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Acute and chronic lead exposure and intelligence quotient among Indonesian adolescents: a cross-sectional study

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Article Info	ABSTRACT
	Lead exposure is a persistent environmental health concern that can impair cognitive function in adolescents. Therefore, this study aims to examine the association between acute and chronic lead exposure and intelligence quotient (IQ) scores among Indonesian adolescents. A cross-sectional study was carried out involving 39 adolescents who were chosen through purposive sampling. Acute exposure was assessed using blood lead levels (n = 15), while chronic exposure was evaluated with hair lead levels (n = 24). IQ was measured using WAIS administered by a licensed psychologist, while associations between the variables were examined utilizing the Chi-square test. The results revealed that chronic lead exposure was significantly linked to below-average IQ (OR = 1.90; 95% CI: 1.07–3.36), while acute exposure had a weaker relationship (OR = 0.35; 95% CI: 0.13–0.89; p = 0.022). These results indicated the importance of long-term environmental exposure control.

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1. INTRODUCTION

The results of the 2023 PISA are supported by the World Population Review report published in 2024, showing that the average intelligence quotient (IQ) of Indonesians is 78.49. This figure places Indonesia in 129th place out of 197 countries tested [1]. Various factors can influence the low average IQ found in the country, such as environmental pollution resulting from industrialization and modern human activities. Exposure to heavy metals, such as lead, has been associated with reduced IQ. Studies on the impacts of lead disclosure on adolescents' mental health found that concentrations above 5 micrograms/dL lowered IQ scores by up to 4.9 points. The results are plausible, particularly considering that environmental pollution is among the factors causing damage to the central nervous system (CNS). This form of pollution is usually caused by different factors, including contaminants from motor vehicle exhaust. Consequently, schools located relatively close to highways are more vulnerable, with students being at risk of having lower IQ scores [2].

Lead affects the body's internal organ systems, including the nervous system [3]. The metal's capacity to traverse the blood-brain barrier (BBB) via active transport mechanisms moderated by divalent metal transporter 1 (DMT1) and ZIP proteins suggests its potential to collect in the central nervous system (CNS) [4], [5]. Furthermore, fetuses and young children are specifically susceptible to the neurological effects of lead because their developing nervous systems absorb a larger proportion. A previous study supports this, indicating that adolescents have a significantly higher balance of circulating lead reaching the brain compared to adults [6]. Adolescents have been shown to potentially become inattentive, hyperactive,

and irritable with low lead exposure. This demographic, when exposed to higher lead levels, may experience deferred growth, reduced intelligence, short-term memory loss, and hearing loss. At higher concentrations, this toxic metal can lead to irreversible brain damage and potentially death [7].

According to previous studies, low-level lead exposure can substantially impact IQ, as well as the behavior, concentration, and attention span of adolescents, leading to peripheral neuropathy. The metal can also lead to decreased motor activity because it causes the loss of the myelin sheath that insulates nerves. This significantly impairs the transmission of nerve impulses, leading to muscle faults, especially in the outer muscles, fatigue, and poor coordination [8]. A previous study revealed that beef and chicken sold in open-air markets along heavily trafficked roads can harbor lead contamination in the air [9].

Industrialization has been shown to increase the risk of soil and water pollution, which are susceptible to lead exposure. Typically, this toxicity is caused by the metal smelting industry, textile dyeing, fuel (gasoline residue), and the addition of chemical pesticides in agriculture (pesticide residue) [10], [11]. The environmental factor that has been a primary concern in the emergence of problematic behavior is the social environment. This includes parenting patterns and social circles. However, a broader understanding of the environment is needed, since behavior is not only influenced by the social environment but also by the physical environment. This elucidation is supported by a recent study on intelligence in Indonesia, which found 2 influential factors, namely genetics and the environment. Environmental factors are related to nutrition, education, and social interaction. Heavy metal exposure is often found in the physical environment of modern societies characterized by industrial progress, including heavy metal toxicology from lead [12].

Despite extensive evidence linking lead exposure to cognitive impairment, few studies have directly compared acute and chronic exposure patterns in the same population, especially in low- and middle-income countries. In Indonesia, rapid urbanization and traffic- related pollution increase the risk of sustained lead exposure among adolescents. This study proposes to investigate the relation between blood and hair lead levels and IQ scores, providing evidence to inform school-based and environmental health interventions.

2. METHOD

This study design was a cross-sectional quantitative study, using purposive non-random sampling to ensure inclusion of the source of lead exposure (gasoline residue), age, duration, and length of lead exposure in a day. The study participants were divided into two groups: an acute and a chronic group exposed to lead, as shown in Table 1. Ethical approval confirmed that the study protocol met all institutional and international ethical standards. The small sample size may decrease statistical power and limit generalizability. Confounding variables in this study included lifestyle and occupation.

Table 1. Sampling procedure

Group	Inclusion criteria	Lead exposure samples	Instrument	sample preparation	IQ test instrument and procedure	Number of samples
Acute group	At the age of 18 years worked as an online motorcycle taxi driver for 3 years working time of 8 hours per day.	Lead levels in blood of students	GFAAS instrument in the Health Laboratory Center (BLK) in Yogyakarta.	Taking 3 cc of blood samples, which were collected in a purple vacuum tube and stored in an ice box.	IQ data was assessed by observing the WAIS test results, which had been accompanied by norms to categorize IQ levels by a professional psychologist from Nuha Solution (psychological examination services) in Surakarta.	15 students
Chronic group	In the age 18 years in grade XII (have been in school for 3 years) 8 hours of study time per day school location on the side of the highway.	Lead levels in the hair of students	AAS instrument at the Center for Environmental Health Engineering and Disease Control (BBTKLPP) in Yogykarta.	Taking hair samples (100-200 hairs), after which the samples were tied with cotton thread at the root end, cutting each as close as possible to the scalp (2 mm), and placing them in a tamper-proof envelope, and closed appropriately.		24 students

Data analysis was achieved using SPSS version 23. Both descriptive and inferential statistical methods were applied to interpret the collected data. Descriptive statistics were used to present the distribution of participants. These results were presented as means, standard deviations, and frequency distributions to provide an overview of the study population. Inferential analysis employed the Chi-square test to evaluate the odds of IQ decline in individuals with acute compared to chronic lead exposure. The significance threshold was established at $p < 0.05$, with a 95% confidence interval.

3.   RESULTS AND DISCUSSION

The results showed that lead levels were still within normal limits according to CDC standards. The CDC recommends safe blood lead levels of less than 10 μg/dL for adults and less than 5 μg/dL for adolescents. This recommendation was based on a previous study in children aged 6 to 16 years from the NHANES III dataset, which demonstrated a significant link between blood lead levels below 5 μg/dL and poor academic performance [13], [14]. Chronic examination parameters using hair, lead levels were said to be in normal thresholds when the level in the hair sample was <4.0 μg/g [15]. When assessed by acute and chronic lead levels, these remained within normal limits. However, when assessed by IQ scores, the average for chronic exposure was lower than that of acute exposure, as shown in Figure 1.
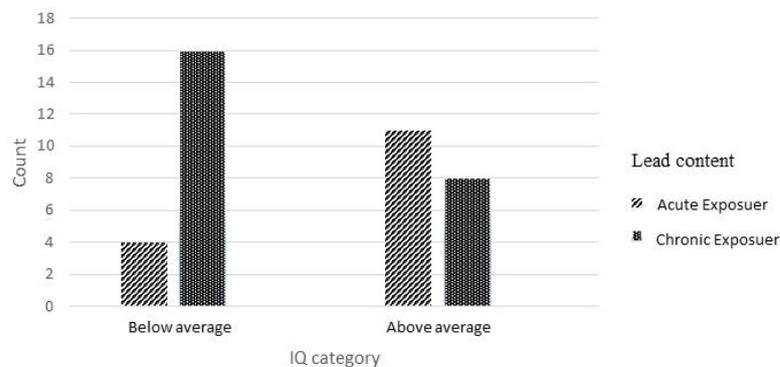

Figure 1. IQ category graph based on type of exposure (acute and chronic)

Acute exposure required a longer reaction time than chronic exposure, and those in 2 years did not cause significant cognitive decline. The effects of lead exposure on cognitive parameters have been widely documented in chronic exposure studies, particularly with respect to memory and learning. Lead replaced calcium in various regulatory events involving calmodulin, disrupting energy metabolism and calcium release from mitochondria, which leads to the priming of programmed cell death. These neurophysiological changes disrupted synaptic connectivity and neurogenesis, both of which play essential roles in neural plasticity. Lead exposure played a significant role in synaptic neurotoxicity, with the related cognitive changes linked to its buildup in astroglia and microglia. Astrocytes form the BBB and perform homeostatic regulatory functions that support long-term potentiation, which is important for synaptic plasticity, learning, and memory [16]-[18].

Chi-square test results indicated a p-value of 0.022 (0.05), indicating that both acute and chronic exposure had a statistically significant impact on IQ decline. Acute lead exposure (OR: 0.345, 95% CI = 0.133-0.899) showed a negative effect on IQ, but it was milder than chronic exposure (OR: 1.900, 95% CI = 1.073-3.363). This study observed that chronic lead exposure, assessed through hair samples, was more strongly associated with reduced IQ than acute exposure measured by blood lead levels. Based on previous observations, environmental exposure to lead caused neurotoxic effects, which manifested as changes in nervous system function, such as cognitive impairment, mental health or mood disorders, and neuromotor dysfunction [19].

In the context of this exploration, Table 2 showed that the group with chronic lead exposure resulted in 66.7% of adolescents having below-average IQs. Meanwhile, acute exposure showed that 33.3% also had below-average IQs. Lead poisoning in adolescents could reduce intelligence. Based on observations, when lead levels found in the blood of adolescents were 3 times the normal limit (normal intake is around 0.3 milligrams per day), there was a decrease in IQ below 80. This form of brain dysfunction typically occurred because lead competitively replaced key minerals such as zinc, copper, and iron, which were essential for regulating CNS function. This reduced an adolescent's chances of success in school [20].

Adolescent students with IQ decline experienced difficulties in developing adaptive behavior, which directly impacted their daily lives. Common problems faced by this demographic included learning difficulties, adjustment difficulties, and personality issues [21]. Learning activities were directly related to intellectual abilities. This was evidenced by the fact that learning required at least the ability to remember and understand, as well as the capability to identify cause-and-effect relationships. Adolescent students with IQ decline exhibited difficulty thinking abstractly. For this group of individuals, any learning experience must be related to concrete objects. This condition was associated with weak short-term memory, poor reasoning, and difficulty in developing ideas [22].

A previous study reported that adolescent students with IQ decline experienced cognitive deficits, reflected in cognitive processes like perception, memory, idea development, evaluation, and reasoning. When engaging this demographic in learning activities, it was expected that the use of complex language could be completely avoided. The language used must be in the form of short, concrete, single sentences in order to foster easy understanding among adolescents with IQ decline [23].

This was supported by the Chi-square test results (Table 3), which indicated a p-value of 0.022 (0.05), indicating that both acute and chronic exposure had a statistically significant impact on IQ reduction. Adolescents with higher levels of lead were affected by delayed growth, decreased intelligence, memory complications (short-term memory), and hearing impairment at a higher level of severity. Furthermore, lead caused irreversible brain damage and even death [6]. Memory components were proven to influence academic achievement in addition to psychometric intelligence. Specifically, working memory (WM), the ability to process and retain information, was associated with performance on various cognitive tasks, such as reasoning and verbal comprehension. As reported by previous explorations, a relationship existed between WM and intelligence, as well as between short-term memory, WM, and IQ [24].

Toxic metals like lead, mercury, and cadmium have adverse effects, leading to neurodevelopmental disorders, neurodegenerative diseases, and growth delays in adolescents [25]. Moreover, the use of lead in industry had resulted in widespread environmental contamination and severe toxicity, including neurological diseases, developmental problems in adolescents, and chronic diseases [26]. Globally, the usage of tetraethyl lead in gasoline was a significant contributor to air pollution and lead exposure. The ongoing growth in blood lead levels after the ban on leaded gasoline was supposed to result from environmental exposure, particularly given the proximity of residential areas to industries prone to lead contamination.

Lead was ubiquitous and neurotoxic, particularly harmful to adolescents, who were more vulnerable than adults to its toxic effects. The prevalence of lead poisoning and iron deficiency had been observed to be high in socioeconomically vulnerable populations, negatively impacting neurocognitive development in adolescents. Observations indicate that over half of the US people was exposed to harmful lead levels in childhood, stemming from the historical use of leaded gasoline. Although the overall impact of childhood lead exposure on mental health and character traits in the US population has not yet been evaluated. A significant portion of mental illness symptoms and adverse personality traits in US adolescents over the past 75 years could be linked to lead exposure. The potential harmful impact of this toxic metal on psychiatry, medicine, and adolescent health might be more significant than previously estimated [27].

Once inside the CNS, lead disrupts neural homeostasis by inhibiting neurotransmitter systems, increasing oxidative stress, and activating microglial cells. This led to neuroinflammation and nerve damage [28]. Other studies have shown that lead was proven to inhibit the function of NMDA receptors, thereby disrupting synaptic plasticity and learning processes [29]. Several studies consistently highlight the negative impact of lead exposure on children's mental and behavioral development. Previous study showed a strong negative relationship between lead levels and visual-perceptual progress in children with learning problems, as measured by the Bender Visual-Motor Gestalt Test. The study demonstrated that even minimal lead exposure could harm visual-motor skills [8]. Other studies showed that exposure to lead severely affected learning and memory, as well as IQ of children, found to be inversely proportional to blood lead levels [30].

Lead was referred to as a heavy metal, along with mercury, chromium, cadmium, and arsenic. This metal generally enters the human body through the digestive system, respiratory system, and skin [31]. Lead's toxicology was dangerous because its ionic mechanism enabled it to substitute for other bivalent cations like Ca^{2+}, Mg^{2+}, Fe^{2+}, as well as monovalent cations such as Na+. As stated in a previous exploration, the metal could invariably affect fundamental biological processes in the human body [32]. Continuous lead accumulation in the body significantly affected various processes, including disrupting intercellular signaling, cell adhesion, protein folding and maturation, ionic transport, apoptosis, enzyme regulation, and neurotransmitter release [33]. Lead further influenced sodium ion concentration, which is crucial for vital biological functions such as responding to stimuli in excitatory networks for cell-to-cell communication, neurotransmitter uptake (including dopamine, choline, and GABA), and managing calcium utilization and retention by synaptosomes. The interaction between lead and sodium also interfered with sodium's normal function [34], [35].

The impact of both chronic and acute lead exposure on IQ scores, when not addressed seriously through policy and public education, could increase the risk of adolescent students with IQ decline, making the demographic less suited for executive-level jobs where decision-making was considered core. According to [30], lead exposure at levels of 10-30 µg/dL was linked to a 2 to 3-point drop in IQ scores during the study. Furthermore, a 1 µg/dL increase in blood lead level was linked to a 0.5-point decrease in IQ test scores for both arithmetic and reading skills.

The educational challenges adolescent students with IQ decline often face made the group vulnerable to employment-related issues, particularly due to low work skills and reduced productivity. This diminished productivity was observed to be closely related to chronic nutritional problems commonly experienced by individuals in the group. Persistent nutritional deficiencies invariably increased the risk of conditions such as anemia and stunting, both of which were frequently caused by iron deficiency. A lack of iron reduced the brain's oxygen supply, which affected neurotransmitter function, decreased synaptic plasticity, and led to cognitive decline. Furthermore, a previous exploration stated that a 1g/dL drop in hemoglobin levels lowered IQ scores by 2–3 points [36]. Among the environmental contributors to iron deficiency, exposure to heavy metal lead was reported to be a significant factor.

Table 2. Descriptive data on lead exposure in chronic and acute exposure groups

Description	Chronic exposure		Acute exposure	
	Lead in hair (µg/g)	IQ test scores	Blood lead level (µg/L)	IQ test scores
Min	0.01	52	10.6	85
Max	0.468	136	17.8	106
Mean	0.175	80.79	10.4	92.64
Standard deviation	0.137	23.668	39.21	5.87

Table 3. The Chi-square test results for lead levels versus IQ

Variable	Below average IQ (n = 20) Total (%)	Above-average IQ (n = 19) Total (%)	Total (n = 39) Total (%)	OR (95% Confidence Interval)	p-value[a]
Acute exposure (Blood sample in µg/L)	4 (26.7)	11 (73.3)	15 (100.0)	0.345 (0.133 - 0.899)	0.022*
Chronic exposure (Nail sample µg/g)	16 (66.7)	8 (33.3)	24 (100.0)	1.900 (1.073 - 3.363)	

Figure 2 shows the environmental impact of industrialization, including transportation, which contributed to air pollution. This form of air pollution contaminates water and soil, creating a pathway for heavy metal exposure, particularly lead, to accumulate in the environment and enter the human body through respiration and digestion. As previously stated, both chronic and acute exposure to heavy metals could produce toxicological effects, particularly by interfering with nutrient absorption, and this could essentially lead to conditions such as anemia and stunting. Anemia and stunting reduced the amount of oxygen circulating in the body, including to the brain. A decreased oxygen supply, whether due to low hemoglobin levels or elevated lead exposure, could impair cognitive function and lower intelligence scores [37], [38]. Over time, both chronic and acute lead exposure lowered not only intelligence but also immunity levels [21]. Considering this situation, it was essential to state that as cognitive and physical health deteriorated, individuals became less productive. As a result, the probability of school dropouts as well as unemployment invariably increased, all of which were factors that contributed to rising poverty and crime rates.

In the health sector, policies targeting residential areas and schools vulnerable to pollution exposure must mandate routine health screenings to monitor risks related to impaired nutrient absorption, anemia, and vitamin D deficiency. Students identified as being at risk for anemia and vitamin D deficiency must also be provided with targeted interventions, including supplementation and a nutritious diet tailored to specific nutritional needs. Previous investigations reported that adolescents exposed to lead frequently had lower vitamin D levels and higher inflammatory markers. Lead-induced chronic inflammation could impair vitamin D absorption in adolescents, which in turn may promote the development of immune-mediated diseases. This consistently highlighted the importance of interventions to lower lead exposure and safeguard adolescents from immunological diseases and negative health effects [39].

Lead exposure remained a very significant public health concern, contributing to an estimated 0.9 million deaths and 21.7 million disability-adjusted life years lost globally due to prolonged exposure. WHO estimated that approximately 30% of idiopathic developmental intellectual disabilities were attributable to long-term lead exposure. Considering the fact that over 80% of the general population, without any known occupational or environmental exposure, showed detectable levels of lead. Therefore, systematic

investigations to identify potential sources of lead contamination were essential for mitigating further exposure and associated risks [27], [40]. This study had several limitations, such as a small sample size, bias in sampling, and the absence of control for confounding factors such as nutritional status, socioeconomic status, and parental education level. Further study was needed to determine whether these results were causal, and it was important to implement exposure prevention as early as possible.

Figure 2. Low performance and productivity caused by lead exposure

4. CONCLUSION

In conclusion, chronic lead exposure shows a stronger association with reduced IQ compared to acute exposure. These results emphasize the importance of long-term environmental exposure control, particularly in school environments near major traffic sources.

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Noviana Dewi	✓	✓			✓	✓	✓	✓	✓	✓			✓	✓
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C	:	Conceptualization	I	:	Investigation
M	:	Methodology	R	:	Resources
So	:	Software	D	:	Data Curation
Va	:	Validation	O	:	Writing - Original Draft
Fo	:	Formal analysis	E	:	Writing - Review & Editing

Vi : Visualization
Su : Supervision
P : Project administration
Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

No conflict of interest.

INFORMED CONSENT

All participants were thoroughly briefed on the study's objectives, procedures, potential risks, and benefits, as well as provided written informed consent prior to participation. The study followed the ethical principles of the Declaration of Helsinki, ensuring confidentiality, anonymity, and voluntary participation.

ETHICAL APPROVAL

This study acquired approval from the UMP Health Study Ethics Committee, Indonesia (Ethical Clearance No. KEPK/UMP/83/III/2022). Ethical approval confirmed that the study protocol met all institutional and international ethical standards.

DATA AVAILABILITY

The data supporting the study results are available from the corresponding author upon proper request.

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