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Neurocognitive consequences of occupational heavy metal exposure among electronic waste sorting workers in Thailand

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Abstract

Electronic waste sorting workers in Thailand are chronically exposed to heavy metals, including lead (Pb), cadmium (Cd), and nickel (Ni), in informal work settings characterized by limited use of personal protective equipment and suboptimal hygiene practices. This study aimed to evaluate the associations between heavy metal exposure, individual risk factors, and neuropsychological performance among workers. A cross-sectional study was conducted involving 76 exposed workers and 49 non-exposed controls. Data were collected using structured interviews, surface wipe sampling of workplace dust for Pb, Cd, and Ni, and blood metal measurements. Neuropsychological function was assessed using the Digit Span Forward Test (DSFT) and Digit Span Backward Test (DSBT). The mean ages of the exposed and non-exposed groups were 47.39±12.64 and 49.92±8.46 years, respectively. Surface dust concentrations of Pb, Cd, and Ni were significantly higher in the exposed group than in controls (all p<0.001). In contrast, blood metal concentrations did not differ between groups (Pb: 6.41±1.49 vs 6.41±1.62μg/dL, p=0.885; Cd: 0.97±0.39 vs 0.91±0.28μg/L, p=0.501; Ni: 2.60±0.48 vs 2.52±0.45μg/L, p=0.689). No significant difference was observed in DSFT scores between groups (p=0.912). However, DSBT scores differed significantly (p<0.001), with the exposed group scoring higher (2.23±0.55) than the non-exposed group (1.72±0.39). Among exposed workers, simple linear regression identified education (β=0.353, p=0.002), income (β=0.257, p=0.025), age (β=-0.236, p=0.041), and alcohol consumption (β=-0.231, p=0.044) as significant predictors of DSFT performance. However, DSBT scores differed significantly (p<0.001). Drinking alcohol, smoking, Pb in dust, and working area size were significant predictors of DSBT performance (p=0.020, 0.022, 0.013, and <0.001, respectively). These findings indicate that cognitive performance among Thai informal e-waste workers is more strongly influenced by socioeconomic factors and surface lead contamination than by blood metal levels. Interventions focusing on education, income support, and routine workplace surface cleaning, supported by surface-based environmental monitoring and community health volunteers, are critical for protecting cognitive health in this vulnerable population.

Keywords: Heavy metal, electronic waste sorting workers, memory impairment, Digit Span Test, Thailand

Introduction

The rapid growth in reliance on electrical appliances and electronic devices has led to a marked increase in production capacity to meet consumer demand. Consequently, electronic waste (EW)

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generation has surged globally, with significant increases observed across Asia [1,2]. In Thailand, considerable quantities of EW are produced in several regions, notably in Northeastern provinces such as Ubon Ratchathani [3]. Workers involved in sorting and burning EW, called EW sorting workers (EWSW) are exposed to various hazardous substances including lead or plumbum (Pb), cadmium (Cd), nickel (Ni), mercury (Hg), and arsenic (As) through activities such as collecting computers and televisions and dismantling batteries, cathode ray tubes, electrical wires, battery cables, and circuit boards [4]. Such exposures pose significant health risks for EWSW, necessitating focused occupational health investigations.

The European Directive 2011/65/EU (Restriction of Hazardous Substances–RoHS) regulates the use of Pb, Cd, and Ni in electrical and electronic equipment, underscoring the need for vigilant monitoring of these toxic substances in recycling and informal waste-handling settings [5]. Chronic exposure to Pb, Cd, and Ni may result in peripheral and central nervous system dysfunction, impairing cognitive functions such as perception, memory, and comprehension [6-10]. Workers in metal-coating facilities with low to moderate blood levels of these metals exhibit neuronal alterations that affect perceptual processes, including memory [11]. Pb, Cd, and Ni exposures contribute to cognitive decline, characterized by diminished intellectual abilities, language deficits, and impaired comprehension [12-14].

Risk factors for neuropsychological impairment in EWSWs include several factors, including personal factors such as sex, age, monthly income, and body mass index [6] as well as job-related factors such as the length of work [15], number of working hours [16], working area size [17], the amount of exposure to Pb, Cd, and Ni dust [18], and the blood levels of Pb, Cd, and Ni [18-19]. In addition, factors related to self-care behavior, such as washing hands, not changing one's clothes, and washing one's body immediately after returning home [15], and not wearing personal safety equipment [20], are also associated with neuropsychological impairment in EWSWs.

In Thailand, the government extends health protection to workers in the informal sector, including EWSWs, under the Labour Protection Act, ensuring that their occupational rights and welfare, including working hours and overtime, are safeguarded in a manner comparable to those of formal employees [21]. The Act on the Control of Occupational and Environmental Diseases places strong emphasis on surveillance, prevention, and the provision of health care for workers, both within and outside the formal employment system, including those in the informal sector [22]. This can be achieved by monitoring the working environment of workers, including evaluating air concentrations of heavy metal dust [23] and dust on work surfaces [18, 24]. Furthermore, blood monitoring for Pb, Cd, and Ni using standardized analytical methods such as Occupational Safety and Health Administration (OSHA) sampling and Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) analysis ensures accurate quantification of exposure levels. Neurological surveillance, such as evaluating abnormal nervous system symptoms and administering the digit span forward test (DSFT), which is a measure of memory function, is also recommended [25, 26].

Data on the direct exposure of EWSWs to Pb, Cd, and Ni, and their effects on the nervous system, are limited. A study assessing short-term memory in male Pb-exposed workers at a battery recycling plant in Italy found significant impairment of executive functions and short-term memory, even at blood lead levels previously considered safe (mean 56.4 μg/dL) [11]. However, no studies have been conducted among EWSWs in Thailand. While international studies demonstrate neurotoxic effects in industrial settings [11, 27], evidence specific to informal e-waste recycling contexts, where workers face mixed metal exposure, minimal safety infrastructure, and unique behavioral risk factors, remains absent. This study addresses this gap by integrating environmental surface sampling, blood biomonitoring, and standardized neuropsychological assessments to evaluate how occupational exposure to Pb, Cd, and Ni, along with modifiable risk factors, affects cognitive function in Thai EWSWs. This study aimed to evaluate the effects of risk factors and exposure to heavy metals, including Pb, Cd, and Ni, on neuropsychological impairments and reduced memory in EWSWs in Thailand.

Methods

Study design and study population

An analytical cross-sectional study was conducted from November 2020 to April 2021 in Ban Kok Municipality, Khueng Nai, Ubon Ratchathani Province, Thailand. The study population included EWSWs who sorted, removed, and burned electronic parts, collected EW, and waited for EW to be sold within their neighborhood. The nonexposed group consisted of village volunteers living in nearby subdistricts, matched to the exposed group by age, sex, and socioeconomic background, representing individuals from the same community but without occupational exposure to heavy metals. Ethical and administrative approval to conduct the study was obtained from the Ubon Ratchathani Provincial Public Health Office and Ban Kok Subdistrict Health Promoting Hospital. All participants provided written informed consent after receiving detailed verbal and written explanations in Thai regarding the study objectives, procedures, potential risks and benefits, data confidentiality measures, and their right to withdraw at any time without penalty or impact on healthcare services.

Sample criteria

Participants in the exposed group were required to meet all of the following criteria: (1) EWSWs residing in Ban Kok Subdistrict Municipality and Khueang Nai District, Ubon Ratchathani Province; (2) age ≥18 years; (3) engagement in EW sorting, electrical wire burning, or activities related to the storage and sale of EW; and (4) involvement in household-based electronic waste separation for a duration exceeding 6 months. The nonexposed group consisted of individuals with no documented occupational or domestic exposure to Pb, Cd, or Ni. Participants with a history of chronic medical illness, neurological injury, or psychiatric treatment, as well as those who were unable to complete the full study protocol, were excluded. Participants meeting any exclusion criterion were not enrolled or were removed from analysis accordingly. This selection minimized potential confounding from geographic, dietary, and lifestyle factors while isolating occupational exposure effects.

Sample size and sampling method

The sample size was calculated using the Dupont and Plummer formula [28], which is used when the exact population is unknown. The formula was as follows: $n=(Z2\alpha/2\ \sigma2)/e2$, where confidence level $(Z\alpha)=1.96$ and $e=0.05$. Based on the variance estimate ($\sigma=0.22$) reported by Kshirsagar *et al.* [29], a sample size of at least 74.37 people was required to estimate the percentage with an error of <5 at a confidence level of 95%. To ensure adequate representation and minimize operational discrepancies during data collection, purposive sampling was applied within the defined study area. Thus, the exposed group comprised 76 participants, slightly exceeding the minimum required sample size. In accordance with the study design, the nonexposed group was required to comprise more than one-third of the exposed group; therefore, 49 participants were recruited into the nonexposed group [24].

Data collection

Before field implementation, the principal investigator conducted standardized training for all research assistants to ensure consistency, reliability, and methodological rigor in participant recruitment, interview administration, and biological sample collection. Validated instruments and calibrated equipment supported data collection to ensure accuracy and reproducibility. Data on sociodemographic characteristics, health-related behaviors, and occupational exposure variables were obtained using a structured interview form. The content validity of the instrument was evaluated by three independent experts in occupational health and safety. The level of agreement among experts was quantified using the Index of Item Objective Congruence (IOC), with an overall IOC of 0.726 for the interview form, indicating acceptable content validity.

Risk factors assessment

Risk factors were assessed using a structured interview form comprising three main sections. The first section collected personal factors using five items: sex, age, monthly income (in Thai Baht), education level, and body mass index (BMI, kg/m^2). Participants completed these items through selected-response and fill-in-the-blank formats. The second section evaluated health behavior factors through four items addressing alcohol consumption patterns, smoking habits, and eating behaviors in relation to food consumption within the work area, underlying medical conditions, and current medication use. The third section examined job-related factors using five items: years of employment in electronic waste sorting, average daily working hours, work area size, past occupational history, and consistent use of personal protective equipment. Participants responded to a combination of multiple-choice selections and open-ended responses where appropriate.

Sample collection to determine the levels of Pb, Cd, and Ni dust on work surfaces

Surface samples from the workplace were collected by swiping a pre-cleaned, standardized sample collection paper in an S-shaped pattern, systematically moving from left to right and along the edges of the paper frame (template) to ensure comprehensive coverage. To minimize contamination and loss of particulate matter, the paper was immediately folded in half with the sampled side inward. Each folded sample was placed into a labeled, sterile collection tube for transport. Samples were stored under controlled conditions during transit to prevent degradation or contamination.

The particulate matter composition was analyzed to quantify concentrations of Pb, Cd, and Ni following analytical protocol ID-125G, which targets metal and metalloid particulates in workplace atmospheres. This method employs Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) to achieve sensitive and accurate elemental detection. Quality control procedures included the use of field blanks, duplicate samples, and certified reference materials to ensure analytical precision and accuracy. Calibration curves were generated daily, and instrument performance was verified with standard check solutions.

Analytical analyses were performed at a certified laboratory in Bangkok, Thailand, accredited for heavy metal quantification, ensuring reliability and reproducibility of the data. For the nonexposed control group, surface dust samples were systematically collected from household environments to evaluate potential background contamination originating from sources such as soil or ambient dust. Sampling was performed in accordance with Occupational Safety and Health Administration (OSHA) method ID-125G (revised 2019), which specifies standardized procedures to ensure consistent, representative sampling of surface particulates. Inhalation exposure assessments were not included in this protocol, as the focus was on surface contamination [30].

Surface dust was collected using pre-cleaned sampling materials and an established wiping technique over a defined area to obtain reproducible results. Each sample was carefully handled to avoid cross-contamination and immediately placed into sterile, labeled containers for transport to the analytical laboratory under controlled conditions. Metal quantification for Pb, Cd, and Ni was conducted using inductively coupled plasma optical emission spectrometry (ICP-OES) with axial plasma observation on an Agilent 5110 spectrometer (Agilent Technologies, USA). The limits of quantification were 0.05 μg/100 cm^2 for Pb, 0.01 μg/100 cm^2 for Cd, and 0.05 μg/100 cm^2 for Ni [31].

Quality assurance measures included analyzing field blanks, method blanks, and replicate samples to detect contamination or analytical variability. Calibration standards traceable to certified reference materials were used to establish accurate calibration curves, with routine instrument performance checks conducted throughout the analysis sessions to maintain analytical precision. Parallelly, whole-blood samples from study participants were analyzed by ICP-OES under the same rigorous quality control framework, with detection limits of 0.05 μg/dL for Pb, 0.01 μg/L for Cd, and 0.05 μg/L for Ni, ensuring high accuracy and reproducibility in biological exposure assessment.

Evaluation of the concentrations of Pb, Cd, and Ni in the blood of exposed and nonexposed individuals

A registered nurse collected venous blood samples from participants at the Tambon Health Promoting Hospital (THPH) following standardized protocols as specified in reference [24]. Blood was drawn into sterile, trace-metal–free collection tubes to prevent contamination.

Samples were gently inverted to ensure proper mixing with anticoagulants when applicable and immediately stored in refrigerated conditions (4°C) to preserve sample integrity. The collected blood specimens for Pb, Cd, and Ni analysis were transported to Khueang Nai Hospital, Khueang Nai District, Ubon Ratchathani Province, within 24 hours of collection, maintaining a cold chain during transit to prevent degradation or contamination, thereby ensuring accurate and reliable quantification of metal concentrations.

Assessment of neuropsychological impairment and decreased memory

Neuropsychological assessment of memory and cognitive function was conducted using the Digit Span Test (DST), which evaluates attention and working memory through the recall of orally presented numerical sequences. The Digit Span Forward Test (DSFT) was administered by presenting sequences of digits ranging from 1 to 8 at a rate of 1 digit per second. Participants were instructed to repeat the digits in the same order, beginning with the shortest sequence and progressing to longer sequences contingent upon accurate recall. The Digit Span Backward Test (DSBT) was administered using the same procedure, except that participants were required to recall the digit sequences in reverse order. For both tests, participants were allowed a second attempt if an initial response was incorrect. Failure on the second attempt resulted in a score equal to the longest correctly recalled sequence. Each test consisted of seven sequence levels, with two trials per level, yielding a maximum possible score of 14 points for both the DSFT and DSBT. Each correctly recalled digit sequence was assigned one point, whereas an incorrect response received zero points. The total score for each test was calculated as the sum of correctly recalled sequences, ranging from 0 to 14. In both tests, higher scores indicate better cognitive performance, reflecting greater attention span and working memory capacity.

Statistical analysis

Group comparisons were performed using independent t-tests or Mann–Whitney U tests, and chi-squared tests for categorical variables. Simple linear regression analyses were conducted to examine associations between DST scores. Statistical significance was set at $p<0.05$. Data were analyzed using SPSS version 21.0 (IBM Corp., Armonk, NY, USA).

Results

Participants characteristics

A total of 125 participants were included in the study, comprising 76 individuals in the exposed group and 49 in the nonexposed control group. Data from both groups were analyzed to assess differences in demographic, behavioral, occupational, and health-related characteristics relevant to electronic waste exposure (**Table 1**). Male participants were significantly more prevalent in the exposed group than in the non-exposed group ($p<0.001$). Educational attainment also differed significantly between groups, with a higher proportion of participants with primary-level education in the exposed group ($p=0.028$). No statistically significant differences were observed between the groups for age, body mass index, years of employment, or daily working hours.

Table 1. Characteristics of exposed and non-exposed groups

Variable	Exposed group, n=76	Non-exposed group, n=49 (%)	*p*-value
	n (%)	n (%)	
Sex			
Male	35 (55.3)	4 (8.2)	<0.001 *a
Female	41 (44.7)	45 (91.8)	
Age (years), mean±SD	47.39±12.64	49.92±8.46	0.148 b
Education			0.028 *a
No formal education	0 (0)	1 (2.0)	
Primary education	55 (17.0)	24 (49.0)	
Secondary education	17 (22.4)	22 (44.9)	
Diploma/associate degree	4(5.3)	2(4.1)	
Body mass index (BMI) (kg/m^2)	23.72±5.12	24.65±3.57	0.196 b
Alcohol consumption (yes)	39 (51.3)	40 (81.6)	0.003 *a
Current cigarette smoking (yes)	21 (27.6)	41 (83.7)	0.409

Variable	Exposed group, n=76	Non-exposed group, n=49 (%)	*p*-value
	n (%)	n (%)	
Presence of underlying disease (yes)	26 (34.2)	11 (22.4)	0.160 [a]
Use of medication for the underlying disease (yes)	26 (34.2)	11 (22.4)	0.160 [a]
Food consumption within the work area			0.326 [a]
Breakfast	1 (1.3)	2 (4.1)	
Lunch	75 (98.7)	47 (95.9)	
Dinner	0 (0)	0 (0)	
Working hours, mean±SD	7.80±0.980	7.96±0.286	0.354 [b]
Work area (m^2), mean±SD	180.16±306.18	0±0.00	-
Years of employment (years), mean±SD	7.56±7.6	10.25±13.69	0.656 [b]
Monthly income (USD), mean±SD	\$175±\$99	\$146±\$81	0.002 *b
Mask wearing while working (yes)	0 (0)	6 (12.2)	0.003 *a

[a] Analyzed using Chi-squared test or Fisher's exact test
[b] Analyzed using Mann–Whitney U
* Statistically significant at $p<0.05$

Health behavior-related factors

Health-related behaviors differed between the groups (**Table 1**). Alcohol consumption was significantly more prevalent among non-exposed workers than exposed workers ($p=0.003$). In contrast, smoking status, presence of underlying disease, medication use, and food consumption within the work area did not differ significantly between the groups (all $p>0.05$).

Job-related characteristics

Job-related characteristics were largely comparable between exposed and non-exposed workers (**Table 1**). The mean Years of employment and average daily working hours did not differ significantly between groups ($p=0.656$ and $p=0.354$, respectively). Although the exposed group reported a larger mean work area than the non-exposed group, this difference was not statistically significant ($p=0.635$). In contrast, monthly income was significantly higher among exposed workers ($p=0.002$) (**Table 1**). Regarding personal protective equipment, mask use differed significantly between groups: none of the exposed workers reported mask use, whereas only a small proportion of non-exposed workers did ($p=0.003$).

Comparison of surface wipe contamination and blood metal concentrations between exposed and non-exposed groups

Surface wipe analyses demonstrated significantly higher concentrations of Pb, Cd, and Ni in the exposed group compared with the non-exposed group (all $p<0.001$), reflecting substantial differences in environmental contamination across work settings (**Table 2**). However, no significant differences were observed in blood concentrations of Pb, Cd, and Ni between the two groups ($p>0.05$), suggesting that short-term systemic metal levels may not directly correspond to surface contamination at the time of assessment (**Table 2**).

Table 2. Comparative analysis of Pb, Cd, and Ni concentrations in surface wipe samples and blood among exposed and non-exposed participants

Variable	Exposed (n=76)		Non-exposed (n=49)		*p*-value
	Mean±SD	Range	Mean±SD	Range	
Surface Pb (µg/100 cm^2)	245.042±613.910	0.170–3,412.00	0.609±0.934	ND–3.80	<0.001 *b
Surface Cd (µg/100 cm^2)	0.375±0.662	ND–3.20	0.1673±1.171	ND–8.20	<0.001 *b
Surface Ni (µg/100 cm^2)	46.115±75.740	0.180–368.0	28.1970±63.022	ND–368.00	<0.001 *b
Blood Pb (µg/dL)	6.41±1.49	3.01–10.84	6.41±1.6	3.29–9.74	0.885 [a]
Blood Cd (µg/L)	0.97±0.39	0.22–2.09	0.91±0.28	0.3–1.53	0.501 [b]
Blood Ni (µg/L)	2.60±0.48	1.55–4.05	2.52±0.45	1.24–3.61	0.689 [b]

ND: Not detected (<LOQ)
[a] Analyzed using Student's t-test
[b] Analyzed using Mann–Whitney U

Neuropsychological impairments

Neuropsychological performance was evaluated using DSFT and DSBT, with mean scores derived from two testing sessions per participant (**Table 3**). The mean DSFT score was 3.63±1.69 (95%CI: 3.43–3.82) in the exposed group and 3.64±0.94 (95%CI: 3.37–3.91) in the non-exposed group, with no significant difference between groups (p=0.912). Median DSFT scores were identical at 3.5 in both groups, with ranges of 1.5–5.0 and 2–6 in the exposed and non-exposed group, respectively. For the DSBT, the exposed group (2.23±0.55; 95%CI: 2.10–2.36) demonstrated a significantly higher mean score than the non-exposed group (1.72±0.39; 95%CI: 1.61–1.83), with a statistically significant difference between groups (p<0.001).

Table 3. Comparison of Digit Span Forward (DSFT) and Backward (DSBT) test scores derived from two testing sessions between exposed and non-exposed groups

Test	Group	Mean±SD (95%CI)	Median (min-max)	Range	*p*-value
DSFT	Exposed (n=76)	3.63±1.69 (3.43–3.82)	3.5 (1.5–5.0)	3.5	0.912
	Non-exposed (n=49)	3.64±0.94 (3.37–3.91)	3.5 (2–6)	4	
DSBT	Exposed (n=76)	2.23±0.55 (2.10–2.36)	2.0 (1–3)	2	<0.001*
	Non-exposed (n=49)	1.72±0.39 (1.61–1.83)	2.0 (1–2)	1	

DSFT: Digit span forward test; DSBT: Digit span backward test

Factors associated with DSFT performance among exposed individuals

Simple linear regression analysis was conducted to identify factors associated with DSFT performance among exposed participants (**Table 4**). Age was significantly and inversely associated with DSFT scores (β=-0.236, p=0.041), indicating lower performance with increasing age. In contrast, education level showed a significant positive association with DSFT scores (β=0.353, p=0.002), with higher educational attainment associated with better performance. Income was also positively associated with DSFT scores (β=0.257, p=0.025). Alcohol consumption demonstrated a significant negative association with DSFT performance (β=-0.231, p=0.044).

No significant associations were observed between DSFT scores and sex, body mass index, smoking status, presence of underlying disease, or medication use (**Table 4**). Furthermore, environmental and occupational exposure variables, including Pb, Cd, and Ni concentrations in surface dust and blood, duration of employment, and working area size, were not significantly associated with DSFT performance (all p>0.05) (**Table 4**).

Factors associated with DSBT performance among exposed individuals

Simple linear regression analysis identified two variables significantly associated with DSBT performance among exposed participants (**Table 5**). Drinking alcohol, smoking, Pb in surface dust, and working area size were significant predictors (p=0.020, 0.022, 0.013, and <0.001, respectively), whereas blood metal concentrations were not associated with DSBT performance (all p>0.05).

Discussion

This study examined the associations between heavy metal exposure and neuropsychological performance among EWSW, with particular emphasis on short-term and working memory assessed using DSFT and DSBT tests. No significant differences were observed in blood metal concentrations or DSFT scores between exposed and non-exposed groups. However, DSBT scores differed significantly between groups. Regression analyses within the exposed group identified several individual- and environment-level factors associated with cognitive performance, suggesting that contextual and sociodemographic determinants may better explain neuropsychological variability than by contemporaneous blood metal levels alone. These findings further indicate that blood-based biomarkers may have limited sensitivity for capturing cumulative or low-level neurotoxic effects, particularly in settings characterized by widespread community background contamination that may obscure contrasts between occupationally exposed and non-exposed individuals.

Table 4. Factors associated with Digit Span Forward Test (DSFT) performance among exposed individuals (n=76)

Variables	Unstandardized coefficients (B)	Standard error	Standardized coefficients (R) Beta	t-test	*p*-value	95% Confidence interval for B	
						Lower bound	Upper bound
Sex (female vs male**)	-0.200	0.195	-0.118	-1.024	0.309	-0.588	0.189
Age (year)	-0.016	0.008	-0.236	-2.085	0.041*	-0.031	-0.001
Body mass index (BMI) (kg/m²)	0.019	0.022	0.103	0.894	0.374	-0.024	0.063
Education (high vs low**)	0.520	0.160	0.353	3.250	0.002*	0.201	0.838
Income (USD)	6.997E-5	0.000	0.257	2.283	0.025*	0.000	0.000
Drinking alcohol (yes vs no**)	-0.388	0.190	-0.231	-2.045	0.044*	-0.767	-0.010
Smoking (yes vs no**)	-0.040	0.124	-0.037	-0.322	0.748	-0.287	0.207
Presence of underlying disease (yes vs no**)	-0.336	0.202	-0.190	-1.664	0.100	-0.739	0.066
Use of medication for the underlying disease (yes vs no**)	-0.091	0.082	-0.127	-1.100	0.275	-0.255	0.074
Food consumption within the work area (yes vs no**)	-1.393	0.841	-.189	-1.657	0.102	-3.069	0.282
Mask wearing while working (yes vs no**)	-	-	-	-	-	-	-
Pb in dust (µg/100 cm²)	0.000	0.000	-0.096	-0.826	0.411	0.000	0.000
Cd in dust (µg/100 cm²)	0.096	0.148	0.075	0.649	0.518	-0.199	0.391
Ni in dust (µg/100 cm²)	-0.001	0.001	-0.099	-0.852	0.397	-0.004	0.001
Blood Pb (µg/dL)	-0.023	0.066	-0.040	-0.346	0.730	-0.154	0.108
Blood Cd (µg/dL)	0.135	0.252	0.062	0.535	0.595	-0.367	0.637
Blood Ni (µg/dL)	-0.097	0.206	-0.054	-0.469	0.640	-0.507	0.314
Duration of work (years)	-0.032	0.024	-0.173	-1.515	0.134	-0.081	0.017
Working area (m²)	2.574E-5-5	0.000	0.009	0.080	0.936	-0.001	0.001

Heavy metal concentrations were quantified using inductively coupled plasma–optical emission spectrometry (ICP-OES; Agilent 5110, axial plasma mode). Surface contamination levels were evaluated against Occupational Safety and Health Administration (OSHA) permissible limits, defined as 200µg/100cm² for lead (Pb) and 0.5µg/100cm² for cadmium (Cd); no OSHA reference limit is specified for nickel (Ni).
*Statistically significant at $p<0.05$
*Reference group

Table 5. Factors associated with Digit Span Backward Test (DSBT) performance among exposed individuals (n=76)

Variables	Unstandardized coefficients (B)	Standard error	Standardized coefficients (R) Beta	t-test	*p*-value	95% Confidence interval for B	
						Lower bound	Upper bound
Sex (female vs male**)	0.142	0.127	0.129	1.121	0.266	-0.110	0.395
Age (year)	0.005	0.005	0.116	1.005	0.318	-0.005	0.015
Body mass index (BMI) (kg/m²)	-0.009	0.014	-0.070	-0.602	0.549	-0.037	0.020
Education (high vs low**)	0.070	0.111	0.073	0.634	0.528	-0.151	0.292
Income (USD)	-1.871E-5	0.000	-0.105	-0.911	0.365	0.000	0.000
Drinking alcohol (yes vs no**)	0.291	0.123	0.266	2.371	0.020*	0.046	0.535
Smoking (yes vs no**)	-0.183	0.078	-0.262	-2.338	0.022*	-0.338	-0.027
Presence of underlying disease (yes vs no**)	0.088	0.134	0.077	0.662	0.510	-0.178	0.355
Use of medication for the underlying disease (yes vs no**)	-0.004	0.054	-0.008	-0.070	0.945	-0.112	0.104
Food consumption within the work area (yes vs no**)	-0.273	0.557	-0.057	-0.491	0.625	-1.383	0.836

Variables	Unstandardized coefficients (B)	Standard error	Standardized coefficients (R) Beta	t-test	*p*-value	95% Confidence interval for B	
						Lower bound	Upper bound
Mask wearing while working (yes vs no**)	-	-	-	-	-	-	-
Pb in dust (µg/100 cm²)	0.000	0.000	-0.285	-2.556	0.013*	0.000	0.000
Cd in dust (µg/100 cm²)	0.16	0.097	0.019	0.167	0.868	-0.176	0.209
Ni in dust (µg/100 cm²)	-0.001	0.003	-0.048	-0.416	0.679	-0.006	0.004
Blood Pb (µg/dL)	-0.020	0.043	-0.055	-0.478	0.634	-0.106	0.065
Blood Cd (µg/dL)	0.207	0.163	0.147	1.275	0.206	-0.117	0.531
Blood Ni (µg/dL)	-0.008	0.134	-0.007	-0.060	0.953	-0.276	0.260
Duration of work (years)	0.011	0.016	0.083	0.713	0.478	-0.021	0.043
Working area (m2)	-0.001	0.000	-0.394	-3.683	<0.001*	-0.001	0.00

Heavy metal concentrations were quantified using inductively coupled plasma–optical emission spectrometry (ICP-OES; Agilent 5110, axial plasma mode). Surface contamination levels were evaluated against Occupational Safety and Health Administration (OSHA) permissible limits, defined as 200µg/100cm² for lead (Pb) and 0.5µg/100cm² for cadmium (Cd); no OSHA reference limit is specified for nickel (Ni).

*Statistically significant at $p<0.05$

**Reference group

Four factors significantly predicted DSFT performance among exposed EWSWs: age, education level, income, and alcohol consumption (**Table 4**). Age showed a significant negative association with DSFT performance, indicating poorer phonological short-term memory among older EWSWs. This finding is consistent with well-established evidence of age-related neurobiological changes, including gray matter reduction in the left inferior parietal lobule and prefrontal cortex, white matter degradation in frontoparietal networks, and declines in dopaminergic signaling, all of which are critical for phonological processing and processing speed [32-36]. Age-related deterioration in auditory processing may further compromise verbal span performance [37]. Notably, the observed association was detectable within a working-age population with a mean age of 47.39 years, suggesting that cognitive aging may interact with occupational and environmental stressors earlier than traditionally expected. These results underscore the importance of age-stratified occupational health strategies, including periodic cognitive screening and targeted interventions for older workers in neurotoxic environments.

Educational attainment emerged as the strongest predictor of DSFT performance, exceeding the influence of age. Higher education was associated with better memory performance, in line with previous findings from low- and middle-income settings [38,39]. This association likely reflects the role of cognitive reserve, the capacity to maintain cognitive functioning through more efficient neural networks and compensatory mechanisms despite neural insults [32,40-42]. Neuroimaging studies indicate that individuals with higher educational attainment exhibit more efficient brain activation patterns during memory tasks [43]. In the context of informal EWSWs, who often lack formal occupational health services and rely on community-based health support, education may provide a critical buffer against neurotoxic exposures [22]. The magnitude of this association suggests that community-level education and skills training programs may represent a practical, scalable approach to mitigating cognitive risks among informal-sector workers [44,45].

Income was also positively associated with DSFT performance. Higher income may support cognitive health through multiple pathways, including improved nutrition, particularly intake of nutrients essential for brain function [46,47], reduced chronic psychosocial stress, better sleep quality, and greater access to healthcare services [48,49]. In home-based e-waste operations, higher income may additionally enable workers to improve working conditions or purchase basic protective equipment. These findings highlight the role of socioeconomic vulnerability in shaping cognitive health outcomes and suggest that addressing poverty and income inequality is integral to neuroprotection among informal-sector workers [22]. Even modest economic support or income-enhancing interventions may therefore yield meaningful cognitive health benefits.

Alcohol consumption was negatively associated with DSFT performance, consistent with evidence that alcohol exerts neurotoxic effects on brain regions involved in memory and phonological processing [50-53], with measurable impacts observed even at moderate levels of intake [54]. This finding is particularly relevant given that more than half of exposed workers reported alcohol consumption. Unlike many occupational exposures inherent to informal e-waste work, alcohol use represents a modifiable risk factor. Alcohol reduction initiatives may therefore offer a feasible and cost-effective strategy to preserve cognitive function among EWSW, especially when integrated into broader community health programs.

Our study further identified four factors significantly associated with DSBT performance among exposed workers using simple linear regression (**Table 5**): drinking alcohol, smoking, Pb in dust, and working area size. Consistent with the DSFT findings, drinking alcohol was also positively associated with DSBT scores, suggesting broader neurotoxic effects of alcohol on both short-term and working memory domains [50-54]. Smoking showed a significant inverse association with DSBT performance, consistent with established evidence that tobacco exposure impairs working memory through neurotoxic mechanisms [55], representing another modifiable risk factor in this population.

Workplace Pb contamination was the only environmental exposure significantly associated with DSBT performance. The observed inverse association indicates that higher surface Pb levels are linked to poorer working memory, highlighting the particular vulnerability of executive functions to lead to neurotoxicity [4,11,18,23]. Lead interferes with dopaminergic and GABAergic neurotransmission, disrupts synaptic plasticity, and induces oxidative stress in executive control regions such as the dorsolateral prefrontal cortex and anterior cingulate cortex—areas essential for the maintenance and manipulation of information in working memory [6,9,12,19]. Notably, these neurocognitive effects have been documented even at low or subclinical exposure levels, consistent with our findings based on surface contamination rather than blood biomarkers.

For Thai home-based e-waste workers, these results emphasize the importance of feasible, low-cost exposure reduction strategies. Practical measures such as regular wet-mopping of work surfaces, frequent handwashing before meals, and physical separation of work and living areas may substantially reduce lead exposure. Given that these workers rely primarily on local health officers and community health volunteers rather than formal occupational health services [55], community-based education programs focusing on simple hygiene and surface-cleaning practices may represent an effective and scalable approach to protecting cognitive health.

Alcohol consumption and smoking represent modifiable behavioral risk factors associated with impaired working memory among exposed workers [50-53,55]. Based on these findings, the public health implications point to the need for several targeted interventions to protect cognitive health among Thai informal EWSWs. These include: (1) educational interventions and health literacy programs to strengthen cognitive reserve, given that education was the strongest protective factor for cognitive function [32]; (2) economic support measures, such as fair pricing for recycled materials and income assistance, as higher income was significantly associated with better cognitive performance; (3) alcohol reduction and smoking cessation programs, given their significant associations with impaired cognitive function; (4) reduction of workplace surface lead contamination through regular wet-mopping and cleaning practices in home-based work settings [18,23]; (5) prioritization of environmental monitoring of surface contamination rather than reliance on blood biomarkers, which showed no association with cognitive performance [15,23,40]; and (6) avoidance of food consumption within work areas to minimize hand-to-mouth transfer of surface contaminants and reduce indirect exposure pathways. These public health implications are consistent with Thailand's Action Plan for Informal Workers (2020–2022) [56] and the Occupational Diseases and Environmental Diseases Control Act B.E. 2562 [22]. Given that informal e EWSWs primarily depend on health officers and community health volunteers rather than formal occupational health services, strengthening community-based strategies using practical, low-cost interventions is essential for protecting cognitive health in this vulnerable population.

This study has some limitations. The cross-sectional design precludes causal inference and captures exposure and neuropsychological performance at a single time point only. Surface wipe and blood metal measurements primarily reflect recent exposure and may not adequately represent cumulative or long-term neurotoxic effects. Both exposed and non-exposed participants resided within e-waste–affected communities, which may have attenuated exposure contrasts and reduced the ability to detect between-group differences. Future longitudinal studies are needed to determine whether sustained occupational exposure to heavy metals leads to progressive cognitive decline among informal EWSWs. Informed by the present findings, intervention strategies should prioritize educational programs to strengthen cognitive reserve, reduce workplace surface contamination through routine cleaning practices, and alcohol reduction initiatives. Environmental monitoring of surface contamination appears more informative than blood biomarkers for assessing exposure relevant to cognitive outcomes. Unlike formal-sector workers who benefit from structured occupational health systems, Thai informal EWSWs rely largely on community health volunteers; therefore, strengthening community-based approaches is critical to the successful implementation and sustainability of preventive interventions.

Conclusion

This study demonstrates that neuropsychological performance among Thai informal EWSWs is shaped by a combination of individual, socioeconomic, and environmental factors rather than by blood metal concentrations alone. Performance on the Digit Span Forward Test was independently associated with age, educational attainment, income level, and alcohol consumption, whereas Digit Span Backward Test performance was significantly associated with alcohol consumption, smoking, surface lead contamination, and working area size. Notably, blood concentrations of Pb, Cd, and Ni were not associated with either cognitive outcome, suggesting limited sensitivity of blood biomarkers for detecting neurocognitive effects in low-level, chronic exposure settings. In contrast, surface lead contamination showed a measurable association with working memory impairment, underscoring its relevance as an exposure indicator and the importance of avoiding food consumption within work areas.

Ethics approval

Approval from the Research Ethics Committee. The researcher submitted an application for research ethics approval from the Human Research Ethics Committee, Faculty of Public Health, Burapha University, Certificate No. G-HS051/2563, and the Human Research Ethics Committee, Ubon Ratchathani Provincial Public Health Office, Certificate No. SSJ.UB.2563-104 Acknowledgments

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Competing interests

The authors declare that there is no conflict of interest.

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Underlying data

Derived data supporting the findings of this study are available from the corresponding author on request.

Declaration of artificial intelligence use

AI-based language models, such as ChatGPT and Claude, were employed to improve grammar, sentence structure, and readability of the manuscript only. We confirm that all AI-assisted processes were critically reviewed by the authors to ensure the integrity and reliability of the results. The final decisions and interpretations presented in this article were solely made by the authors.

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