. The average age of the children in the sample was 9.48 years (SE = 0.005), with a 95% confidence interval ranging from 9.47 to 9.49. In terms of race, 72.9% of the sample identified as White (SE = 0.006), and 27.1% identified as Black (SE = 0.006). The sample was fairly balanced by gender, with 47.6% of participants identifying as female (SE = 0.007) and 52.4% as male (SE = 0.007). Regarding the marital status of the household, 34.0% of children lived in an unwed household (SE = 0.006), while 66.0% lived in a married household (SE = 0.006).

Table 1. Descriptive Data Overall

	Mean	Std. Err. (SE)	[95% conf. interval]
Age	9.480	0.005	9.470 9.490
	%	SE	[95% conf. interval]
Race			
White	0.729	0.006	0.717 0.740
Black	0.271	0.006	0.260 0.283
Gender			
Female	0.476	0.007	0.463 0.489
Male	0.524	0.007	0.511 0.537
Marital Status of the Household			
Unwed Household	0.340	0.006	0.327 0.352
Married Household	0.660	0.006	0.648 0.673

3.2. Summary of Multigroup Structural Equation Model

Table 2 and Figure 1 present the results of the multigroup structural equation modeling for the pathways from socioeconomic status (SES) to tobacco use initiation via total cortical volume, stratified by racialization as either White or Black. Overall, the results highlight the differences in the pathways from SES to tobacco use initiation via total cortical volume between adolescents racialized as Black and White.

For adolescents racialized as White, the analysis indicates several significant predictors of tobacco use initiation. Total cortical volume is negatively associated with tobacco use initiation ($B = -0.028$, $SE = 0.012$, 95% CI = [-0.053, -0.004], $p = 0.022$), suggesting that higher cortical volume is linked to lower tobacco use risk. Age is positively associated

with tobacco use initiation ($B = 0.087$, $SE = 0.011$, $95\% \text{ CI} = [0.065, 0.108]$, $p < 0.001$), indicating that older adolescents are more likely to initiate tobacco use. The income-to-need ratio also negatively predicts tobacco use initiation ($B = -0.032$, $SE = 0.012$, $95\% \text{ CI} = [-0.054, -0.009]$, $p = 0.006$), suggesting that better socioeconomic conditions reduce the risk of tobacco initiation. However, low neighborhood income does not significantly predict tobacco use initiation ($B = -0.015$, $SE = 0.011$, $95\% \text{ CI} = [-0.037, 0.008]$, $p = 0.197$).

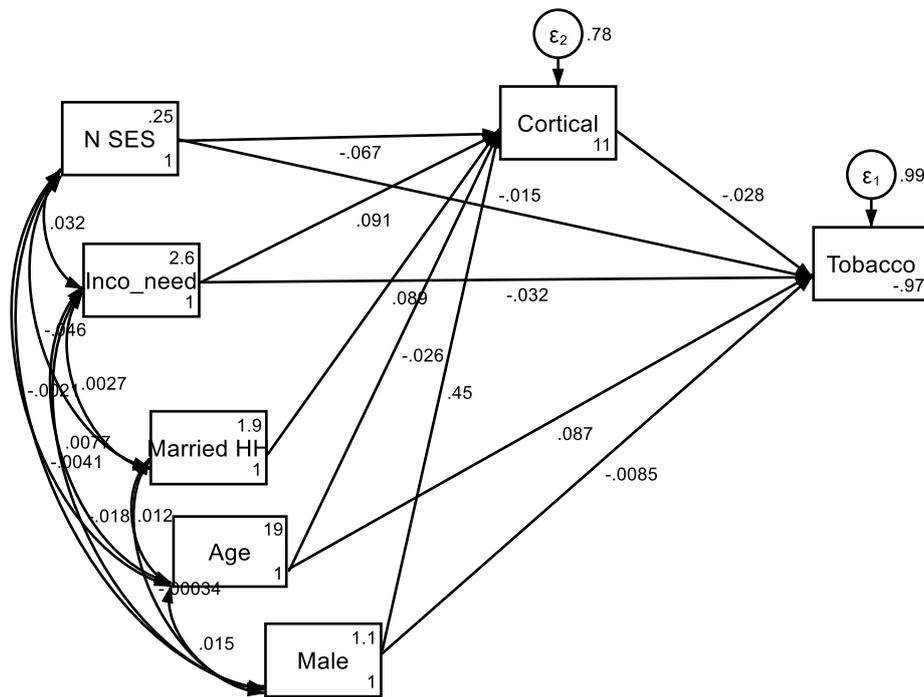
Regarding total cortical volume for adolescents racialized as White, age is negatively associated ($B = -0.026$, $SE = 0.010$, $95\% \text{ CI} = [-0.045, -0.007]$, $p = 0.008$), and male gender positively predicts larger cortical volume ($B = 0.450$, $SE = 0.009$, $95\% \text{ CI} = [0.433, 0.467]$, $p < 0.001$). The income-to-need ratio is positively associated with cortical volume ($B = 0.091$, $SE = 0.010$, $95\% \text{ CI} = [0.071, 0.110]$, $p < 0.001$), while low neighborhood income is negatively associated ($B = -0.067$, $SE = 0.010$, $95\% \text{ CI} = [-0.087, -0.048]$, $p < 0.001$). The model intercept is significant ($B = 10.902$, $SE = 0.206$, $95\% \text{ CI} = [10.497, 11.306]$, $p < 0.001$).

For adolescents racialized as Black, the findings indicate that total cortical volume does not significantly predict tobacco use initiation ($B = -0.004$, $SE = 0.023$, $95\% \text{ CI} = [-0.048, 0.040]$, $p = 0.865$). Age shows a trend toward significance ($B = 0.038$, $SE = 0.020$, $95\% \text{ CI} = [-0.002, 0.077]$, $p = 0.063$), while the male gender and income-to-need ratio do not significantly predict tobacco use initiation ($B = -0.002$, $SE = 0.022$, $95\% \text{ CI} = [-0.045, 0.042]$, $p = 0.931$; $B = 0.023$, $SE = 0.022$, $95\% \text{ CI} = [-0.020, 0.067]$, $p = 0.290$). Low neighborhood income also does not significantly predict tobacco use initiation ($B = -0.015$, $SE = 0.021$, $95\% \text{ CI} = [-0.056, 0.027]$, $p = 0.482$). The intercept is not significant ($B = -0.447$, $SE = 0.452$, $95\% \text{ CI} = [-1.333, 0.439]$, $p = 0.323$).

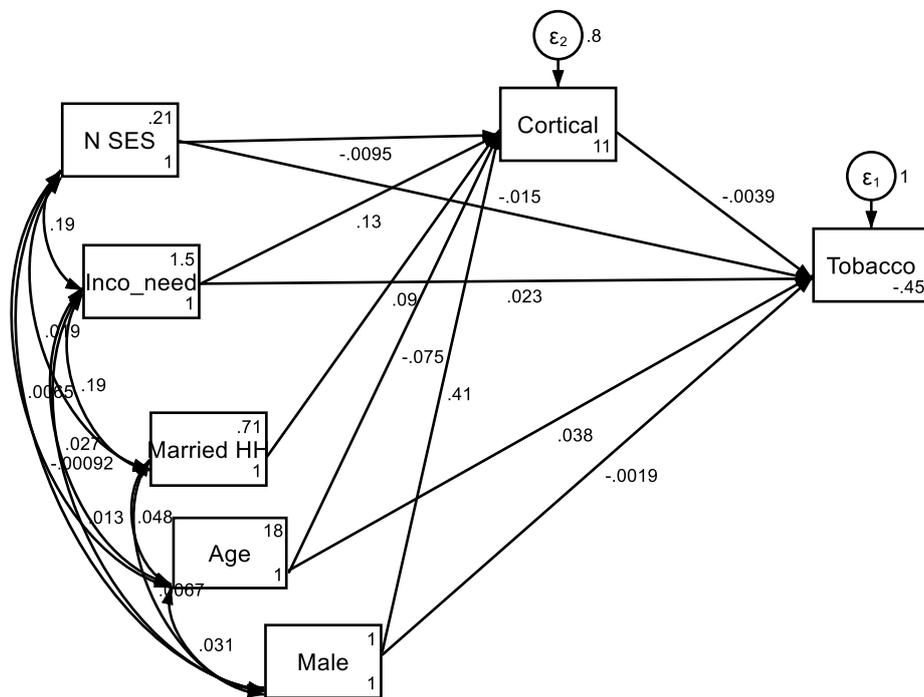
For total cortical volume among adolescents racialized as Black, age negatively predicts cortical volume ($B = -0.075$, $SE = 0.018$, $95\% \text{ CI} = [-0.111, -0.040]$, $p < 0.001$). Male gender is positively associated with cortical volume ($B = 0.413$, $SE = 0.017$, $95\% \text{ CI} = [0.380, 0.445]$, $p < 0.001$). The income-to-need ratio positively predicts cortical volume ($B = 0.129$, $SE = 0.020$, $95\% \text{ CI} = [0.089, 0.168]$, $p < 0.001$), while low neighborhood income does not show a significant association ($B = -0.009$, $SE = 0.019$, $95\% \text{ CI} = [-0.048, 0.029]$, $p = 0.626$). The intercept is significant ($B = 11.308$, $SE = 0.364$, $95\% \text{ CI} = [10.594, 12.022]$, $p < 0.001$).

Table 2. Summary of multigroup structural equation model

		B	SE	95%	CI	p
Racialized as White						
Outcome	Predictor					
Tobacco Use Initiation						
	Total Cortical Volume	-0.028	0.012	-0.053	-0.004	0.022
	Age	0.087	0.011	0.065	0.108	< 0.001
	Male	-0.008	0.012	-0.033	0.016	0.493
	Income to Need Ratio	-0.032	0.012	-0.054	-0.009	0.006
	Low Neighborhood Income	-0.015	0.011	-0.037	0.008	0.197
Total Cortical Volume						
	Age	-0.026	0.010	-0.045	-0.007	0.008
	Male	0.450	0.009	0.433	0.467	< 0.001
	Income to Need Ratio	0.091	0.010	0.071	0.110	< 0.001
	Married Household	0.089	0.010	0.070	0.108	< 0.001
	Low Neighborhood Income	-0.067	0.010	-0.087	-0.048	< 0.001
Racialized as Black						
Tobacco Use Initiation						
	Total Cortical Volume	-0.004	0.023	-0.048	0.040	0.865
	Age	0.038	0.020	-0.002	0.077	0.063
	Male	-0.002	0.022	-0.045	0.042	0.931
	Income to Need Ratio	0.023	0.022	-0.020	0.067	0.290
	Low Neighborhood Income	-0.015	0.021	-0.056	0.027	0.482
Total Cortical Volume						
	Age	-0.075	0.018	-0.111	-0.040	< 0.001
	Male	0.413	0.017	0.380	0.445	< 0.001
	Income to Need Ratio	0.129	0.020	0.089	0.168	< 0.001
	Married Household	0.090	0.018	0.054	0.126	< 0.001
	Low Neighborhood Income	-0.009	0.019	-0.048	0.029	0.626



Racialized as White



Racialized as Black

Figure 1. Summary of structural equation models

Note: Data Source: ABCD Study; HH: Household; N SES: Neighborhood Socioeconomic Status; Tobacco: Tobacco Initiation; Cortical: Total Cortical Volume

4. Discussion

Diversity in neuroscience research is essential for understanding how brain development and behavior may vary across different racial and ethnic groups. Stigmatizing this diversity not only perpetuates harmful stereotypes but also leads to inaccurate scientific conclusions and misguided policy decisions. The Adolescent Brain Cognitive Development (ABCD) study offers a unique opportunity to explore the complex interplay between social, environmental, and biological factors in a diverse sample, helping to address gaps in the literature. Failing to recognize this diversity could lead to the incorrect assumption that achieving socioeconomic (SES) equity alone would eliminate racial disparities in development and behavior. This belief overlooks the deeply rooted structural inequalities that affect minoritized and racialized populations and may result in the continuation of policies that do not address the broader social context contributing to these disparities.

The aim of this study was to examine racial variation in the pathways from family and neighborhood SES to tobacco use via cerebral cortical volume. We hypothesized that the positive associations between SES and total cortical volume, as well as between cortical volume and tobacco initiation, would be weaker for Black adolescents compared to White adolescents. This hypothesis was grounded in the framework of Marginalization-Related Diminished Returns (MDRs), which posits that minoritized and racialized groups experience fewer benefits from higher SES due to structural inequalities.

Our findings confirmed that the pathways from SES to brain structure and from brain structure to tobacco use were both weaker in Black adolescents compared to White adolescents. Specifically, we found that the link between income (through the needs-to-income ratio) and total cortical volume was significantly attenuated in Black youth. Similarly, the association between larger cortical volume and a lower likelihood of initiating tobacco use was also weaker in Black youth. These results were consistent over the 4-6 years of follow-up in the ABCD dataset.

These findings align with the existing Marginalization-Related Diminished Returns (MDRs) literature, which has demonstrated that the health and developmental benefits of higher SES are often diminished for racial and ethnic minorities. Our study adds to this body of work by showing that the weakened associations between SES, brain development, and behavior extend to neural structures like the cerebral cortex and health behaviors like tobacco use in adolescents.

Importantly, these diminished returns are not due to any biological inferiority or superiority of one racial group over another. Instead, they reflect the long-standing effects of structural racism, including segregation, social stratification, and systemic inequality. These structural inequities are deeply rooted in the historical legacies of slavery, Jim Crow laws, and ongoing forms of racial discrimination. These social conditions have created environments where even high SES does not afford the same protective benefits to Black individuals as it does to White individuals, due to the cumulative effects of stress, discrimination, and reduced access to resources.

Structural racism deeply impacts all aspects of life for individuals racialized as Black, and SES alone is not sufficient to protect against its pervasive effects [62-67]. While higher SES provides certain advantages, such as access to better resources and opportunities, it does not shield Black individuals from the systemic inequalities embedded in institutions, policies, and social practices. As an umbrella cannot stop the rain [68], SES cannot fully mitigate the racial discrimination and structural barriers that Black people face. In fact, race is often more visible and salient than SES, meaning that even Black individuals at higher SES levels continue to experience significant discrimination and marginalization. Research shows that Black individuals with higher incomes and education levels often encounter more intense forms of discrimination, particularly in professional and social environments, as they challenge societal stereotypes. This persistent exposure to racism

across SES levels undermines the potential protective effects of higher SES on health, brain development, and behavior, contributing to the Marginalization-Related Diminished Returns (MDRs) observed in the pathways from SES to outcomes such as brain structure and tobacco use. These realities underscore the need to address structural racism directly, as SES alone cannot counterbalance the entrenched racial inequalities that shape the lives of Black individuals [69-74].

4.1. Limitations

While this study offers important insights, several limitations should be noted. First, the ABCD study is ongoing, and the follow-up period, while substantial, is still limited to early adolescence. Longitudinal data extending into late adolescence and early adulthood will be critical for understanding the long-term effects of these pathways. Second, while we controlled for several key variables, unmeasured confounding factors such as community-level stressors or access to healthcare may also influence the observed associations. Finally, although the ABCD dataset is diverse, further research is needed to explore these pathways in other minority groups, such as Hispanic and Native American adolescents.

4.2. Future Directions

Future research should focus on policies and interventions aimed at undoing the effects of structural inequalities. This includes providing resources that can help equalize opportunities, such as improved educational systems, equitable access to healthcare, and support for families in low-SES communities. The role of peers, schools, and family environments should also be examined as potential buffers against the negative effects of low SES. Research should move beyond merely describing the problem of inequality to developing solution-based approaches that address the underlying social determinants of health and behavior.

4.3. Implications

The implications of this study are clear: addressing racial disparities in brain development and behavior requires more than improving SES alone. Policymakers and researchers must consider the broader social context, including the pervasive effects of structural racism, if they hope to reduce health disparities. Programs aimed at reducing tobacco use or improving adolescent brain health need to be tailored to account for the unique challenges faced by minority youth, particularly in terms of how SES-related benefits are constrained by systemic barriers.

5. Conclusion

In conclusion, this study highlights the importance of considering racial variation in the pathways from SES to brain development and behavior. Our findings support the MDRs framework, showing that Black adolescents experience weaker links between SES, brain structure, and tobacco use than their White peers. These results underscore the urgent need to address structural racism and to design interventions that can help equalize the effects of SES across diverse populations, ultimately promoting better health outcomes for all youth.

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