Environmental Research 201 (2021) 111639

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Registration status, mercury exposure biomarkers, and neuropsychological assessment of artisanal and small-scale gold miners (ASGM) from the Western Region of Ghana

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ARTICLE INFO

Keywords:
Mercury
Mining
Vulnerable populations
Biological monitoring
Public health
ASGM

ABSTRACT

The artisanal and small-scale gold mining (ASGM) sector is estimated to be the largest anthropogenic source of mercury pollution worldwide, and not surprisingly human exposures in this sector are amongst the highest of all population groups. While formalization of the sector has been proposed as a solution to help improve health and safety within ASGM sites, there are few empirical studies in support of this notion. The objective of this study was to assess if individuals working in ASGM sites that are registered have reduced mercury exposures and better neuropsychological scores than workers from unregistered sites. To achieve this objective, we studied biological samples (urine, hair) and survey data from a study of 404 ASGM workers (of which, 295 worked in registered ASGM sites) conducted in Tarkwa (Ghana) in 2014. Between miners working in registered and unregistered sites, there were few differences in socio-demographic characteristics. Median urinary mercury concentration (specific gravity-corrected) among those from unregistered mines was nearly 3-fold higher than those from the registered mines (18.5 versus 6.6 μg/L), and in the overall population the median concentration was 10.0 μg/L, and ranged from 0.3 to 2499 μg/L. Mercury biomarkers varied across ASGM work categories (e.g., those who burned or amalgamated had the highest) and users of personal protective equipment. Nearly 30% of the study population indicated having some challenges concerning, for example, reduced appetite, hair loss, or excess salivation. Ataxia and rigidity of gait were absent in most of the participants, and for those with slight, moderate, or marked responses, there were no differences between miners from registered and unregistered sites, across work groups, as well as in reference to mercury biomarker measures. For the pencil tapping, Frostig, matchbox, and Wechsler tests, no striking differences were found though a correlation was found between urinary mercury levels and matchbox scores among those who amalgamate and burn, and scores were similar to past studies using the same tests in ASGM sites. We believe this is the first study to compare mercury exposures and neuropsychological test results between miners from registered and unregistered ASGM sites. In doing so, the research findings provide the necessary evidence for stakeholders and parties of the Minamata Convention considering various response options to help fulfill their obligations.

1. Introduction

The artisanal and small-scale gold mining (ASGM) sector is estimated to directly employ 14–19 million people worldwide (Steckling et al., 2017). Upwards of 100 million people live in ASGM communities, and are thus reliant on the sector (UN Environment, 2019). Several health concerns exist among ASGM community members such as chronic exposure to dust and noise, unsanitary working conditions, and lack of personal protective gear (Basu et al., 2015a; Gibb and O'Leary, 2014).

In ASGM communities, the use of mercury is of particular health concern (Gibb and O'Leary, 2014; Steckling et al., 2017; UN Environment, 2019). Notably, the sector is estimated to be the world's largest anthropogenic source of mercury emissions (i.e., 838 tonnes emitted to air in 2015) (UN Environment, 2019), and as such ASGM communities

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https://doi.org/10.1016/j.envres.2021.111639
Received 10 April 2021; Received in revised form 25 June 2021; Accepted 1 July 2021
Available online 7 July 2021

procure, store and handle relatively large amounts of mercury which may pose risk to community members. In the mining process, after gold-containing ore or silt is ground into a powder form, liquid mercury is added to the mixture to create an amalgam (Esdaile and Chalker, 2018). Subsequent burning of this amalgam concentrates the gold into a pellet but releases mercury, in its gaseous elemental form (Hg^0), into the air. The released elemental mercury vapor poses both an occupational and environmental threat. Occupationally, those involved in small-scale mining (both directly and indirectly), as well as area residents, may inhale high levels of elemental mercury and/or be exposed to inorganic mercury-contaminated components (e.g., soil, foods). Mercury used in the ASGM sector may also enter aquatic bodies where it has the potential to become biomethylated, following which the resulting methylmercury compound may accumulate and bio-magnify in food webs thus posing a risk to fish consumers.

Contamination of human populations and ecological components by mercury has been observed in many ASGM sites worldwide, such as those in Brazil (Lebel et al., 1998), Indonesia (Bose-O'Reilly et al., 2010a), Tanzania (Bose-O'Reilly et al., 2010c), and Ghana (Basu et al., 2015a; Rajaee et al., 2015a). Not surprisingly, biomonitoring studies in these sites demonstrate relatively high exposures to mercury compounds (both elemental mercury and methylmercury) among ASGM workers as well as community residents (Bose-O'Reilly et al., 2017; Gibb and O'Leary, 2014). For example, from the 2018 UN Global Mercury Assessment, mercury concentrations in urine sampled from members of ASGM populations worldwide were about 30 to 200-fold higher than levels measured in general populations (Basu et al., 2018). Exposures to mercury in ASGM communities have been linked with neurotoxicity and other adverse health outcomes (Gibb and O'Leary, 2014; Steckling et al., 2017).

The ASGM sector has several mentions in the Minamata Convention (i.e., Article 7 and Annex C), and in particular, there is a requirement of countries with ASGM activities that are "more than insignificant" (Article 7.3) to develop and implement a national action plan that includes public health strategies to protect vulnerable populations. One way to realize this, as mentioned in the Minamata Convention (Annex C 1-c), as well as reports from the International Labour Organization and other researchers, is to take steps to formalize the ASGM sector (Basu et al., 2015b; International Labour Organization (ILO), 1999; Siegel and Veiga, 2009). While it is believed that formalization of the sector will help improve health and safety within ASGM sites, there are few empirical studies in support of this notion.

The objective of this study was to assess if individuals working in ASGM sites that are registered have reduced mercury exposures and better neuropsychological scores than workers from unregistered ASGM sites. To achieve this objective, we leveraged biological samples and survey data from a cross-sectional study of 404 ASGM workers conducted in the Tarkwa municipality of Ghana's Western Region in 2014, of which 294 workers were registered and the rest were not (Calys-Tagoe et al, 2015, 2017). Ghana is one of the world's most important gold mining countries with activities dating back over 1000 years, and within Ghana the Western Region is particularly active in mining. Gold mining contributes to nearly 50% of the country's national exports with most workers employed in the ASGM sector (Basu et al., 2015c). The majority of ASGM activities in Ghana are estimated to occur in unregistered sites. The process of ASGM registration in Ghana requires the owner to inform the government (Minerals Commission) of where they set up their mining operation, perform an environmental assessment, and pay a fee, and these steps may be too burdensome or costly for many groups to follow.

2. Methods

2.1. Study population

A cross-sectional study was carried out in Tarkwa (Ghana) in March and April of 2014 as detailed previously (Calys-Tagoe et al, 2015, 2017). Briefly, ASGM miners (n = 404) were recruited from nine ASGM sites of which five sites were registered and the others were not. The registered mine sites were randomly selected from a list maintained by the Minerals Commission, but recruitment from unregistered sites required the use of networking through contact zones as we have previously detailed (Calys-Tagoe et al., 2015). Human ethics approvals were obtained from the Ethics Review Committee of the Ghana Health Service (GHS) (ID No. GHS-ERC: 24/05/13) and the Institutional Review Board (IRB) at the University of Michigan (ID No. HUM00086183).

2.2. Mercury measurements

Total mercury concentrations were measured in urine and hair based on recent biomonitoring guidance reports (WHO, 2018; Basu et al., 2018; Višnjevec et al., 2014) and consideration of mercury stable isotope information gleaned from human biomarkers from ASGM sites (Sherman et al., 2015). Spot urine samples (5–15 mL) were collected from participants at the time of the interview (usually mid-morning), kept at room temperature in-country, and then stored frozen (−20 °C) once received at McGill University. There is no reason to believe that variable storage conditions affected the mercury measurements since we analyzed for total mercury content and the element cannot be broken down, though additional research may be needed on this aspect. For a subset of individuals who provided urine samples, hair was also obtained. Hair was cut as close as possible to the scalp, placed on a sticky-note, and stored in a plastic bag until analysis. Hair samples were washed once with acetone and twice with deionized water, and dried for mercury analysis. Given the challenges associated with interpreting hair total mercury data obtained from ASGM communities (Sherman et al., 2015), these results are largely presented in the Supplementary Materials and should be viewed with caution.

Analysis of total mercury concentrations in hair and urine was carried out with a Direct Mercury Analyzer 80 (DMA-80, Milestone Inc, CT) according to U.S. EPA Method 7473 as previously described by our group (Basu et al., 2014; Rajaee et al., 2015b). Briefly, 500 μL of urine was vortexed and placed into a quartz sampling boat. Hair was washed twice with acetone, rinsed with Milli-Q water, and dried overnight. About 2–5 mg of hair was weighed into a nickel sampling boat. Once placed into the DMA-80, the biological samples were decomposed at 800 °C, and the liberated mercury vapor was captured onto a gold trap following which the element was desorbed from the trap and carried to an absorbance cell (253.7 nm) for quantification.

Accuracy and precision of the method were measured by the use of reference materials for urine (QMEQAS10U-04, Centre de Toxicologie/INSPQ) and hair (NIES CRM #13, Japanese National Institute for Environment Studies, NIES). Additionally, each batch run contained procedural blanks and replicate runs. The analytical detection limit was calculated as the concentration of mercury which gave a detectable signal above the background noise at greater than the 99% confidence level, so that the detection limit was calculated as 3 times the standard deviation of the mean blank value. A specific gravity measurement of the urine was taken with a refractometer (Atago 4410mPAL 10s). The mean specific gravity in this study population was 1.0228, and urinary mercury data are presented as being specific gravity adjusted, unless indicated otherwise.

2.3. Survey

The ASGM-focused Health Assessment Questionnaire developed by Bose-O'Reilly and colleagues, under a UNIDO/UNDP/GEF-sponsored initiative, was utilized here (Veiga and Baker, 2003). This survey instrument has since been tested in several ASGM sites worldwide, including in Indonesia, Mongolia, Philippines, Tanzania, and Zimbabwe (Bose-O'Reilly et al., 2017). The survey instrument was first reviewed by co-authors with Ghana Health Service to ensure applicability with the study population. The survey instrument was interviewer-administered by a research team led by a physician with training in occupational and environmental health (BNLCT).

The survey instrument was broad, and in the current study, we focused on data concerning socio-demographic characteristics and mining work history (previously detailed in Calys-Tagoe et al., 2017; Calys-Tagoe et al., 2015). Neuropsychological information was collected using two approaches. First, self-reported information was collected on a range of neurological symptoms (e.g., sleep disturbances, well-being) as well as mental and physical health. Second, neuropsychological tests were performed that included gait tests (ataxia and rigidity), digit span test (part of the Weschler Memory Scale; assess short-term memory), matchbox test (assess motor coordination and concentration), Frostig test (assess tremor and visual-motor function), and pencil tapping test (assess intentional tremor and coordination).

2.4. Data analysis

The collected data were stored electronically and double-keyed to ensure accuracy. Preliminary data analysis included a tabulation of descriptive statistics for all measurements to understand the basic features of the dataset. Mercury biomarker values and the measured neuropsychological tests were not normally distributed and thus non-parametric statistics (Mann-Whitney U tests, Kruskal-Wallis analysis of variance on ranks, and spearman correlations) were used to analyze the data. Data were also categorized and analyzed using chi-square tests. The primary comparison of interest was between miners from the registered and unregistered sites. Secondary comparisons focused on potential differences across self-reported work categories and mercury exposure groups. The level of statistical significance was $p < 0.05$. The data were analyzed using R Studio version 1.4.

3. Results and discussion

3.1. Population demographics

Between the two groups of ASGM miners, there were few differences in socio-demographic characteristics (Table 1). About 75% of the miners were less than 40 years of age, with a median age of 32. Close to 30% of the miners had reported having completed at least senior high school and nearly two-thirds of them reported living with a partner. The socio-demographic characteristics of the study population are similar to past ASGM studies from Ghana (Mensah et al., 2016; Paruchuri et al., 2010; Rajaee et al., 2015c) and elsewhere worldwide (Bose-O'Reilly et al., 2017), though we note here that the study population was predominately male, unlike most other studies.

Table 1
Socio-demographic characteristics and mercury biomarker levels of the study population according to mine registration status.

	Miners Working in a Registered ASGM site (n = 295)	Miners Working in an Unregistered ASGM site (n = 109)	All ASGM Workers (n = 404)
Age (mean ± SD years)	34.0 ± 10.8	33.2 ± 10.0	33.8 ± 10.6
Male (%)	89.8	98.2	92.1
High School Completed (%)	26.8	33.1	28.5
Living with Partner (%)	67.5	61.4	65.8
Duration (months) Worked in ASGM (median, 25–75% in brackets)	48 (12–108)	60 (24–144)	48 (12–120)
Urine Total Mercury Concentrations (μg/L, SG-adjusted), median values (25–75% in brackets), sample size	6.6 (3.0–18.1), n = 177	18.5 (9.4–46.3), n = 92	10.0 (3.2–30.0), n = 269
Hair Total Mercury Concentrations (μg/g), median values (25–75% in brackets), sample size	2.6 (1.6–3.5), n = 115	4.4 (2.8–9.8), n = 36	2.8 (1.8–4.3), n = 151

3.2. Work profiles

Participants indicated to have worked in the ASGM sector for a duration ranging from 1 month to 30 years, with a median work duration of 4 years (Table 1). Participants reported working in their current ASGM site for 2 years and this did not vary between registered and unregistered sites. However, individuals currently working in an unregistered mine reported having worked in the ASGM sector 50% longer than those currently working in a registered mine.

All participants reported having been involved in one or more of seven key ASGM activities we queried for, namely excavation (45%), carrying loads (8%), crushing and grinding (46%), sifting and shanking (14%), washing and sluicing (38%), amalgamation (37%), and burning (41%). More than 50% of the respondents indicated being routinely involved in more than one activity, with 25% being involved in four or more activities regularly. The involvement of miners in multiple work tasks has been previously documented in Ghana (Paruchuri et al., 2010; Rajaee et al., 2015c). While there were no statistically significant differences between miners from the registered and unregistered sites in terms of the number of work activities that they reported being currently involved with, the proportion of miners from unregistered sites involved in amalgamation (46% vs. 33%) and burning (59% vs. 32%) was significantly higher than that for those from the registered sites.

3.3. Mercury exposures

Mercury biomarker data (i.e., total mercury concentrations in urine and hair) were available from 269 (66%) of the overall study population and the sociodemographic profiles of these individuals were similar to that of the larger study population (Supplementary Material 1). The quality of the mercury biomarker measurements was deemed to be good based on a review of the analytical accuracy, precision, and detection limit values (Supplementary Material 2). All measurements taken were above the analytical detection limit.

In the study population, the median urinary mercury concentration (corrected for specific gravity, which averaged 1.0228) was 10.0 μg/L, and ranged from 0.3 to 2499 μg/L (with the 25th and 75th percentile values being 3.2 and 30.0 μg/L respectively) (Fig. 1a; Table 1; Supplementary Material 3). The median urinary mercury concentrations among those from unregistered mines were nearly 3-fold higher than those from the registered mines, and this was of statistical significance. This approximate 3-fold difference was also evident across the interquartile range of exposure. Finally, the maximum value recorded amongst the miners from unregistered sites was 2499 μg/L versus 335 μg/L in the miners from registered sites. To our knowledge, this is the first study to compare mercury biomarker levels between miners from registered and unregistered sites, and in doing so provides important evidence that aspects associated with registration may help reduce mercury exposures.

The mercury biomarker values we report here are comparable with data from ASGM workers elsewhere. For example, the 2018 UN Global Mercury Assessment compiled mercury exposure data from across the world, and an examination of that dataset specifically for the ASGM sector reveals 17 studies involving 3463 participants from which a pooled median urinary mercury concentration of 5.8 μg/L (IQR 3.0–14.4 μg/L) was calculated (Basu et al., 2018). The urinary biomarker values we report here are similar to a past study of 343 ASGM workers from Prestea, Ghana (mean value of 14.8 μg/L (Mensah et al., 2016)) though somewhat higher than urinary mercury levels in communities across Ghana as part of a national review activity, which

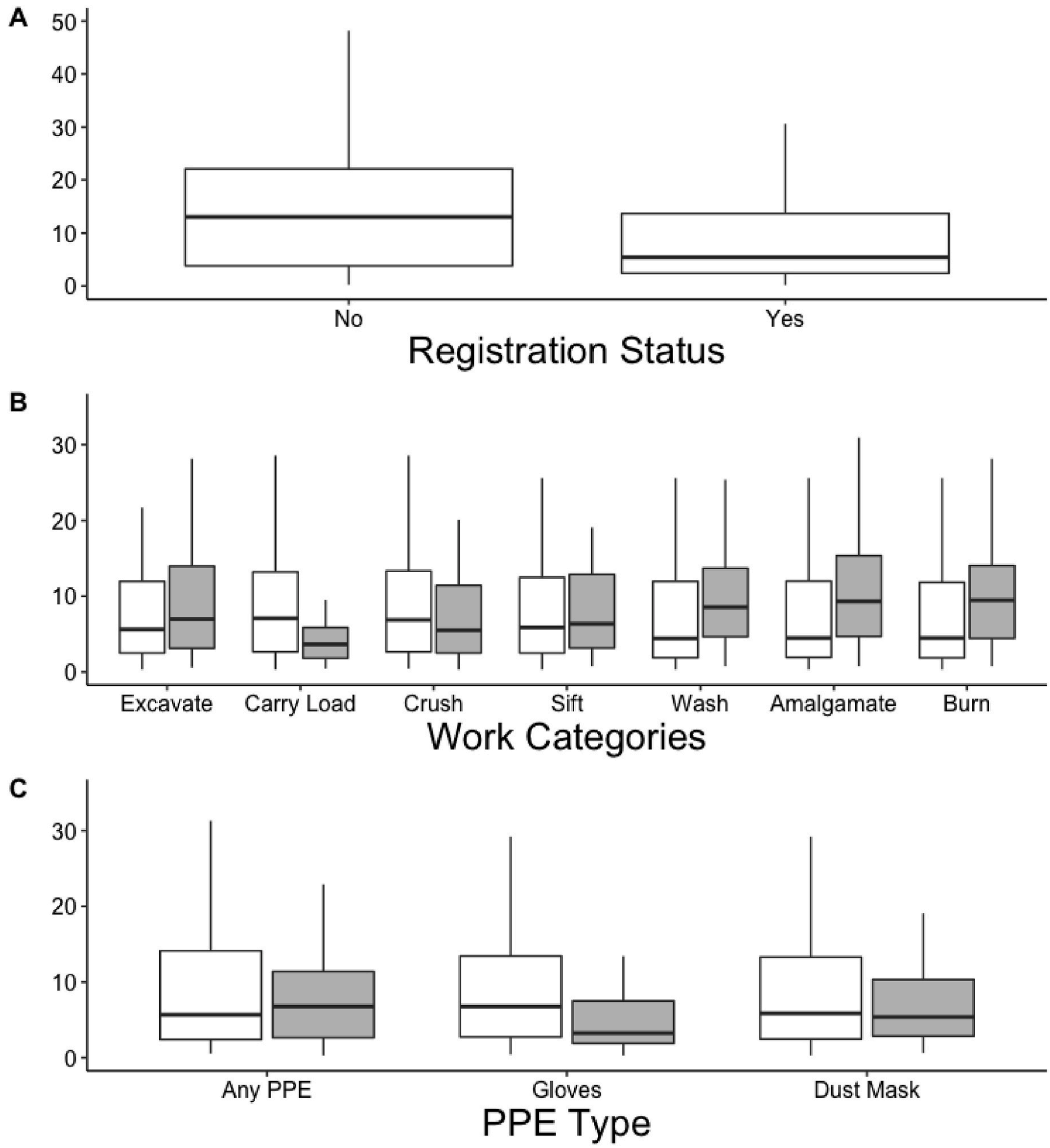

Fig. 1. Boxplots of urinary mercury concentrations (vertical axis; μg/L specific-gravity corrected) for: A) miners working in registered versus unregistered ASGM sites; B) miners involved in different ASGM work categories; and C) miners use of personal protective equipment (PPE). In plots B and C, those indicating "yes" to performing a certain ASGM work activity or using a certain PPE are shaded.

included some ASGM communities (Basu et al., 2015a). There was a small investigation of miners (n = 15) from the same geographic region as the current study, and the authors reported a median urinary level of 3 μg/L though levels in the non-mine working controls were higher (3.6 μg/L; n = 17) (Asante et al., 2007). Two studies of ASGM workers from Ghana's Upper East region documented median urinary mercury levels of 2.5 μg/L (Paruchuri et al., 2010) and 3.4 μg/L (Rajaee et al., 2015b), though the maximum levels in these studies (708 and 998 μg/L, respectively) suggest a similarly high range of exposures.

Urinary mercury levels were compared across self-reported worker groups (Fig. 1b; (Supplementary Material 3). Median levels were highest in those who burned (19.1 μg/L) and amalgamated (17.1 μg/L), followed by those who sifted (12.5 μg/L), washed (12.0 μg/L), crushed (9.4 μg/L), and excavated (9.3 μg/L), with those carrying loads having the lowest value at 3.4 μg/L. This rank-order in median values held true when the higher exposure levels (i.e., 75th percentile, maximum) were examined. Significant differences were found among individuals who self-reported involvement in washing and sluicing (1.5-fold higher), amalgamation (2.5-fold higher), and burning (3.2-fold higher) versus those who did not report involvement in the activity. Other studies have shown similar patterns in mercury exposure across ASGM work categories. For example, amalgam burners in Ghana's Upper East region had significantly higher urinary mercury levels (median level of 44 μg/L) than other occupational groups (Paruchuri et al., 2010), and this difference has also been reported in studies of ASGM workers from Indonesia (Bose-O'Reilly et al., 2010b), Tanzania (Bose-O'Reilly et al., 2010c), and Colombia (Calao-Ramos et al., 2021).

In the current study population, 106 participants (39.5%) indicated to have used some form of personal protective equipment and their median urinary Hg values were 27% lower (9.4 versus 11.9 μg/L) than those reported to not having used personal protective equipment (Supplementary Material 3). More specifically, those wearing gloves (n = 45) and masks (n = 40) had median urinary mercury levels that were 60% (4.7 versus 11.6 μg/L) and 21% (8.5 versus 10.7 μg/L) lower, respectively, than individuals reporting to not wearing such items. Similarly, a study of ASGM workers in Ghana's Upper East region found that mean urinary mercury levels were two-fold lower in individuals who used personal protective equipment versus those who did not (4.0 versus 8.0 μg/L) (Paruchuri et al., 2010). While in the current study none of the observed differences associated with the use of personal protective equipment were of statistical significance, the differences nonetheless are important and warrant further investigation. Previous research in the current study population noted that miners working in an unregistered site experienced more injury episodes (and not using personal protective equipment during the time of injury) compared to miners working in a licensed site (Calys-Tagoe et al., 2017).

The urinary mercury levels were categorized according to Germany's Human Biomonitoring (HBM) Commission with HBM-1 (7 μg/L) representing a level at which there is no risk of adverse health effects, and HBM-2 (25 μg/L) representing a level at which adverse health effects are possible thus needing risk reduction measures to be taken (Schulz et al., 2007). In the overall study population, 27% of the participants were in the high level category (i.e., exceeded HBM-2 value of 25 μg/L), and 62% were in both the alert level (i.e., between 7 and 25 μg/L) and high level categories. The distribution of miners in these categories differed significantly according to an individual's site (Fig. 2). Among the miners at registered sites, 20% of the participants were in the high level category, and 52% were in both the alert level and high level categories. In comparison, 40% of the miners at unregistered sites were in the high level category, and 80% from this group were in both the alert level and high level categories. We also ran one-sample Wilcoxon signed rank tests to determine if the median urinary mercury concentration differed from a given HBM level. In doing so, the median urinary mercury value for the entire study population was significantly greater than the HBM-1 level (i.e., alert range), as well as for the registered and unregistered miner groups.

Hair was sampled from 151 individuals (including 115 miners from registered sites). The median total mercury level in this biomarker was 2.8 (1.8–4.3; 25th and 75th percentile) μg/g, with median (25th and 75th percentile) concentrations in the registered and unregistered miners being 2.6 (1.6–3.5) and 4.4 (2.8–9.8) ug/g, respectively (Supplementary Material 4). Mercury in hair generally reflects exposure to methylmercury through dietary sources. However, care is needed when interpreting total mercury levels in hair sampled from ASGM sites given that large amounts of elemental mercury are usually used in the mining process and that gaseous elemental mercury tends to contaminate the

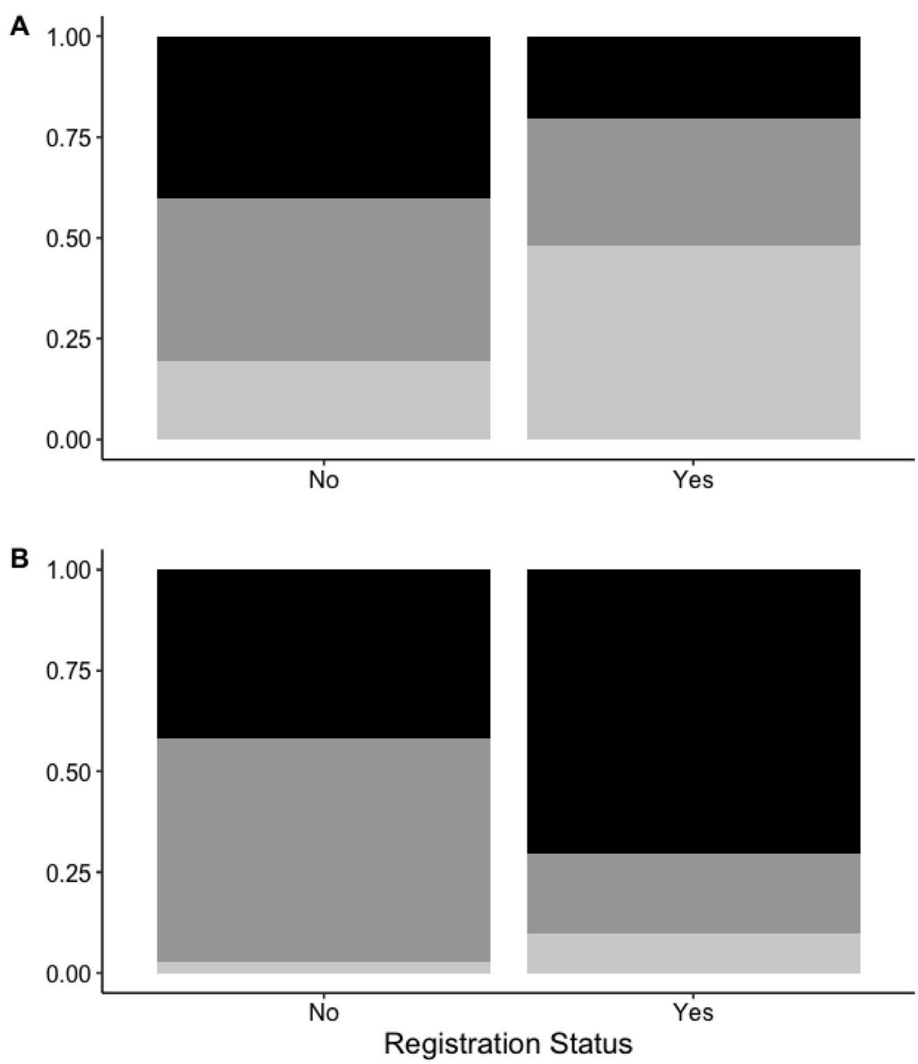

Fig. 2. Proportion of (A) urine and (B) hair total mercury levels from miners in unregistered and registered ASGM sites in relation to guidance levels proposed by Germany's Human Biomonitoring (HBM) Commission. For a given group, the proportion categorized in the "low" level is shaded light grey, those in the "alert" level are shaded dark grey, and those in the "high" level are shaded black.

local ecosystem including air. This mercury may bind exogenously to the hair follicle of ASGM workers and is not easily removed. Studies using mercury stable isotopes (Sherman et al., 2013, 2015) and chemical speciation (Calao-Ramos et al., 2021; Veiga and Baker, 2003; Wickliffe et al., 2021) have concluded that simple measures of total mercury in hair (as done in our study) generally over-estimate exposures and are thus not reliable, and that more sophisticated analytical approaches are needed to conclude the true source of the mercury in hair (i.e., diet or occupation) from which judgements can be made. Accordingly, here we do not dwell on the hair mercury data and reserve this information for Supplementary Material 4.

Recognizing that proper measurements of mercury in hair generally reflect dietary exposures to methylmercury, and concerns in some ASGM communities about methylmercury exposures, here we assessed participants' food consumption using the 2008 Ghanaian Demographic Health Survey (DHS). In 24-h preceding the interview, participants were asked whether items from particular food groups were consumed ("yes" or "no"). Focusing specifically on fish, participants noted consuming fish twice daily (i.e., 25th, 50th, and 75th percentile values were 14, 14, and 21 servings per week, respectively). Approximately half (51%) of the study population reported consuming fresh fish, 74% consumed it dried, and 30 different fish types were reported. The most often consumed and/or purchased types of fish were herring (48.3%), tilapia (43.3%), and salmon (41.7%). There are notable challenges with our approach here given that the identification of fish species is generally challenged in this community, that fish is typically mixed into various soups (i.e., hard to estimate portion sizes or particular fish species), and that meals are often shared. While we did not measure mercury levels in any particular fish in the current study, past research of fish mercury levels across Ghana has shown them to be relatively low (Rajaee et al., 2015a). When fish consumption data (i.e., servings per week) were related to hair mercury measurements, there was no association found (Supplementary Material 5).

3.4. Neuropsychological findings

Self-reported neurological symptoms are summarized (Supplementary Material 6). In terms of general health questions, nearly 30% of the study population indicated having some challenges concerning, for example, reduced appetite, hair loss, or excess salivation. Some of the survey questions focused on well-being, and 15–34% of the study population noted weekly issues concerning nervousness, sadness, heart palpitations, nausea, or numbness. There were seven questions focused on physical health, and 60% of the miners reported that aspects have worsened since they began mining. There were five questions focused on mental health, and 32% of the miners reported that aspects have worsened since they began mining.

These subjective (self-reported) measures of neurological symptoms can be compared to past studies of ASGM workers in Indonesia, Mongolia, Philippines, Tanzania, and Zimbabwe (summarized in Bose-O'Reilly et al., 2017) given that the same survey instrument was used in all these studies. In general, there was good agreement in responses between our study and these other ones, though we note that more individuals in the current study indicated issues with sleep disturbances (~60% here versus 12–40%), and around 50% of the current study population expressed concerns over well-being (e.g., feel nervous, feel sad, palpitations, nausea, numbness) versus ~10–40%. We also recognize that similar questions were asked of ASGM workers in Prestea (Ghana), with inconclusive findings with the exception of numbness (Mensah et al., 2016).

Of the 23 self-reported neurological measures, four of them (appetite, restful sleep, nausea, numbness) were significantly different between the miners at registered and unregistered sites. In these instances, miners from registered sites indicated better health than those from unregistered sites in terms of nausea and numbness, while the opposite was found for appetite and restful sleep. A review of the self-reported neurological measures shows little difference between the two groups of miners. When these self-reported neurological measures were compared against mercury biomarker levels, there were no clear associations (Supplementary Material 6). The self-reported data were also summarized into physical and mental scores as per details in the UNIDO/UNDP/GEF-sponsored initiative (Bose-O'Reilly et al., 2017). While there were no striking differences between miners from registered and unregistered sites, there were differences in mental scores within a few work categories (Supplementary Material 7).

Beyond the self-reported tests, more objective tests of neuropsychological symptoms were used as done previously by Bose-O'Reilly et al, 2017. in studies of ASGM sites across several countries (Bose-O'Reilly et al., 2017). Gait was observed by a physician (Supplementary Material 8). Ataxia of gait was absent in most (92.4%) of the participants, and for those with slight, moderate, or marked ataxia of gait, there were no differences between miners from registered and unregistered sites, across work groups, as well as in reference to mercury biomarker measures. Similarly, rigidity of gait was absent in most (87.6%) of the participants, and for those with some diminution of swing, there were no differences between miners from registered and unregistered sites, across work groups, as well as in reference to mercury biomarker measures. These observations are different from those made in the various studies by Bose-O'Reilly et al., 2017 in which, for example, ataxia of gait was found in 11.5% of study participants classified as 'non-exposed' and up to 35.9% in those considered 'high exposed' (Bose-O'Reilly et al., 2017).

For the pencil tapping, Frostig, matchbox, and Wechsler tests, the numerical scores recorded in the current study (Supplementary Material 9) were similar to values reported in the larger compilation by Bose-O'Reilly et al. involving 1242 individuals from ASGM sites in 5 countries (Bose-O'Reilly et al., 2017) (Supplementary Material 10). In general, for these tests, miners from unregistered sites performed better than those from registered ones. This difference was of statistical significance when the scores were analyzed as continuous variables, though not when they were categorized. In reviewing the data of these four tests with respect to the seven job categories, 10/28 comparisons were of statistical significance when the data were analyzed as continuous variables and 9/28 were significant when the data were categorized. Focusing on examples in which a particular work group fared worse, we note that those indicating yes to carrying loads did worse in all four tests, while those focusing on sifting tended to fare better.

The pencil tapping, Frostig, matchbox, and Wechsler test scores were also compared against the mercury biomarkers. In general, there were no statistically significant differences of note (Supplementary Materials 11 and 12). The data were further investigated according to registration status and work activities. In doing so, a significant (albeit weak) correlation was found between urinary mercury levels and matchbox scores among those who amalgamate ($r = 0.25$) and burn ($r = 0.24$).

4. Concluding remarks

We believe this is the first study to compare mercury exposures and neuropsychological test results between miners from registered and unregistered ASGM sites. In doing so, the research findings provide the necessary evidence for stakeholders and parties of the Minamata Convention considering various response options to help fulfill their obligations. Here we discuss some of the most noteworthy aspects of this study.

First, there are significant differences in mercury biomarker levels between miners from registered and those from unregistered sites, and this is an important observation. The difference in urinary biomarker levels between the groups was about 3-fold, and this held consistent across the exposure range. There were few variables we measured between the groups to help explain this finding, though the proportion of miners at unregistered sites involved in amalgamation and burning was significantly higher than those at the registered sites. It is not entirely

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