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Commentary

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Addressing neurological health outcomes from low exposure to volatile organic compound mixtures in workplaces: progress and future directions

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Abstract

Numerous workplaces handle solvent-based products, exposing workers to complex and changing mixtures of volatile organic compounds (VOCs), many of which are neurotoxic. In this commentary, we highlight key findings from research on VOC exposures in the workplace and their consequences for the central nervous system (CNS). We also provide a case study of nail salons as exposure sites. A few nail salon studies have suggested adverse health effects at low-level complex mixture VOC exposures, including significant neurological symptoms such as headaches, dizziness, difficulty concentrating, and memory loss, even when VOC exposures are below occupational exposure limits. Limited evidence specific to the health effects on nail salon workers relies on self-reported health outcomes or broad tests of mental abilities, using self-reported exposure surrogates that can lead to exposure misclassification. Unfortunately, assessing risk one chemical at a time with its respective threshold limit—or even using the traditional industrial hygiene mixtures approach—has not been sufficient to identify key VOCs or groups of VOCs most strongly linked to CNS health outcomes in nail salon workers. Scientific methodology used to understand low-level VOC mixture health effects in this population must evolve to measure chemical mixtures more easily and accurately, employ sensitive and culturally appropriate methods to assess neurological health effects, use advanced statistical methods, and develop strategies to prevent these debilitating health outcomes. Research evaluating possible health consequences at low exposure levels is still critical for guaranteeing the health of workers exposed to VOC, even with ongoing safer alternative substitution efforts.

Keywords VOC, nervous system health, nail technicians, solvents

Introduction

The use of organic solvents in the workplace has been strongly linked to neurological health outcomes (Woodall and Smith 2008; Bolden et al. 2015). Many volatile organic compounds (VOCs), which are used as solvents, are known neurotoxicants that can affect the central nervous system (CNS). Occupational studies have associated exposure to certain VOCs, even at low levels (ie well below occupational exposure limits), with

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neurological symptoms, including headaches, dizziness, and fatigue (Grandjean and Landrigan 2014). For example, research in different workplaces has reported loss of hearing, color vision, and CNS symptoms in workers exposed to toluene levels as low as six parts per million, or ppm (Triebig et al. 1988; Vrca et al. 1996). Chronic exposure (CE) to ethyl acetate, an ingredient in numerous workplace solvent products, has been linked to corneal clouding, skin, nose, and throat irritation, and nervous system depression at ppm level exposures (Tsai et al. 1997; Lewis 2004).

A review of epidemiological studies investigating the neurobehavioral effects of occupational exposure to solvent mixtures (Meyer-Baron et al. 2008) concluded that VOC mixtures affect cognitive and motor functions (ie attention, memory, motor performance, and constructional abilities) and demonstrated clear exposure–effect relationships. Several occupational studies observed poorer performance on neuropsychological tests among low-to-moderate solvent-exposed worker populations (Meyer-Baron et al. 2008). Only seventeen articles out of 53 within the meta-analysis provided detailed information on the VOC mixture constituents. Some studies were able to discern which VOC had the greatest impact on neurobehavioral outcomes; in the case of carpet layers, it was toluene and n-hexane (Muijser et al. 1996).

Epidemiological studies have used various data analysis approaches when handling exposure to VOC mixtures. For example, some research used a composite or surrogate exposure measure. In 2018, Fiedler et al. (2018) observed relationships between total VOC (TVOC) in the air and neurobehavioral outcomes. Empirical studies on neurobehavioral health from VOC mixtures have calculated an exposure index, or EI, which divides air concentrations by threshold limit values to create a single exposure variable for data analysis (ACGIH 2025). However, there are numerous instances where threshold limit values were not based on CNS endpoints. Some epidemiological investigations computed an EI using a few area samples instead of personal samples (Escalona et al. 1995), which is not an optimal measure of worker exposure (U.S. NRC 1997). Some researchers used exposure surrogates like years of exposure, personal protective equipment usage, and job tasks to retroactively estimate job exposure matrices (Fiedler et al. 2018). Other researchers estimated CE by multiplying EI by years of exposure (Saddik et al. 2009).

In this commentary, we selected the case study of nail salons to walk the reader through the typical worker VOC exposures and the suggestive, but very limited, research available on CNS health. Through this commentary, we aim to renew interest in the research community regarding the health effects of low-level VOC exposures in workplaces by sharing insights gained from research in the nail salon industry.

Case study: VOCs in nail salons and neurocognitive health

About 212,700 nail salon workers were estimated to be actively employed in the US in 2023 (U.S. BLS 2025). Manicures, pedicures, polish application, and nail enhancements cost the U.S. $19.1 billion in 2021 (Ward et al. 2022; Statista 2025). Nail salons use products that release VOCs, including toluene, acetone, isopropyl alcohol, and ethyl and butyl acetates (U.S. FDA 2025), some of which are listed in safety data sheets (SDS). Lab emission tests show that declared VOC constituents are a small subset of the VOC ingredients emitted (Huzar and Wodnicka 2011; Heaton et al. 2019). Despite strong scents, most nail salon workers' breathing zones contain VOCs below occupational air exposure standards (Quach et al. 2011; Ceballos et al. 2019).

Nail salons have structural constraints that impact health and safety measures. Typically, nail salons are small businesses that often have limited space and ventilation (Thompson et al. 2025). Salon workers do not always wear personal protective equipment that is effective against chemical exposures and also work long hours, often 7 days a week, increasing their potential for exposure (Nails 2018, 2019, 2020; Pavilonis et al. 2018; Zhong et al. 2019). For example, when technicians wear gloves to reduce skin exposures, they may prioritize biological hazards typically found on their job and wear latex gloves over wearing chemically protective gloves, such as nitrile gloves (Ceballos et al. 2019). Furthermore, when using respiratory protection, their client-oriented environments create barriers for them to use respirators that are known to be protective against VOC exposures (eg, half-face respirators with VOC cartridges), and they often choose surgical masks or N95s, which protect them against dust but not necessarily against VOCs (Wang et al. 2023; NIOSH 2026). Although some masks are made with a charcoal cloth marketed to protect wearers against VOCs, these masks are not certified by NIOSH (NIOSH 2026) and are only recommended to protect for very short periods of time against nuisance—not toxic—odors (OSHA 2026), nor are they commonly observed in use in nail salons. Thus, not surprisingly, a few studies have documented self-reported health concerns in this worker population, particularly CNS symptoms, including headaches, fatigue, difficulty concentrating, memory problems, mood disturbances, dizziness, and peripheral neuropathy (ie numbness or tingling) (Roelofs et al. 2008; Ward et al. 2022; Choi et al. 2023).

Exposure to complex VOC mixtures in nail salons

Substantial research has documented the presence of complex VOC mixtures in the indoor air of nail salons (Lamplugh et al. 2019; Quiros-Alcala et al. 2019). Toluene, formaldehyde, ethyl methacrylate, and ethyl acetate are common VOC, known to be ingredients in nail products (Ceballos et al. 2019; Heaton et al. 2019). However, some VOCs are not listed as ingredients on nail product SDS, despite significant quantities of these chemicals being found in nail products (Kope Lovich et al. 2015; Young et al. 2018). A recent study revealed a large group of fragrance VOCs in the indoor air of nail salons (Jia et al. 2024), with benzaldehyde, 2-ethylhexanol, d-limonene, and 2-butoxyethanol found at higher median concentrations compared to other fragrance VOCs, likely from cleaning, personal care, and nail care products, added to enhance their scent while masking any unpleasant odors.

Inhalation of VOCs may occur during nail preparation, sculpting, painting, or polish removal (Heaton et al. 2019). Nail workers' breathing zones often contain numerous VOCs, but their concentrations are substantially below occupational exposure limits (Ceballos et al. 2019; Zhong et al. 2019). Direct contact, glove permeability, or air absorption via the skin can cause dermal absorption of nail product chemicals, while ingestion could occur via contaminated hands, eating, or smoking (National Academies of Science 2009), although this has not been verified in a study.

Besides external measures of VOC exposure, there have been, to our knowledge, only two studies using internal measures of exposure in nail salon workers by collecting biomarkers of exposure such as blood (Ceballos et al. 2019) and urine (Moradi et al. 2019). Ceballos et al. (2019) collected blood samples before and after work shifts to correlate inhalation exposures from 10 Greater Boston nail technicians. Blood biomarkers indicated elevated levels of nail care product VOCs, such as BTEX (benzene, toluene, ethylbenzene, and xylenes) and ethyl acetate, when compared to typical U.S. population levels at the time of the study as documented by the National Health and Nutrition Examination Survey (NHANES) (CDC 2018). Comparing workers' pre- and post-shift measurements also indicated increased VOC absorption during the workday. Blood biomarkers are used in VOC research, as they often reflect exposure across all exposure routes. Parent or intact VOCs in blood are the closest measure of "burden," or tissue and organ concentrations, as unmetabolized VOCs in the blood reach all organs, including the brain, which may cause neurotoxicity (Chambers et al. 2021). Urine samples are also used as exposure biomarkers because intact and metabolized VOCs travel to the urinary system from the blood. Moradi et al. (2019) collected urine samples from 36 Iranian beauty technicians in work environments with comparable inhalation exposure levels while measuring higher detection rates for unmetabolized VOCs in urine than that of the blood measured by the Ceballos et al. (2019) study. At collection, parent VOCs can be quantified directly in urine using internal standards (Chambers et al. 2021), but urine levels are frequently more variable than blood levels. Although methodologies and laboratories may have caused variances in the Ceballos and Moradi studies, more polar VOCs like ketones and esters are typically greater in urine than blood, assuming complete equilibration (Chambers et al. 2021). In VOCs with rapidly cleared or nonspecific metabolites, blood measures may better indicate mid-shift or end-of-shift exposure to the parent compounds than urine metabolites (ACGIH 2025). Regardless, interpretation of both blood and urine biomarkers must consider the short half-life for most VOCs of less than 1 h (Brugnone et al. 1983; Nise et al. 1989; Chambers et al. 2021); thus, biomarker results are better at measuring recent exposures. While urine is less invasive, blood is the gold standard workplace exposure biomarker for certain VOCs, such as toluene (ACGIH 2025). However, urine would be more feasibly collected for long-term repeated exposure measures.

Neurological function and VOC exposures in nail salons

Many nail technicians are also salon owners, requiring multiple skills to be successful in their profession. Therefore, neurobehavioral health is vital for career success beyond skilled manual labor. Furthermore, nail salons are often family businesses, so health effects are experienced within family groups. Nail salons are primarily owned and staffed by females (94%), Vietnamese (51%), and workers under 40 (Nails 2020), who are not always English proficient (UCLA 2026). A predominant female profession may put these workers at a higher risk of developing neurological health outcomes more typically associated with females, such as depression or multiple sclerosis (Hanamsagar et al. 2016). Cultural and language barriers, together with a lack of health and safety expertise and the hectic day-to-day typical of a small business, may also impede their ability to navigate health and safety recommendations and resources (Lentz et al. 2001).

Limited research from nail salons has reported CNS dysfunction symptoms associated with VOC exposures.

In Michigan, 150 English-speaking nail technicians exposed to solvents and acrylates experienced neurological symptoms and learning and memory issues (LoSasso et al. 2001, 2002). Workplace size, ventilation, and hours worked exhibited a dose-response relationship with the intensity of symptoms (LoSasso et al. 2001). An olfaction test score, an early predictor of neurological impairment, was poorer in a follow-up examination of 33 English-speaking nail technicians (LoSasso et al. 2002). In California, Nguyen et al. (2022) administered cognitive functioning and depression standardized instruments that had been adapted into Vietnamese language to 155 nail technicians and found that self-reported nail salon exposure was linked to worse cognitive function.

Discussion

Despite progress in understanding the health effects of VOCs compared to decades ago, there is still much to be learned about the health effects of low-level mixtures of solvents. Advancement in epidemiological studies to determine CNS health effects of low-level VOC mixtures requires advancement of both exposure and neurological assessments relevant to immigrant populations, which are often the most highly exposed at workplaces. Pre/post-shift studies can be used to examine acute effects of VOC exposure, while longer-term longitudinal studies are necessary for examining effects due to CE. Future studies with adequately powered sample sizes could better explore the interactions between VOCs, taking into consideration a wide range of exposure levels and years in the profession, as well as the use of new statistical models for handling complex mixtures in epidemiological studies, which have not been used with VOCs (Keil et al. 2021; McGee et al. 2023).

From our case study of nail salons, the exposure assessment research gaps identified for understanding the impact of low-level solvents will require additional studies to determine the best exposure metrics for larger epidemiologic studies, including different biomarkers over several days to consider carryover effects (ie exposures during the workday that may be related in part to the exposure from the days before). However, there are trade-offs to using environmental samples or versus exposure biomarkers, the latter are not best when there is reverse causation or confounding by physiology (Weisskopf and Webster 2017). Additional opportunities exist in the use of real-time and multi-sensor instrumentation in the nail salon environment or by the workers themselves, as low-cost, real-time multi-port sensors have been developed for health safety and medical detection (Wang et al. 2025). Choice of exposure metric will depend in part on the biology of the outcome, for example, acute vs. chronic effects, or whether a given effect is due to cumulative exposure, peak exposure, etc. VOC concentrations in blood and urine have short half-lives, suggesting use of multiple samples if one is interested in effects that are not very acute. However, in the nail salon setting, it is likely that the external occupational exposures are very consistent over time, in which case even an exposure measure with a short-half life may reflect longer-term exposures reasonably well, especially if combined with work history data. Studies that assess interclass correlation coefficients to assess these aspects of within- vs. between-person exposure variability would be useful in this regard.

In terms of advancing VOC mixture health research, occupational neurocognitive health studies could consider exposures to chemicals beyond VOCs. Numerous other chemical groups in the nail salon environment could be neurotoxicants, including semi-volatile compounds (SVOC) found in these indoor settings, such as polychlorinated biphenyls (PCBs), flame retardants, plasticizers, and pesticides (Weschler and Nazaroff 2008). Opportunities also exist to assess the effects of regional or federal policy changes on workers' neurological health, particularly those changes that impact VOC exposures by introducing safer alternatives. These recommendations could apply to other workplaces exposed to VOCs.

Assessment of possible CNS effects from exposure to VOCs in the nail salon setting has been sparse and often was accomplished using self-reported symptoms, sometimes in conjunction with self-reported surrogates (LoSasso et al. 2001, 2002), which may also lead to exposure misclassification in evaluating exposure-outcome relationships. Because nail salon workers are often Vietnamese immigrants, the use of validated neurocognitive assessment instruments is challenging because few tests are available in Vietnamese. Although some studies have relied on American tests given in English (LoSasso et al. 2001, 2002), the cultural validity of these assessment instruments is not well known, and the tests themselves may or may not be acceptable to study participants (White 2004; White et al. 2009). Nguyen et al. (2022) used a translated version of the Montreal Cognitive Assessment instrument, a screening test of general mental status that had been translated into Vietnamese. This is more culturally appropriate, but the test has relatively few items, limiting its sensitivity and specificity to detect a range of subtle exposure effects.

Because solvents and VOCs typically affect the functions mediated by the frontal-limbic systems of the brain, future studies should assess frontal (ie attention, inhibitory control, working memory) and limbic functions (ie mood states, short-term memory) (Baker and White 1985; White et al. 1994, 1995; White and Proctor 1997; White and Brand 2019). However, these tests are often verbal and do not appear to be available in Vietnamese. A possible solution to this problem is the adaptation of tests that employ nonverbal stimuli with translated instructions. This approach has been effectively used in international settings with non-English speakers and with participants who do not find tests using words and letters to be appealing (White et al. 1996, 2003; Grandjean et al. 1997). In the ideal situation, normative data appropriate to the population under study would be available for the tests. However, when applying tests in the absence of appropriate norms, investigators can use raw data, adjusted for age, gender, education, and other characteristics. Ideally, standardized, validated, sensitive tests of specific types of cognitive functioning should be developed that apply to specific populations for which such tests are not now available (eg, Vietnamese immigrants).

Conclusion

The study of the health effects of VOC exposures has lost some momentum in the last few decades. However, if we look back at the pioneering VOC studies from the past, simplistic exposure metrics were used to assess associations with CNS effects. Today's exposure assessment and epidemiological methods provide better tools for studying this question. Future studies are needed to address research gaps by conducting larger epidemiological studies with robust exposure and statistical assessments, aiming to identify critical VOCs or VOC groups that significantly impact CNS health outcomes in workers, even at low exposure levels, and using more comprehensive and culturally and language appropriate neurological assessments. Ultimately, developing CNS-system-specific occupational exposure limits for more VOCs and updated industrial hygiene mixture methods would help advance best practices in workplaces for preventing these adverse health outcomes. As more prevention efforts, including nail salon programs and safer cosmetic policy efforts, are being adopted around the U.S., exposure to key concerning VOCs, such as formaldehyde or toluene, may decrease. Still, it is essential to continue studying this worker population to ensure that substitutions do not merely replace one chemical with another with mixture effects that may also lead to adverse health outcomes.

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Author contributions

DMC: Conceptualized and wrote the original draft. CJ/TFW: Methodology. RFW: Conceptualization and methodology. All authors significantly reviewed, edited, and contributed to the final draft.

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Conflicts of interest

The authors report that no competing financial interests are to be declared.

Data availability

No data were used in this study.

Disclaimers

The contents of this manuscript are solely the responsibility of the authors and do not necessarily represent the official views of CDC or the NIH.

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