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Original article

Assessing Neurobehavioral Alterations Among E-waste Recycling Workers in Hong Kong

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A B S T R A C T

Background: E-waste workers in Hong Kong are handling an unprecedented amount of e-waste, which contains various neurotoxic chemicals. However, no study has been conducted to evaluate the neurological health status of e-waste workers in Hong Kong. This study aimed to evaluate the prevalence of neurobehavioral alterations and to identify the vulnerable groups among Hong Kong e-waste workers.
Methods: We recruited 109 Hong Kong e-waste workers from June 2021 to September 2022. Participants completed standard questionnaires and wore a GENEActiv accelerometer for seven days. Pittsburgh Sleep Quality Index and Questionnaire 16/18 (Q16/18) were used to assess subjective neurobehavioral alterations. The GENEActiv data generated objective sleep and circadian rhythm variables. Workers were grouped based on job designation and entity type according to the presumed hazardous level. Unconditional logistic regression models measured the associations of occupational characteristics with neurobehavioral alterations after adjusting for confounders.
Results: While dismantlers/repairers and the workers in entities not funded by the government were more likely to suffer from neurotoxic symptoms in Q18 (adjusted odds ratio: 3.18 [1.18–9.39] and 2.77 [1.10–7.46], respectively), the workers from self-sustained recycling facilities also have poor performances in circadian rhythm. Results also showed that the dismantlers/repairers working in entities not funded by the government had the highest risk of neurotoxic symptoms compared to the lowest-risk group (i.e., workers in government-funded companies with other job designations).
Conclusion: This timely and valuable study emphasizes the importance of improving the working conditions for high-risk e-waste workers, especially the dismantlers or repairers working in facilities not funded by the government.

1. Introduction

Rapid technological change makes electronic equipment more affordable and drives people to replace the old version at an unprecedented pace, producing more and more electronic waste (e-waste) that harms the ecosystem and human health [1,2]. The global e-waste generation in 2019 reached 53.6 million tons (Mt) and is projected to reach a staggering level of 120 Mt by 2050 [3],

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making e-waste one of the fastest-growing domestic waste streams. While high-income countries generated more e-waste per capita, they generally exported up to 80% of e-waste to developing countries for further processing [3]. Moreover, nearly 70%–83% of the e-waste flow was not managed in an environment-friendly manner [3,4].

E-waste recycling is one of the focuses of urban mining, which mainly extracts and purifies precious metals from e-waste to make a profit and save resources [5], which produced a global value of USD 57 billion in 2019 [3]. Thus, the considerable revenue attracts people, especially those in developing countries, to do their business by recycling e-waste [6,7]. However, in low- and middle-income countries (LMICs), most e-waste is recycled and handled by the informal sectors with rudimentary methods and without engineering and administrative control [3,8]. Hence, e-waste recycling releases enormous amounts of hazardous chemicals into the working environment [9], worsening e-waste workers' health status, particularly those informal e-waste workers [10,11].

The pollutants from e-waste could heavily deteriorate human health, particularly the nervous system, as many of these chemicals are highly toxic to the neurological system [1,12]. The poisonous effects of e-waste exposure on the central and peripheral nervous system at the early stage could manifest in subtle preclinical neurobehavioral alterations. For instance, children and neonates growing up in the informal recycling area had a higher prevalence of attention-deficit hyperactivity disorders and neurobehavioral development disorders [13]. Additionally, a high prevalence of insomnia was found among the e-waste workers in Thailand [14]. Several neurobehavioral alterations were observed when exposing zebrafish to the e-waste extracts (i.e., printed circuit boards), such as memory, social interaction, and cognition impairments [15]. Similarly, evidence regarding the neurobehavioral effects could also be found in the individual toxicants from e-waste elements, such as lead [16,17].

Hong Kong, a vital part of the Greater Bay Area, faces increasing and acute challenges to the rapidly growing e-waste that needs to be handled locally. Citizens in Hong Kong generated much more e-waste than the global level (i.e., 20.2 kg/capita/year vs. 7.3 kg/capita/year) [3]. Hong Kong received an additional 1000 tons of e-waste daily from other developed regions for further processing [18]. However, with the new policy banning the import of waste products to mainland China and a new producer responsibility scheme for waste electrical and electronic equipment in Hong Kong enacted in 2018 [18,19], the local e-waste industry must handle more e-waste. While e-waste recycling workers in Hong Kong are currently facing a soaring amount of e-waste, no study has ever been conducted to assess the front-line e-waste workers' health risks. This study evaluated the prevalence of neurobehavioral alterations (i.e., neurotoxic symptoms, sleep, and circadian rhythm) among Hong Kong e-waste industry workers and the health risk faced by workers with different occupational characteristics.

2. Materials and methods

2.1. Study participants and research materials

This cross-sectional study successfully recruited 114 workers from 15 e-waste recycling entities (i.e., three government-funded organizations and 12 entities not subsidized by the government) from June 2021 to September 2022 in Hong Kong (Supplementary Table 1), with an estimated response rate of about 29.2% (i.e., 114/390). Five participants were excluded from the study because of the incompleteness of the questionnaire, the proportion of complete questionnaires was 95.6% (i.e., 109/114). Final statistical analyses were conducted among the remaining 109 participants with complete questionnaires.

Participants were recruited through the following three ways: (1) invited by our collaborative research partners (i.e., the EcoTech Professional Association of Hong Kong and the Occupational Safety & Health Council); (2) invited by e-mail or phone call according to a list of government-funded e-waste recycling companies; and (3) trained research assistants approached e-waste recycling workshops/shops and invited the on-site workers in person. After obtaining the agreement from the management and written consent from the participating workers, the questionnaires were independently completed by the participants themselves using their native language (i.e., Cantonese) or through face-to-face interviews conducted by trained research assistants. Only a small number of participants responded to the questionnaires by phone (<10%). Eligible participants were those responsible for collecting, repairing, dismantling, and sorting electronic waste. The research team also visited the workplace personally to record the workplace environment and recycling process with the necessary assistance of a safety officer from the participating company.

The Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee approved this study (CREC No.: 2020.039). Written consent forms were obtained before the interview commenced.

2.2. Assessments based on questionnaires

A structured questionnaire was used to collect basic socio-demographic characteristics (e.g., date of birth, gender, smoking and drinking habits, education attainment, marital status, monthly family income, physical activity, disease history, dietary habits, etc.) and occupational history.

The occupational questionnaire included job designation, type of company entity, length of work in the e-waste industry, personal protective equipment (PPE), occupational safety and health (OSH) measures, and history of exposure to occupational pollutants. We also visited the working sites of all participants and communicated with the managers to collect information related to the recycling process and working environment (Supplementary Table 1).

According to the reported health risk levels of e-waste recycling workers [20,21], we grouped the participants into high- and low-risk groups. The low-risk group was workers who were not involved in dismantling or repairing e-waste by their job designation or working in government-funded entities by the type of entity. Otherwise, they were in the high-risk group.

The Pittsburgh Sleep Quality Index questionnaire was used to assess the subjective sleep quality of e-waste workers in the month preceding the interview [22]. The Pittsburgh Sleep Quality Index questionnaire contains seven items, and each component scores 0 to 3, resulting in the total score ranging from 0 to 21. A total score $\geq$5 was considered as having poor sleep quality. Short sleep duration was defined if the self-reported sleep duration was less than six hours. We used the sleep duration and bedtime to generate the mid-sleep time (MST) (i.e., MST = bedtime + sleep duration/2) to reflect the sleep phase following a 24-hour cycle a day [23].

Questionnaire 16 (Q16) and Questionnaire 18 (Q18) (i.e., the version modified from Q16, which deleted three questions but added five new questions to Q16) were translated into Chinese according to a standard procedure. We adopted both Q16 and Q18 (i.e., containing a total of 21 questions) in our study to more comprehensively assess neurotoxic symptoms among the Chinese

Table 1
Sociodemographic characteristics among e-waste workers with different categories

n (%)	Overall (n = 109)	Job designation			Type of entity		
		Others* (n = 40)	Dismantling or repairing (n = 69)	p	Government-funded (n = 56)	Others† (n = 53)	p
Age (mean ± SD)	48.3 ± 11.6	48.9 ± 12.1	47.9 ± 11.4	0.692	48.6 ± 12.0	47.9 ± 11.4	0.785
Gender							
Male	64 (58.7)	23 (57.5)	41 (59.4)	0.999	35 (62.5)	29 (54.7)	0.529
Female	45 (41.3)	17 (42.5)	28 (40.6)		21 (37.5)	24 (45.3)	
Habitually smoking cigarette							
No	84 (77.1)	30 (75.0)	54 (78.3)	0.878	40 (71.4)	44 (83.0)	0.226
Yes	25 (22.9)	10 (25.0)	15 (21.7)		16 (28.6)	9 (17.0)	
Habitually drinking alcohol							
No	89 (81.7)	30 (75.0)	59 (85.5)	0.267	42 (75.0)	47 (88.7)	0.110
Yes	20 (18.3)	10 (25.0)	10 (14.5)		14 (25.0)	6 (11.3)	
Education attainment							
Middle school or below	90 (82.6)	28 (70.0)	62 (89.9)	**0.018**	47 (83.9)	43 (81.1)	0.895
Above middle school	19 (17.4)	12 (30.0)	7 (10.1)		9 (16.1)	10 (18.9)	
Marital status							
Married	76 (69.7)	25 (62.5)	51 (73.9)	0.301	40 (71.4)	36 (67.9)	0.850
Widower/single/divorced	33 (30.3)	15 (37.5)	18 (26.1)		16 (28.6)	17 (32.1)	
Household income							
<20,000	18 (48.6)	8 (21.6)	10 (16.7)	0.467	9 (19.1)	9 (18.0)	0.933
20,000–39,999	39 (40.2)	12 (32.5)	27 (45.0)		18 (38.3)	21 (42.0)	
≥40,000	40 (41.2)	17 (45.9)	23 (38.3)		20 (42.6)	20 (40.0)	

Bold font means $p < 0.05$.
* Others refer to job designation other than dismantling or repairing e-waste, such as collecting or sorting e-waste, forklift driver, project manager, and technician in e-waste recycling factories.
† Others refer to those entities not subsidized by the government, such as non-governmental organizations, private companies, and private shops.

participants [24,25] as no evidence shows whether the sensitivity and specificity of Q18 are better than Q16 among Chinese e-waste recycling workers. The Q16/Q18 consists of 16/18 questions with yes/no answers to the symptoms associated with neurotoxicity, including emotion, memory, sensation, concentration, and others. The score for each item in Q16/Q18 was zero for answering "no" and one point for replying "yes" for individual symptoms. According to the authors' recommendations of these scales, the neurotoxic symptoms were classified as positive for a total score ≥3 in Q16 and ≥5 in Q18, which achieved an optimum and balanced sensitivity and specificity [24,25].

2.3. Assessment based on GENEActiv accelerometer

Workers wore a GENEActiv accelerometer (Activinsights Ltd., Cambridgeshire, UK) on their non-dominant wrist for seven consecutive days to determine their objective sleep status and circadian rhythm. We excluded 21 participants with less than a five-day (120 hours) total real-wearing duration from the final analysis.

The objective sleep parameters were generated by the R package "GGIR". R package "Season" was used to calculate the circadian rhythm parameters [midline statistic of rhythm (MESOR) and amplitude]. MESOR is the adjusted mean level of the circadian rhythm. Amplitude is the magnitude of the rhythm, representing the distance between the peak level and MESOR [26]. We also used the R package "nparACT" to assess the non-parametric circadian rhythm variables, including interdaily stability (IS), intradaily variability (IV), and relative amplitude (RA). IS measures the stability of the rest–activity rhythm between different days and thus quantifies the extent of the rest–activity pattern coupling the 24-hour light–dark cycle, varying between 0 and 1 (0 = weakest coupling, 1 = strongest coupling). In contrast, IV captures the fragmentation of the rest–activity rhythm, ranging from 0 to 2 (0 = perfect sine wave, 2 = worst sine wave). RA is calculated from the relative difference between the averaged activity level for 10 hour with maximal movement (M10) and 5 hour with minimal movement (L5) [$RA = (M10 - L5)/(M10 + L5)$].

2.4. Statistical analysis

To facilitate the additional calculation, we also divided the continuous parameters into dichotomous variables (high vs. low or late vs. early) according to the respective mean or median, unless those with well-defined cut-off points.

Statistical differences for normal or non-normal distributed continuous variables were tested by independent *t*-tests or Mann–Whitney test, respectively. The chi-square test was used to compare the statistical difference for categorical variables. Unconditional logistic regression models were conducted to obtain the odds ratio (OR) or adjusted OR (AOR) for the associations of job designation and the type of entity with neurobehavioral alterations after adjusting for age only or further adjusting for other potential confounders (physical activity, tea-drinking habit, coffee-drinking habit, and family income). All statistical analyses were performed by R, 4.2.2.

3. Results

3.1. Sociodemographic and occupational characteristics

As shown in Table 1, no significant difference was found among most selected characteristics between workers in different categories (job designation and type of entity), except in a significantly higher percentage of workers with relatively low educated levels who were designated to dismantle or repair e-waste (89.9%).

Table 2 summarizes the occupational characteristics among e-waste workers and between different categories. A relatively larger proportion of the workers had worked in the e-waste industry for less than five years (67.6%). A majority of them identified their workplaces as having optimal occupational practices, such as ventilation systems (93.6%), OSH training (81.7%), and PPE guidelines or posters (89.0%). While the selected occupational characteristics were similar among the workers with different job designations, those working in entities without government funding were likelier to report no job rotation system (69.8%) or no occupational pollutant exposure history (66.0%) at the workplace. Moreover, fewer workers in these self-sustained

Table 2
Occupational characteristics among e-waste workers with different categories

n (%)	Overall (n = 109)	Job designation			Type of entity		
		Others* (n = 40)	Dismantling or repairing (n = 69)	p	Government-funded (n = 56)	Others† (n = 53)	p
Duration in the e-waste industry							
≤5 years	73 (67.6)	31 (77.5)	42 (61.8)	0.140	47 (83.9)	26 (50.0)	**< 0.001**
>5 years	35 (32.4)	9 (22.5)	26 (38.2)		9 (16.1)	26 (50.0)	
Working hours per week							
≤50 hours	57 (52.3)	25 (62.5)	32 (46.4)	0.154	23 (41.1)	24 (64.2)	**0.026**
>50 hours	52 (47.7)	15 (37.5)	37 (53.6)		33 (58.9)	19 (35.8)	
Ventilation systems at the workplace							
Without	7 (6.4)	4 (10.0)	3 (4.3)	0.258	3 (5.4)	4 (7.5)	0.711
With	102 (93.6)	36 (90.0)	66 (95.7)		53 (94.6)	49 (92.5)	
Job rotation system							
Without	57 (52.3)	25 (62.5)	32 (46.4)	0.154	20 (35.7)	37 (69.8)	**< 0.001**
With	52 (47.7)	15 (37.5)	37 (53.6)		36 (64.3)	16 (30.2)	
Occupational safety and health training							
Without	20 (18.3)	10 (25.0)	10 (14.5)	0.267	9 (16.1)	11 (20.8)	0.701
With	89 (81.7)	30 (75.0)	59 (85.5)		47 (83.9)	42 (79.2)	
PPE guidelines or posters at the workplace							
Without	12 (11.0)	7 (17.5)	5 (7.2)	0.119	5 (8.9)	7 (13.2)	0.684
With	97 (89.0)	33 (82.5)	64 (92.8)		51 (91.1)	46 (86.8)	
Change working clothes before returning home							
Yes	88 (80.7)	34 (85.0)	54 (78.3)	0.543	56 (100.0)	32 (60.4)	**< 0.001**
No	21 (19.3)	6 (15.0)	15 (21.7)		0	21 (39.6)	
Self-reported occupational pollutant exposure							
No	54 (49.5)	19 (47.5)	35 (50.7)	0.899	19 (33.9)	35 (66.0)	**0.002**
Yes	55 (50.5)	21 (52.5)	34 (49.3)		37 (66.1)	18 (34.0)	

Bold font means $p < 0.05$.
* Others refer to job designation other than dismantling or repairing e-waste, such as collecting or sorting e-waste, forklift driver, project manager, and technician in e-waste recycling factories.
† Others refer to those entities not subsidized by the government, such as non-governmental organizations, private companies, and private shops.

companies changed their working clothes before returning home (i.e., 60.4% in self-sustained companies vs. 100% in government-funded companies).

3.2. Neurobehavioral alterations

Multiple indicators were used to reflect the overall neurobehavioral alterations among e-waste workers under different occupational classifications (Table 3). Compared with other job designations, workers dismantling or repairing e-waste had an earlier MST, a more robust circadian rhythm (i.e., significantly higher amplitude and MESOR), and higher scores for neurotoxic symptoms in either Q16 or Q18. Although no significant difference in scores for neurotoxic symptoms between the entity types was observed, participants working in other recycling entities rather than government-funded companies were inclined to have a late MST and a dampened rhythm (i.e., higher IV and lower amplitude).

3.3. Effects of job designation and entity type on neurobehavioral alterations

Taking the low-risk group as the reference, we calculated the associations of the intended neurobehavioral outcomes with dismantling/repairing e-waste or working in entities not funded by the government (Table 4). Workers who dismantled or repaired e-waste products were more prone to suffer from neurotoxic symptoms based on either Q16 (AOR = 2.72, 95% CI: 1.10–7.11) or Q18 (AOR = 3.18, 95% CI: 1.18–9.39). E-waste workers working in organizations not subsidized by the government tended to have delayed MST (AOR = 4.45, 95% CI: 1.76–12.08), late-onset time (AOR = 3.04, 95% CI: 1.09–9.11), and a worse rest-activity rhythm in parameters, such as higher IS (AOR = 0.36, 95% CI: 0.13–0.97), higher IV (AOR = 4.06, 95% CI: 1.49–11.93), and lower amplitude (AOR = 0.24, 95% CI: 0.08–0.69). Working in these private recycling facilities also increased the likelihood of having neurotoxic symptoms in Q18 (AOR = 2.77, 95% CI: 1.10–7.46).

To examine the combined associations of job designation and entity type with neurotoxic symptoms, we took the workers in government-funded companies with other job designations as the reference group to measure the risk for workers in other job combinations (Table 5). Workers disassembling e-waste in entities not funded by the government had the highest chance of having neurotoxic symptoms measured by the Q16 scale (AOR = 4.11, 95% CI: 1.29–14.41), followed by other relatively lower risk combinations with a significant trend (*p*-value for trend: 0.017). A similar but stronger pattern (AOR = 4.87, 95% CI: 1.42–19.52) also manifested in the modified Q18 scale.

4. Discussion

This study is the first research conducted among the grassroots workers employed in the Hong Kong e-waste recycling industry. The results provided first-hand details regarding the occupational characteristics of the local industry, unveiled the prevalence of neurobehavioral alterations, and revealed the associations of the specific occupational category (i.e., job designation and the entity type) with the selected neurological outcomes among e-waste workers.

4.1. Occupational characteristics among the e-waste recycling facilities in Hong Kong

The findings of our study revealed that the overall working environment and OSH practices in the Hong Kong e-waste recycling industry are generally better than those reported in the LMICs [27,28]. Around 90% of our participants reported having a general

Table 3
Neurobehavioral alterations and levels of bio-markers among e-waste workers

Median (IQR) or mean ± SD	Overall ($n = 109$)	Job designation			Type of entity		
		Others* ($n = 40$)	Dismantling or repairing ($n = 69$)	p	Government-funded ($n = 56$)	Others† (n = 53)	p
Subjective sleep parameters from PSQI							
Global score	5.0 (4.0)	4.5 (3.0)	5.0 (4.0)	0.495	4 (4.0)	5.0 (4.0)	0.865
MST	3.1 ± 1.1	3.5 ± 1.2	2.9 ± 1.0	**0.027**	2.7 ± 0.9	3.6 ± 1.1	**< 0.001**
Sleep duration	6.5 ± 1.2	6.5 ± 1.2	6.4 ± 1.1	0.805	6.3 ± 1.3	6.6 ± 0.9	0.169
Objective sleep parameters from GENEActiv							
Onset time	23.7 ± 1.4	23.8 ± 1.5	23.6 ± 1.4	0.530	23.5 ± 1.5	23.9 ± 1.2	0.126
Sleep duration	5.9 ± 0.9	5.8 ± 1.0	6.0 ± 0.8	0.339	5.9 ± 1.1	5.9 ± 0.6	0.958
Sleep efficiency	82 ± 8	82 ± 7	82 ± 9	0.957	83 ± 9	82 ± 7	0.637
Circadian rhythm from GENEActiv							
IS	0.49 ± 0.19	0.50 ± 0.23	0.48 ± 0.18	0.580	0.52 ± 0.20	0.44 ± 0.18	0.056
IV	0.77 ± 0.29	0.77 ± 0.27	0.77 ± 0.30	0.999	0.68 ± 0.25	0.88 ± 0.31	**0.001**
RA	0.57 ± 0.18	0.55 ± 0.19	0.58 ± 0.18	0.576	0.60 ± 0.19	0.53 ± 0.17	0.110
Amplitude	273 ± 146	235 ± 87	293 ± 165	**0.035**	307 ± 173	231 ± 85	**0.009**
Mesor	413 ± 113	372 ± 82	435 ± 122	**0.006**	430 ± 125	393 ± 95	0.129
Q16/Q18 assessed neurotoxic symptoms							
Score for Q16	3.0 (5.0)	2.0 (4.0)	4.0 (5.0)	**0.033**	2.0 (4.5)	3.0 (5.0)	0.702
Score for Q18	3.0 (5.0)	2.0 (4.0)	4.0 (6.0)	**0.014**	2.0 (5.0)	3.0 (5.0)	0.591

Footnotes: Amplitude, magnitude of the rhythm; IS, interdaily stability; IV, intradaily variability; Mesor, midline statistic of rhythm; MST, mid-sleep time; RA, relative amplitude.
Bold font means $p < 0.05$.
* Others refer to job designation other than dismantling or repairing e-waste, such as collecting or sorting e-waste, forklift driver, project manager, and technician in e-waste recycling factories.
† Others refer to those entities not subsidized by the government, such as non-governmental organizations, private companies, and private shops.

ventilation system (natural or fan) or even the local exhaustive ventilation (fume hood) and with PPE guidelines/posters at the workplace. In addition, more than 80% of local workers received OSH training before starting employment. However, it is worth mentioning that most family-run private shops put the recycling zone next to the living area and rarely use PPE when dealing with e-waste (Supplementary Table 1), which needs to be improved.

Studies have reported that the informal sectors are heavily involved in the e-waste recycling industry, but they mainly apply primitive approaches to handle e-waste in a poorly regulated

Table 4
Effects of dismantling or repairing e-waste and working in entities not funded by the government on neurobehavioral alterations among e-waste workers*

	Job designation with dismantling or repairing		Working in entities not funded by the government	
	OR†	AOR‡	OR†	AOR‡
Subjective sleep parameters from PSQI				
Poor sleep quality (score >5)	1.16 (0.51–2.71)	1.06 (0.40–2.86)	0.81 (0.36–1.78)	0.97 (0.38–2.52)
Delayed MST (≥mean)	0.52 (0.22–1.19)	0.46 (0.18–1.15)	**4.36 (1.90–10.52)**	**4.45 (1.76–12.08)**
Short sleep duration (<6 h)	0.96 (0.37–2.67)	0.64 (0.19–2.11)	0.51 (0.18–1.32)	0.39 (0.11–1.27)
Objective sleep parameters from GENEActiv				
Late-onset time (>mean)	1.06 (0.40–2.83)	1.03 (0.34–3.10)	**2.76 (1.09–7.28)**	**3.04 (1.09–9.11)**
Short sleep duration (<6 h)	1.01 (0.40–2.56)	1.11 (0.38–3.20)	1.07 (0.44–2.59)	1.32 (0.50–3.53)
High sleep efficiency (>mean)	0.74 (0.27–1.98)	0.78 (0.25–2.39)	1.39 (0.56–3.50)	1.59 (0.58–4.51)
Circadian rhythm from GENEActiv				
High IS (>mean)	0.87 (0.34–2.19)	1.16 (0.41–3.29)	**0.36 (0.14–0.87)**	**0.36 (0.13–0.97)**
High IV (>mean)	0.85 (0.34–2.11)	1.36 (0.49–3.98)	**3.40 (1.40–8.58)**	**4.06 (1.49–11.93)**
High RA (>mean)	1.41 (0.57–3.62)	1.78 (0.65–5.15)	0.43 (0.17–1.02)	0.46 (0.17–1.16)
High amplitude (>mean)	1.25 (0.49–3.28)	0.96 (0.34–2.81)	**0.30 (0.11–0.75)**	**0.24 (0.08–0.69)**
High mesor (>mean)	2.33 (0.90–6.42)	1.57 (0.55–4.76)	**0.40 (0.16–0.97)**	0.43 (0.15–1.14)
Q16/Q18 assessed neurotoxic symptoms				
Positive (Q16 score ≥3)	**2.29 (1.03–5.21)**	**2.72 (1.10–7.11)**	1.43 (0.67–3.09)	2.20 (0.92–5.42)
Positive (Q18 score ≥5)	**2.87 (1.22–7.27)**	**3.18 (1.18–9.39)**	1.78 (0.81–3.97)	**2.77 (1.10–7.46)**

Footnotes: MST, mid-sleep time; IS, interdaily stability; IV, intradaily variability; RA, relative amplitude; Amplitude, magnitude of the rhythm; Mesor, midline statistic of rhythm.
Bold font means $p < 0.05$.
* Used mean or median of the respective variable in Tables 3 and 4 as the cut-off point, except for those with the defined cut-off point.
† Crude model: Adjusted for the age of the e-waste workers.
‡ Adjusted model: Further adjusted for physical activity, tea-drinking habit, coffee coffee-drinking habit, and family income.

Table 5
Combined associations of job designation and company type with neurotoxic symptoms among e-waste workers*

Neurotoxic symptoms (Q16 score ≥3)		Type of entity		p for trend
		Government-funded	Others†	
Job designation	Others‡	1.00	1.21 (0.22–6.32)	**0.017**
	Dismantling or repairing	1.30 (0.34–5.19)	**4.11 (1.29–14.41)**	
Neurotoxic symptoms (Q18 score ≥5)		Type of entity		p for trend
		Government-funded	Others†	
Job designation	Others‡	1.00	0.97 (0.11–6.50)	**0.009**
	Dismantling or repairing	1.15 (0.25–5.38)	**4.87 (1.42–19.52)**	

Bold font means $p < 0.05$.
* Adjusted for the age of the e-waste workers, physical activity, tea-drinking habit, coffee coffee-drinking habit, family income, and working hours per week.
† Others refer to those entities not subsidized by the government, such as non-governmental organizations, private companies, and private shops.
‡ Others refer to job designation other than dismantling or repairing e-waste, such as collecting or sorting e-waste, forklift driver, project manager, and technician in e-waste recycling factories.

workplace due to shortage of resources [8,9]. Although we did not divide the participating organizations into formal or informal, we considered the entities not subsidized by the government to be similar to informal recycling sectors from other regions since they also had a poorly regulated working environment and handled e-waste in a rudimentary way. Most "informal" recycling sectors in Hong Kong are operated without a job rotation system, which is recommended to mitigate occupational exposure and ergonomic burden [29,30]. Besides, workers working in these entities had low health risk awareness in changing their working clothes before returning home and reporting occupational pollutant exposure history at work, which increased the on-site exposure to them and take-home secondary exposure to their family members. These results aligned with the results from the informal recycling sectors in LMICs [10,20].

4.2. Neurobehavioral health status among e-waste workers in Hong Kong

Previous studies suggested that the workers repairing or dismantling e-waste and working in informal facilities had higher levels of chemical exposure than their counterparts [20,21], resulting in poor health status, including neurobehavioral alterations [1,14]. Therefore, we divided e-waste workers into potentially high-exposed and low-exposed groups to compare the differences and explore their effects on neurobehavioral changes. The workers disassembling or repairing e-waste had elevated scores and rates of neurotoxic symptoms. Likely, a similar but less potent trend between neurotoxic symptoms and workers in self-sustained entities was also observed. Most chemicals from the e-waste recycling process are proven neurotoxicants. Thus, the workers in the assumed high-exposed groups were presumably facing more neurotoxicant exposure from e-waste and having more chances to develop subtle neurotoxic symptoms. A contrary pattern was noticed in these high-risk groups, in which a more robust circadian rhythm was manifested among the dismantlers or repairers, which is out of expectation. One possible explanation could be the dismantling/repairing job designation was highly physically demanding, even for those manually handling e-waste in a sitting position, which would be captured by our sensitive wrist-worn accelerometer [31]. This could result in a higher level of physical activity at work and lead to a better rest–activity rhythm, notwithstanding the activity level at night. This phenomenon could also be partly explained by the longer working hours among dismantlers/repairers, which might lead to more physical activity during the day, a more stable daily routine, and, therefore, a better circadian rhythm [32–34]. As for the worse circadian rhythm among workers in entities not funded by the government, we reckon that the potential effects of being excessively exposed to e-waste pollutants on circadian rhythm were truly revealed and not masked by the physical demand of entity types. Workers in government-funded companies had significantly longer working hours than their counterparts, which could be another reason for their better performance in circadian rhythm parameters. The results regarding job designation and entity type combinations reconfirmed our presumption that the dismantlers or repairers working in the private facilities without subsidy have the highest risk of developing neurotoxic symptoms because both categories were the high exposure groups according to previous studies [20,21].

4.3. Limitations and strengths

Firstly, we only recruited 109 e-waste workers, and the relatively small sample size directly caused some OR with a broader range of 95% CIs. According to our estimation [35], participating workers of this study have already represented 5% of the overall e-waste recycling workers in Hong Kong. Nevertheless, we needed to get the agreement from the management of these entities before approaching the participants. Therefore, the manager might have some extent of influence on participants' answers to some questions, potentially leading to an overestimation of the performance of OSH practice in the e-waste industry in Hong Kong. However, the main focus of this study is the neurobehavioral alterations, and such alterations related to sleep and circadian rhythm were collected by highly objective and reliable accelerometers. Secondly, we categorized our participants into high-risk and low-risk groups according to the assumed exposure level based on the previous studies from the LMICs. However, the experience from other areas may not be suitable to be directly applied in the e-waste recycling industry in Hong Kong, and the hazardous degree of e-waste exposure should be reflected by directly measuring internal chemical levels. Thus, we plan to test two critical kinds of pollutants (i.e., heavy metals and organic pollutants) in the collected urinary samples in the near future. Thirdly, those occupational factors that might bias the results of this study, such as working hours and duration of working in the e-waste industry, were not included in the multivariate models as these factors were not significantly related to the intended outcomes in the univariate analysis. For the non-occupational activities or personal exposures that might bias the associations, we only adjusted for some well-known factors (e.g., physical activity, tea and coffee drinking habits, and family income) in the models since the limited sample size of this study may yield insufficient power to detect a potential confounder with a weak association. Fourthly, instead of using the World Health Organization–recommended Neurobehavioral Core Test Battery

(NCTB) to identify neurobehavioral alterations among the participants in this study [36], we used multiple subjective validated scales and an objective accelerometer to appraise the neurotoxic effects from e-waste exposure. Although NCTB is the international standard, it is time-consuming, and to be effectively tested by the NCTB, people should have 12 or more years of education [36]. Hence, NCTB might not be an appropriate tool for evaluating the neurotoxic effects among e-waste workers with relatively low education levels. Other objective measurements (e.g., noise and chemical measurements at the workplace) were also not conducted in this study. Future studies could include such measurements to provide a more comprehensive occupational exposure profile that was related to the workers' neurological health.

5. Conclusion

This survey provides scientific evidence on the health burden of e-waste recycling workers, especially the neurobehavioral alterations, to inform policymaking for various stakeholders. Although the neurobehavioral performance was acceptable for overall e-waste workers compared to office workers, we identified the e-waste workers in the categorized high-risk groups were associated with neurotoxic effects, particularly those workers responsible for dismantling or repairing e-waste in entities not funded by the government. These findings suggested that citizens should reduce the generation of e-waste, and policymakers should prioritize the resources for the Hong Kong e-waste workers from high-risk groups to improve their health with limited resources. The administrators could help the facilities adopt engineering or administrative control to reduce the dismantler's chemical burden. Considering the positive role of informal e-waste recycling sectors in the environment and sustainability, the regulators could provide OSH training and perhaps subsidies to encourage them to adopt safer recycling methods without hindering their livelihood.

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Authors' contribution

Lap Ah Tse is the project's principal investigator, who designed and supervised the entire study. Gengze Liao managed and analyzed the data and drafted the manuscript. Feng Wang, Shaoyou Lu, and Yanny Yu Hoi Kuen commented on and reviewed the manuscript. Victoria H. Arrandale and Alan CHAN Hoi-shou critically reviewed and revised the manuscript.

Data statement

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2023.12.004.

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