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Possible adverse effects of mining activity on the neurocognitive development of children in the area of Cerro de Pasco (Perú)

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ABSTRACT

Over the last 10 years there have been a number of studies examining the effects of exposure to environmental metal pollution on the population of the area of Cerro de Pasco (Peru). These have documented the prolonged pollution of the area caused by mining activity and recorded its pathological effects on the exposed population. The present work reports associations between the concentrations of metals in the hair of the area's children and their cognitive development, investigates the neurocognitive effects of exposure, and examines the change in environmental metal concentrations over time. Significant differences in hair metal concentrations were detected between exposed (case) and non-exposed (control) populations; in the former, the mean arsenic concentration was three times that of the latter, the cadmium concentration was double, and that of lead six times that of the latter. The mean total IQ of the exposed children was 12.3 points lower than those who were not exposed. Significant correlations were detected between the lead, cadmium, arsenic, manganese and antimony concentrations of the children's (combined exposed and non-exposed) hair and TIQ. In the exposed population, marked increases in hair metal concentrations were recorded between 2016 and 2018 (200 %), later falling by 2021 (though still exceeding the 2016 concentrations). Multivariate analyses involving big data are required to determine the covariables that influence the development of TIQ in exposed children, and to determine whether high toxic metal concentrations are an independent risk factor for cognitive deficit.

1. Introduction

Although some heavy metals are found naturally in living organisms, and indeed are essential for certain basic functions [1], high concentrations of the same can have negative effects on health. The growth in the demand for electronic goods has led to an increase in the mining of the metals required to make them. In high income countries this generally involves specialised machinery and a qualified workforce, but in low and middle income countries such activity is predominantly artisanal, and most mines follow few health and safety regulations; indeed, many are entirely illegal [2].

Recent studies performed in the Cerro de Pasco area (Peru) have documented the prolonged environmental contamination associated with such mining, and the pathological effects this has had on the exposed population. In 2017 a provincial health emergency was declared given the population's high concentrations of lead (in blood), and arsenic, mercury and cadmium (in urine). The 2018 report of the Regional Health Directorate (*Dirección Regional de Salud*; DIRESA) also highlighted the high urine arsenic concentrations of children and pregnant mothers in the studied areas [3].

High body heavy metal concentrations increase the risk of numerous health problems [4], including neurodevelopmental abnormalities [5–8]. The present work reports the associations between the concentrations of metals in the hair of children living in the Cerro de Pasco area and their cognitive development, investigates the neurocognitive effects of exposure, and examines the change in environmental heavy metal concentrations over time.

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2. Results

2.1. Metal concentrations and their relationships with neurocognitive ability and IQ

Eighty one exposed and 17 unexposed children to the mine participated in the study. The gender ratio of the exposed children was 1:1 (39 boys and 42 girls) and two third of the unexposed population were males. Table 1 shows the psychosocial characteristics of the exposed and non-exposed children.

Table 2 shows that the mean hair metal concentrations of the exposed children (case group) were higher than those of the non-exposed children (control group). The concentrations recorded in the exposed children exceeded the MAVs set by the Micro Trace Laboratory [9]. In the exposed children, the mean concentration of the potentially toxic metal antimony (0.11 kg mg/Kg) was twice that recorded in the non-exposed children. In addition, in the exposed children, the mean hair lead concentration was 43 times the MAV, iron was 4 times the MAV, and manganese and aluminium 7 and nearly 4 times their respective MAVs.

Table 3 shows that, for the combined exposed and non-exposed groups, age was directly correlated with hair zinc concentration (r = 0.35; R2 =0,12, p = 0,04), and inversely with the arsenic (r = -0.28; R2 = 8 %; p = 0.005), lead (r = -0.22; R2 = 5 %; p = 0.03) and cadmium (r = -0.20; R2 = 4 %; p = 0.04). No significant relationship was seen between sex and any hair metal concentration, although the cadmium concentration of the boys' hair was notably higher (mean 0.071 mg/kg compared to 0.047 mg/kg in the girls), possibly an indication of differences in this metal's metabolization.

Table 1
Psychosocial characteristics of the exposed and non-exposed children.

	Exposed (Paragsha)	Non-exposed (Carhuamayo)
Characteristics	**(%) (n)**	
Mean age	**10.07 years**	**10.76 years**
Sex		
Boys	48 % (39)	65 % (11)
Girls	52 % (42)	35 % (6)
Mean IQ compared to national average (82 points [34])		
Above average	59 % (48)	94 % (16)
Below average	41 % (33)	6 % (1)
Behavioural symptoms		
Irritability	28 % (23)	24 % (4)
Timidity	17 % (14)	35 % (6)
Stress	68 % (55)	53 % (9)
Health problems		
Respiratory problems	25 % (20)	53 % (9)
Digestive problems	26 % (21)	12 % (2)
Dermatological problems	7 % (6)	0 % (0)
Musculoskeletal problems	19 % (15)	0 % (0)
Neuralgias	19 % (15)	0 % (0)
Blood problems	27 % (22)	6 % (1)
Others	31 % (25)	18 % (3)
Dust in the home (not mentioned in the text)		
None	6 % (5)	24 % (4)
Little	11 % (9)	24 % (4)
Regular	44 % (36)	34 % (6)
A lot	38 % (31)	18 % (3)
Getting out to parks and green spaces		
Yes	46 % (37)	35 % (6)
No	54 % (44)	65 % (11)
Source of drinking water		
Lake/reservoir	15 % (12)	24 % (4)
Public tap/fountain/cistern	16 % (13)	24 % (4)
Tap at home	9 % (7)	52 % (9)
Mine reservoir water	1 % (1)	-
Water provided by the mining company	55 % (45)	-
Others	4 % (3)	-
Source of water for sanitary purposes		
Drain/community pipeline	9 % (7)	6 % (1)
Lake/reservoir	2 % (2)	-
Public tap/fountain/cistern	9 % (7)	94 % (16)
Tap at home	34 % (28)	-
Tubo	1 % (1)	-
Dada por minera	14 % (11)	-
Otros	31 % (25)	-

Table 2
Mean metal/metalloid concentrations in the hair of exposed and non-exposed children.

Metal (mg/kg)	Micro Trace Mineral Lab. MAV [9] (mg/kg)	Detection limit (LD)	Exposed children (Paragsha; case group)	Non-exposed children (Carhuamayo; control group)
Toxic				
Arsenic	< 0.20	0.20	**0.45***	<DL
Lead	< 0.10	0.20	**4.30***	**0.70***
Mercury	< 0.30	0.10	0.25	0.24
Cadmium	< 0.20	0.02	**0.06***	0.03
Potentially toxic				
Nickel	< 0.85	0.2	<DL	<DL
Barium	< 2.65	0.50	0.98	0.91
Aluminium	< 8	5	**30.01***	**20.84***
Antimony	< 0.20	0.02	0.11	0.04
Tin	0.93	0.20	<DL	<DL
Thallium	< 0.01	0.02	<DL	<DL
Beryllium	< 0.03	0.02	<DL	<DL
Non-essential				
Boron	< 0.84	10	<DL	<DL
Essential				
Cobalt	0.15	0.20	<DL	<DL
Chrome	0.15	1	<DL	<DL
Iron	15	4	**61.73***	**37.99***
Manganese	0.50	0.50	**3.61***	**1.64***
Molybdenum	1	0.20	<DL	<DL
Copper	37	0.20	10.44	9.54
Selenium	1.70	0.20	0.67	0.64
Vanadium	0.15	0.20	<DL	<DL
Zinc	227	1	205.73	190.59

* Value exceeds MAV

Table 4 shows the distribution of the main cognitive variables studied in the exposed and non-exposed children:

To study whether the results of the neurocognitive variables differ between cases and controls, a hypothesis test is established using a two-tailed Student's *t*-test for the difference of means at a significance level of $\alpha = 0.05$. The null hypothesis specifies that $\mu 1 = \mu 2$, while the alternative hypothesis states that $\mu 1 \neq \mu 2$. The following statistic is used for calculating the standard error of the difference of means:

$$Total\ df = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{n_2 - 1}}$$

If applied to the different neurocognitive variables in the study, the results obtained are illustrated in Table 5.

The means of all the neurocognitive variables examined were lower in the exposed children except for processing speed index (PSI). The mean total IQ (TIQ) of the exposed children was 12.3 points lower than that of the non-exposed children (82.5 compared to 94.8). In addition, as shown in Fig. 2, only 59 % of the exposed children had a TIQ above the national average of 82 points [10], compared to 94 % of the non-exposed children. Many more of the exposed children had a TIQ in the 'low' or 'very low' ranges compared to the non-exposed children (24.7 % and 12.3 %, and 5.9 % compared to 0 %, respectively). They also had lower verbal comprehension index (VCI) scores, with 21 % compared to 0 % in the low range, and 13.6 % compared to 5.9 % in the very low range. Most of the non-exposed children retuned perceptive analysis index (PAI) results in the 'intermediate', 'normal/high', and 'very

Table 3
Correlations of age and sex with hair heavy metal concentrations.

	Arsenic	Lead	Mercury	Cadmium	Nickel	Barium	Aluminium	Antimony	Thallium	Beryllium	Manganese	Zinc	Copper
Combined exposed and non-exposed groups													
Age	-0.28	-0.22	0.05	-0.20	0.02	0.22	-0.12	-0.08	-0.17	0.00	-0.14	0.35	0.37
Sex	0.01	0.03	0.08	-0.20	0.17	0.21	-0.04	0.09	-0.06	0.00	-0.13	0.17	0.15
Exposed group													
Age	-0.27	-0.20	-0.04	-0.11	0.06	0.23	-0.09	-0.06	-0.17	0.00	-0.10	0.39	0.37
Sex	-0.03	-0.04	0.10	-0.27	0.20	0.21	-0.01	0.13	-0.09	0.00	-0.20	0.14	0.12

Table 4
Distribution of the main cognitive variables studied in the exposed and non-exposed children.

Variable	Mean	Standard Error	95 % Conf. Interval		Minimum value	Maximum value
			Min	Max		
Exposed children						
TIQ	82.56	1.400	79.77	85.34	51	115
VCI	84.53	1.422	81.70	87.36	53	110
PAI	87.09	1.578	83.95	90.23	51	123
WMI	83.85	1.327	81.21	86.49	56	104
PSI	88.51	1.451	85.62	91.31	53	121
Non-exposed children						
TIQ	94.82	3.349	87.72	101.90	62	119
VCI	95.24	3.579	87.65	102.80	57	119
PAI	101.10	3.294	94.13	108.10	77	133
WMI	92.06	3.125	85.43	98.68	71	120
PSI	92.24	3.137	85.58	98.89	75	126

PAI: perceptive analysis index. PSI: processing speed index. TIQ: total intelligence quotient. VCI: verbal comprehension index. WMI: working memory index.

Table 5
Results for hypothesis testing for the difference of means between cases and controls.

Variables	Sample t value	Critical t value	p valour
TIQ	-3.377	±2.074	0.0027
VCI	-2.781	±2.078	0.0111
PAI	-3.836	±2.064	0.0008
WMI	-2.418	±2.073	0.0243
PSI	-1.079	±2.067	0.2915

PAI: perceptive analysis index. PSI: processing speed index. TIQ: total intelligence quotient. VCI: verbal comprehension index. WMI: working memory index.

high' ranges, while the exposed children returned results predominantly in the lower ranges. The exposed children also more often returned working memory index (WMI) results in the low and very ranges (16 % and 16 % compared to 11.8 % and 0 % for the non-exposed children).

Table 6 shows the (usually inverse) correlations (although weak at $r = <0.33$) between hair metal concentrations and TIQ in the combined exposed plus non-exposed children, and the exposed children separately. The strongest correlations were recorded for lead, arsenic, cadmium, manganese and antimony.

Simple linear regression analysis (for the combined groups) showed hair lead concentration to be significantly associated with TIQ ($r = -0.32$; $R = 0.11$; $p = 0.0011$), explaining 11.5 % ($p = 0.011$) of the value for this variable (Fig. 3).

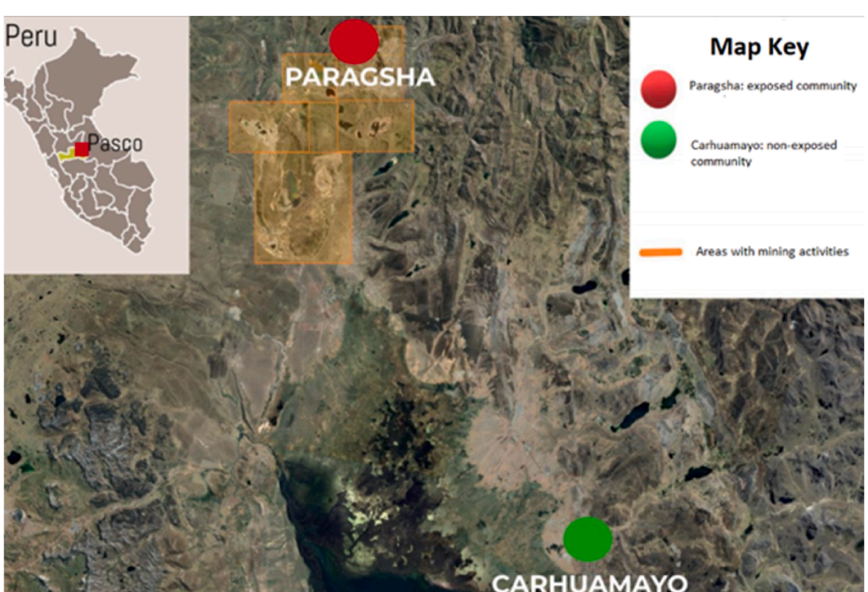

Fig. 1. Geographical distribution of the study areas in Pasco, Peru.

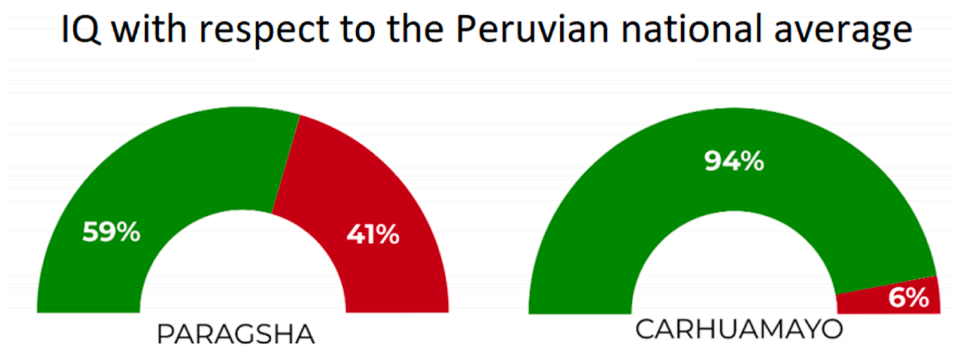

Fig. 2. IQ of the samples compared to the national average value of Peru.

Table 6
Pearson correlation coefficients describing the relationship between hair metal concentrations and total IQ.

Group	Arsenic	Lead	Mercury	Cadmium	Nickel	Barium	Aluminium	Antimony	Thallium	Beryllium	Manganese	Zinc	Copper
Combined exposed/non-exposed	**-0.23**	**-0.32**	0.1	**-0.24**	-0.04	-0.06	-0.09	**-0.21**	-0.03	0	**-0.22**	-0.01	0.07
Exposed	-0.14	-0.18	0.23	-0.15	-0.03	0.02	-0.05	-0.18	0.03	0	-0.11	0.02	0.14

Hair cadmium concentration was also associated, though weaker, with TIQ (r = -0.24; R = 0.06; p = 0.015), as was arsenic (r = -0.23; R = 0.05; p = 0.02), manganese (r = -0.22; R = 0.05; p = 0.03) and antimony (r = -0.21; R = 0.04; p = 0.04). Similar associations were seen between all the above metals and VCI and WMI. A weak, direct relationship was seen between hair mercury and TIQ.

Simple regression analyses were also performed to examine the relationships between hair arsenic, lead, mercury and cadmium (all toxic) and TIQ in the exposed children who fell into the low and very low TIQ ranges (i.e., ≤80 points), but no significant associations were detected.

OLS regression revealed hair lead concentration, adjusted by place of residence (exposed or non-expose area) and the level of maternal education, to be weakly, but significantly, associated with TIQ (r = 0.48; R = 0.23; p = 0.0002). Maternal education level was, in fact, a better predictor of TIQ than the hair lead concentration.

2.2. *Changes in hair heavy metal concentrations over time*

Table 7 shows the mean metal concentrations for the hair samples collected from the exposed population between 2016 and 2021.

The concentrations of metals are measured in mg per kg of hair. The results show that, between 2016 and 2018, there was an increasing trend for hair metal concentrations, while between 2018 and 2021 the trend was downward (except for mercury). However, for most metals, the mean concentration recorded in 2021 was still higher than in 2016; only beryllium and boron returned lower values in 2021 (*this metal was still higher too; see table*). Comparisons of the mean hair metal concentrations in 2018 and 2021 revealed weak correlations (R < 0.25; p < 0.05) for cadmium and manganese, and an approximate 70 % reduction in the hair concentrations of these metals between 2018 and 2021 (Fig. 4).

Table 7
Mean metal concentrations for the hair samples collected from the exposed population between 2016 and 2021.

Metal	Micro Trace Minerals MAV [9] (mg/kg)	Detection limit (DL) (mg/kg)	Exposed children 2016 (mg/kg)	Exposed children 2018 (mg/kg)	Exposed children 2021 (mg/kg)
Toxic metals			**Hair root**	**Hair root**	**Hair root**
Arsenic	< 0.2	0.2	0.4	0.47	0.45
Lead	< 0.1	0.2	3.57	4.58	4.30
Mercury	< 0.3	0.1	0.16	0.24	0.25
Cadmium	< 0.2	0.02	0.07	0.10	0.06
Potentially toxic metals					
Nickel	< 0.85	0.20	0.20	1.96	<LD
Barium	< 2.65	0.5	0.67	1.18	0.98
Aluminium	< 8	5	20.90	30.92	30.01
Antimony	< 0.2	0.02	0.06	0.12	0.11
Tin	0.93	0.20	<LD	42	<LD
Thallium	< 0.01	0.02	<LD	0.02	<LD
Beryllium	< 0.03	0.02	0.02	<LD	<LD

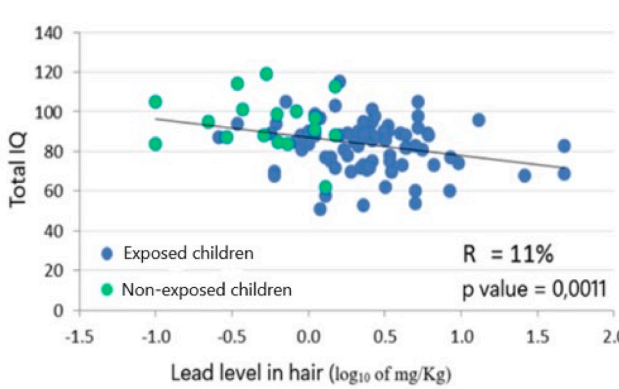

Fig. 3. Simple linear regression analysis describing the relationship between hair lead concentration and TIQ.

3. Discussion

The hair of the children living in Paragsha, i.e., the area exposed to mining activity pollution, had clearly higher concentrations of the elements examined. The difference in the hair concentration of lead between the exposed and non-exposed children was especially notable (4.38 mg/kg compared to 0.70 mg/kg), as it was for arsenic (0.45 mg/kg compared to 0.15 mg/kg) and cadmium (0.06 mg/kg compared to 0.03 mg/kg).

The mean TIQ score for the exposed children (82.5 points) was a full 12.3 points lower than for those who were not exposed (94.8 points), and while 94 % of the latter group had an IQ above the national average (82 points), this fell to 59 % among the former. Moreover, 37 % of the exposed children had an IQ in the low or very low range.

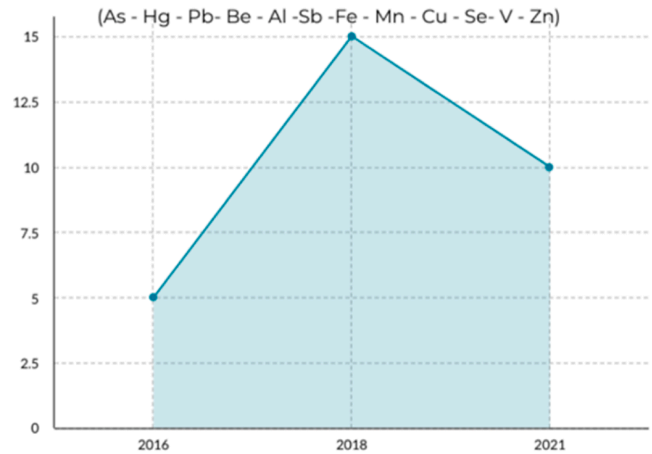

Fig. 4. Mean hair metal concentrations (mg/kg) in the exposed children between 2016, 2018 and 2021.

Taking both groups of children together, weak, inverse correlations were detected between the hair lead, cadmium, arsenic, manganese and antimony concentrations and TIQ. Certain sociodemographic factors were predictive of TIQ (e.g., the combination of maternal education level and area of residence explained 23 % of the TIQ value). Other confounding variables that were not examined may also exist, such as genetic background, educational style and prenatal exposure. Further work involving larger samples and more complete sociodemographic data are needed to determine exactly which metals might most affect neurocognitive development, and what the safe limits of exposure may be.

Between 2016 and 2021 the hair metal concentrations of the exposed children increased (a downward trend was noted between 2018 and 2021, but the 2021 mean values still exceeded those of 2016). This would appear to indicate that the sources of heavy metal pollution are still active in the area exposed to mining activity, and that exposure leads to the accumulation of these metals in the body.

Together, the present results show that hair samples, which are easily collected and analysed, can provide an overview of the degree to which children are exposed to environmental metal pollution. This could provide necessary knowledge for the initiation of remediation processes and the provision of the health and educational services that affected children might need. Despite the inability of the present results to establish a cause-effect relationship between hair metal concentrations and reduction in TIQ, etc., the literature certainly suggests that the above services could be necessary. Exposure to neurotoxic substances can cause alterations in any of the senses, motor abnormalities (even leading to some degree of paralysis), learning difficulties, memory problems, and emotional changes [11]. Previous studies [3,4] have reported that the chronic exposure of children in parts of the Cerro de Pasco area to environmental metal pollution, including heavy metals, is accompanied by health problems such as epistaxis, chronic colic, dermatological abnormalities, white lines in the fingernails, constipation, altered contentment/cheerfulness, and vision problems. Lead, for example, is well known to affect brain development in children, leading to reduced intellectual capacity, behavioural problems such as attention deficit and antisocial behaviour, and reduced educational performance. Unfortunately, these problems can be largely irreversible [12]. One study has linked attention deficit hyperactivity disorder (ADHD) to lead exposure in children aged 8–15 years [13]. It can also cause anaemia, hypertension, kidney failure, immunotoxicity, problems in reproductive function, and cardiovascular and endocrine problems. Such problems may become apparent at blood lead concentrations of < 10 μg/dL [14,15], with every 10 μg/dl increase resulting in a fall in IQ of 2–3 points [16] (this latter study, a meta-analysis, detected no threshold concentration at which lead began to have an effect on IQ).

Present knowledge of how mercury may affect child development has mainly been gleaned from studies on methyl mercury [13,17]. This organic form of mercury has been associated with reductions in IQ, but no studies have examined the effect of elemental mercury. It is, however, known to be nephro-, immuno-, and neurotoxic [18,19]. Indeed, both mercury and methyl mercury vapour are toxic, especially for the brain; they are both rapidly absorbed (mercury vapour at the lungs and methyl mercury vapour at the gut), and since both are lipophilic, they pass easily into the cells of the nervous system, particularly those of the cerebellum. Mercury ions in water are absorbed in the gut and are predominantly nephrotoxic [20]. Children with hair mercury concentrations that exceed the WHO limit have been reported to have an IQ 4.68 points lower than children with concentrations below this limit [21].

Evidence that other metals are toxic is more limited. A study from Quebec, Canada, has reported a significant association between hair manganese concentration (caused by drinking water from a contaminated municipal source) and hyperactive behaviour and disobedience [22]. A Korean study also reports that high blood concentrations of manganese are associated with reduced IQ in children [23]. It is also reported than high umbilical cord blood concentrations of manganese are negatively associated with attention capacity, non-verbal memory, and manual capability in children under three years of age [24]. Reductions of 0.4 IQ points have been reported for each 50 % increase the urine arsenic concentration [25]. Arsenic has also been associated with hyperactivity and verbal capacity problems [26]. The cadmium concentration of children's urine has been linked to learning difficulties and the need for special educational provision, memory problems, reduced IQ and ADHD [27] - findings backed up by the present results. Studies on iron have focused mainly on anaemia, but there is some evidence that excess iron is toxic to newborns; one report indicates an association between high maternal haemoglobin levels and low birth weight, as well as reduction in IQ among infants followed until five years of age [28]. Finally, most of the literature on zinc and copper neurotoxicity focuses on nutritional deficiencies and their effects on the brain. However, one study suggests that, when in excess, these metals can affect the function of the nervous system [29].

It is possible that, with a larger sample size of both populations (Cerro de Pasco and Carhuamayo), this neurocognitive impairment could be related to a particular concentration of specific heavy metals. However, it should be noted that this type of intoxication is due to the presence of a combination of heavy metals and not one specific element. The presence of all the heavy metals together (the multiple exposure) might result in a higher impact of the single elements one by one. Ingestion of only one heavy metal would be considered an extraordinary case and complicates the possibility of an individualised study to understand its effects. The multiple exposure might result in a higher impact of the single elements one by one. In conclusion, the present results provide further evidence that the children living in the area of Cerro de Pasco exposed to environmental heavy metal pollution through mining activities, accumulate these elements in their bodies, with all the neurocognitive and other health risks this might entail.

Hair samples provide a simple way of monitoring their exposure, and the results obtained could be used to guide remediation process and the provision of needed health and educational services.

4. Materials and methods

4.1. Settings and population

Cerro de Pasco, capital of the province of Pasco and located in Central Perú, has a population size of around 80,000 inhabitants. The capital is home to an open pit mine, where activities generate air, water and soil contamination. The study population includes children between the ages of 6 and 16 who were permanent residents in the study area: Paragsha zone in Cerro de Pasco and Carhuamayo city. The open-air mine hole is located at approximately 400 m from Paragsha zone, thereby directly exposing Paragsha to all mining activities. Carhuamayo is located approximately 35 km southeast of Cerro de Pasco and shares similar socio-geographic and atmospheric characteristics.

4.2. Ethics

Participation in the study was voluntary. Parents consented to their children's participation before beginning any involvement in the study.

4.3. Metal concentrations and their relationships with neurocognitive ability and IQ

To examine the relationship between metal concentrations (as detected in the hair) and the neurocognitive abilities and IQ of children, a case-control study was performed in the area of Cerro de Pasco in 2021. Children aged between 6 and 16 years from the district of Paragsha (permanent residents exposed to the effects of mining activity; n = 81 [39 boys, 42 girls]), and from the district of Carhuamayo some 30 km away (not yet exposed, but with impending survey activity; n = 17 [11 boys, 6 girls]), were selected at random. Children known to have suffered brain trauma were excluded, as were those who had suffered a cerebrovascular accident or had some other serious neurological conditions. The children of the two groups had similar sociodemographic characteristics. Fig. 1 shows the geographical distribution of the study areas in Pasco, Peru.

A sample of each child's hair was taken (using scissors made from stainless steel) from the occipital region to determine the level of exposure to metals in recent months. Samples were stored separately in coded, sterile paper bags and sent for analysis by inductively coupled plasma mass spectrometry (ICP-MS) following norm EPA 3051 A 200719 + EPA 6020 B 2014 [30], at a certified laboratory in Italy.

Inductively coupled plasma mass spectrometry has been applied to the determination of over 60 elements in various matrices and it is applicable to the determination of sub-μg/L concentrations of a large number of elements in water samples and in waste extracts or digests and no digestion is required prior to analysis for dissolved elements in water samples [30]. The concentrations of arsenic, lead, mercury, cadmium (all toxic), nickel, barium, aluminium, antimony, thallium, beryllium and tin (all potentially toxic), of the essential elements iron, manganese, molybdenum, cobalt, zinc, chromium, copper, selenium and vanadium, and of the non-essential metalloid boron, were then determined. The mean hair concentrations of these elements for the exposed and non-exposed groups were compared against the maximum acceptable values (MAV) established by the Micro Trace Minerals Laboratory in Germany [9], or, for mercury, that established by the US Environmental Protection Agency (≤1 μg/g) [31].

The children's IQ was determined by Source International with the aid of the *Superdotados Perú* organisation. This involved using the Wechsler Intelligence Scale for Children IV [32] (WISC-V validated for Peruvian children, allowing 60–75 min; performed individually by trained psychologists). The WISC is an intelligence test for children aged 6–16 that measures overall cognitive ability. It assesses different areas of thinking through five main index scores: Verbal Comprehension, which evaluates understanding and reasoning with words; Visual-Spatial, which measures the ability to analyse and solve visual problems; Fluid Reasoning, which tests logical thinking and problem-solving with new information; Working Memory, which assesses the ability to hold and manipulate information; and Processing Speed, which measures how quickly and accurately a child can process simple information. These scores combine to produce a Full-Scale IQ, providing an overall measure of a child's intellectual abilities [33].

Psychosocial characteristics were determined by using a self-made questionnaire: the mother, father or a teacher of each child was interviewed via telephone regarding the socioeconomic characteristics of the family and the development of the child prior of the test. The mother/father/teacher of each child was also asked to complete a 49-point questionnaire on the environmental factors to which each child was exposed, as well as those that might condition IQ, including genetic factors, stress, depression, schizophrenia, mental disability, the conditions under which they developed in-womb, type of birth, use of an incubator, general health, number of meals per day, correct development for age, language or cognitive problems, age at first speech, age at first walking, and age when potty trained. A range of emotional factors were also recorded, including stressors experienced within the family in the last year, irritability, lack of self-esteem or assertiveness, and the frequency of visiting green spaces. Finally, the education level of the parents was recorded, along with the language spoken by the child, the source of drinking water, the source of water for washing etc., approximate family income, and the amount of dust in the home. Controlling for such factors can prevent bias and confusion when interpreting results. The differences in the mean values for the recorded variables between the exposed and non-exposed children were examined using the Student *t*-test. Correlations between hair metal concentrations and age were sought by Pearson coefficient analysis. An eventual statistical correlation between the age and sex of the participants was examined. For this, children of the combined exposed/non-exposed groups, and the exposed children alone were studied by using Pearson's linear correlation coefficients ($-1 < r < 1$) between metals in the hair, age, and sex of the combined cases and controls, as well as the cases separately. The toxic metals (arsenic, lead, mercury, and cadmium), potentially toxic metals (nickel, barium, aluminium, antimony, thallium, beryllium), and those essential metals that can be harmful to health in high concentrations (manganese, zinc, copper) have been included. The possible influence of sex was examined using the same test. The relationships between the metal concentrations of the children's hair and both their neurocognitive abilities and IQ, were also examined by linear correlation (Pearson) analysis. To determine whether the influence of exposure on the measured variables was independent of the other sociodemographic variables examined, stepwise linear regression was performed. Those variables found to be significantly associated with IQ were incorporated into an ordinary least squares model (OLS regression). All statistical analyses were performed using Microsoft Excel software.

4.4. Changes in hair heavy metal concentrations over time (2016–2021)

The mean metal concentrations of the hair roots of children from Paragsha (exposed area) was monitored over the period 2016–2021. In 2016 the hair roots of 82 children aged 3–14 years were examined, in 2018 those of 94 children aged 3–16 years were examined, and in 2021 those of 81 aged 6–16 years, were examined. Pearson correlations were sought between the concentrations detected among the three years. All metal concentrations were determined as above.

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CRediT authorship contribution statement

José Ignacio Muñoz-Barús: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Flaviano Bianchini:** Investigation, Funding acquisition, Data curation, Conceptualization. **Elton Carreiro Da Cunha:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **ordoñez mayan lucia:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation.

Declaration of Competing Interest

Although Flaviano Bianchini is affiliated with Source International (which partially funded the study), there is no conflict of interest that could have influenced the development of the research or its conclusions. The other authors declare no conflicts of interest.

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