Neurological symptoms associated with oil spill response exposures: Results from the Deepwater Horizon Oil Spill Coast Guard Cohort Study

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Abstract

Introduction: The Deepwater Horizon (DWH) oil spill was the largest marine oil spill in U.S. history, involving the response of tens of thousands clean-up workers. Over 8500 United States Coast Guard personnel were deployed in response to the spill. Little is understood about the acute neurological effects of oil spill clean-up-related exposures. Given the large number of people involved in large oil spill clean-ups, study of these effects is warranted.

Methods: We utilized exposure, health, and lifestyle data from a post-deployment survey administered to Coast Guard responders to the DWH oil spill. Crude oil exposure was assessed via self-reported inhalation and skin contact metrics, categorized by frequency of self-reported exposure to crude oil during deployment (never, rarely, sometimes, most/all of the time). Combined exposure to crude oil and oil dispersant was also evaluated. Adjusted log binomial...
regressions were used to calculate prevalence ratios (PRs) and 95% confidence intervals (CI), investigating the associations between oil spill exposures and neurological symptoms during deployment. Stratified analyses investigated potential effect modification by sex, exhaust fume exposure, personal protective equipment (PPE) use, and deployment duration and timing.

**Results:** Increasing frequency of crude oil exposure via inhalation was associated with increased likelihood of headaches (PR\textsubscript{most/all vs. never} = 1.80), lightheadedness (PR\textsubscript{most/all vs. never} = 3.36), difficulty concentrating (PR\textsubscript{most/all vs. never} = 1.72), numbness/tingling sensation (PR\textsubscript{most/all vs. never} = 3.32), blurred vision (PR\textsubscript{most/all vs. never} = 2.87), and memory loss/confusion (PR\textsubscript{most/all vs. never} = 2.03), with significant tests for trend. Similar results were found for crude oil exposure via skin contact. Exposure to both oil and oil dispersants yielded associations that were appreciably greater in magnitude than for oil alone for all neurological symptoms. Sensitivity analyses excluding responders in the highest environmental heat categories and responders with relevant pre-existing conditions indicated robustness of these results. Stratified analyses indicated possible effect modification by sex, PPE use, and heat exposure.

**Conclusions:** This study provides evidence of a cross sectional association between crude oil exposures and acute neurological symptoms in a sample of U.S. Coast Guard responders. Additionally, it suggests that exposure to both crude oil and oil dispersant may result in stronger associations and that heat may interact synergistically with oil exposures resulting in more acute neurological symptoms. Future investigations are needed to confirm these findings.

**Keywords**

Oil spill; Deepwater Horizon; Coast Guard; Crude oil; Neurological symptoms; Exposure

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**1. Introduction**

The Deepwater Horizon (DWH) oil spill was an unprecedented disaster, contaminating the Gulf of Mexico with an estimated 200 million gallons of crude oil (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011; National Institute for Occupational Safety and Health (NIOSH), 2010). The spill released crude oil into the Gulf of Mexico for 87 days until effective well-capping occurred on July 15th, 2010. The multifaceted response of the Unites States Coast Guard (USCG) to this spill included almost 9000 service members, providing support in missions including booming and skimming operations, in-situ burning operations, overseeing beach clean-up, decontamination of equipment, administrative work, and a variety of other tasks. Responders were potentially exposed to varying levels of crude oil mainly via inhalation of volatiles or dermal contact with the crude oil or oily water. (National Institute for Occupational Safety and Health (NIOSH), 2010)

Prior studies have shown that exposure to various components of crude oil, such as toluene (Benignus et al., 2007), benzene (Bahadar et al., 2014), and xylene (Niaz et al., 2015) can be associated with a variety of neurological symptoms including headache, light-headedness/dizziness, difficulty concentrating, numbness/tingling sensations, blurred/double vision, memory loss/confusion, loss of consciousness/fainting (Burbacher, 1993). Only a few studies have investigated the association between neurological symptoms in populations...
exposed to oil spills, such as clean-up workers and residents living near oil spills. These symptoms/conditions included headaches (Carrasco et al., 2006; Ha et al., 2008; Kim et al., 2009; Lyons et al., 1999; Morita et al., 1999; Na et al., 2012; Cheong et al., 2011), dizziness (Carrasco et al., 2006; Peres et al., 2016), and memory loss (Ha et al., 2008).

The association between exposure to oil dispersants, specifically the COREXIT product line used in the DWH response, and health outcomes in humans has received relatively little study. The chemical components of these dispersants, such as dioctyl sodium sulfosuccinate, sodium ricinoleate, or sodium lauryl sulfate induce cytotoxicity and central nervous system perturbations in rats (Sriram et al., 2011). A recent study from the GuLF STUDY population evaluated the association between dispersant exposure and respiratory, dermal, and eye irritation symptoms, but did not include assessment of neurological symptoms. (McGowan et al., 2017) Health effects of dispersants in the DWH response may be further complicated by co-exposure with crude oil.

Given the paucity of research on acute neurological symptoms associated with oil spill clean-up exposures, we carried out a cross sectional evaluation of the association between crude oil and oil dispersants.

2. Methods

2.1. Study population

The DWH Oil Spill Coast Guard Cohort Study population has been described previously (Rusiecki et al., 2017). Briefly, it is comprised of USCG responders (N = 8696) and non-responders (N = 44,823) who were either on active duty or in the Select Reserve during the DWH response, between April 20th and December 17th 2010, for a minimum of one day. These responders were identified from USCG administrative databases. The subset of responders evaluated in the present cross-sectional study (N = 4855) was comprised of both active duty and Select Reserve members who completed a survey administered to responders, typically at the Incident Command Posts, upon completion of their oil spill response deployment. This “exit” survey included questions about their contact with crude oil and oil dispersant. This study was approved by the Institutional Review Boards of the Uniformed Services University, The United States Coast Guard, and The University of North Carolina, Chapel Hill.

2.2. Survey

The exit survey utilized for this analysis was launched on 01 November 2010. The survey queried responders about the timing and duration of their response deployment, their exposures to crude oil/oily water, oil dispersants, combustion engine exhaust, specific symptoms they experienced while deployed, personal protective equipment (PPE) use, and lifestyle factors during the response. The survey was brief, designed to be completed within 15 to 20 min in order to increase participation. Some responders reported deploying multiple
times, however, since this was a small number (N = 292; 5% of survey takers), we have limited the current analysis to data from these individuals’ first deployment only.

2.3. Exposure assessment

In this study, we focused on exposure to crude oil and oil dispersants assessed via self-report from the exit survey. Frequency of exposure to crude oil/oily water was assessed via a 5 point Likert scale (never, rarely, sometimes, most of the time, all of the time) for each of four specific routes of exposure: inhalation, direct skin contact, ingestion, and submersion (e.g., “How often were you exposed to crude oil/oily water via inhalation/direct skin contact/ingestion/submersion?”). The present analyses on exposure to crude oil/oily water focuses on inhalation and skin contact exposure, though the other routes of exposure were considered in constructing an ever/never metric of exposure to crude oil. Frequency of contact with oil dispersants was also evaluated on a 5 point Likert scale based on the question: “How often did you handle, apply, or come in contact with oil dispersants?” Another question was asked about exposure to exhaust fumes (“How often did you inhale exhaust fumes from a car, boat, trailer, or other source of exhaust?”) and was used in our analyses as an adjusting variable in models as well as a potential effect modifier (ever/never).

2.4. Neurological symptoms

Responders reported how often during their deployment they experienced each of the following neurological symptoms: headaches, lightheadedness/dizziness, difficulty concentrating, numbness/tingling sensation, blurred/double vision, and memory loss/confusion. Responses were provided on a 3 level scale: most of the time, sometimes, and never. For the analyses here, we created binary variables for each symptom, representing that they ever experienced it (e.g., reported either most of the time or sometimes) or never experienced it.

2.5. Statistical analyses

For the cross-sectional analyses carried out here, we calculated prevalence ratios (PRs) and 95% confidence intervals (CIs) for crude oil exposure based on four level categorical metrics, comparing rarely, sometimes, and most of the time/all of the time exposed to never exposed for inhalation and for skin contact routes, using multivariate log binomial regressions. We selected this statistical method because odds ratios from logistic regressions tend to overestimate the PR for non-rare outcomes, and log binomial models have shown to better estimate the PR (Barros and Hirakata, 2003). We adjusted models for age group (< 25, 25–34, 35–50, 50+ years), sex, dispersant contact (ever/never), exhaust fume exposure (ever/never), smoking during deployment (ever/never), environmental heat exposure (a four level variable we derived based on publically available hourly heat index (HI) temperatures relevant to each responder’s deployment period, combined with their self-reported amount of time spent outdoors (low time outdoors and median HI < 95 °F; low time outdoors and median HI ≥95 °F; high time outdoors and median HI < 95 °F; high time outdoors and median HI ≥95 °F, as previously described) (Erickson et al., 2018) and hours of sleep per night during deployment (< 4, 4– < 6, 6– < 8, 8+ h)). We also carried out tests for trend to evaluate exposure-response relationships, including the categorical exposure variable as a
continuous variable in each model. Significant exposure-response was considered if this test for trend had a p-value of ≤0.05. To confirm results based on self-reported exposure, we also carried out an analysis using the more objective duration of deployment as the exposure (<30 days, 30–60 days, >60 days), stratifying the study population into those who started their deployment pre-well capping (pre-July 15th) and those who started post-capping.

Since very few Coast Guard responders reported exposure to oil dispersants in the absence of exposure to crude oil, we did not focus on oil dispersant as an exposure in isolation. Rather, we evaluated the combined effects of exposure to both crude oil and oil dispersant compared with exposure to neither for each symptom. We also compared those exposed to oil but not dispersant versus those with exposure to neither. Models for these analyses were adjusted by the same confounders as listed above, with the exception of dispersant exposure.

2.6. Stratified analyses

We carried out stratified analyses to investigate the potential for effect modification in the association between crude oil exposure (ever/never) and the acute neurological symptoms by sex (male/female), exhaust fume exposure (ever/never), use of oil exposure personal protective equipment (PPE) (yes/no), pre- or post-capping date of deployment start (before or after well capping on July 15th 2010), and heat exposure. PPE use was ascertained based on the question, “Did you typically wear any personal protective equipment (PPE) for your work in the vicinity of the spilled crude oil or oily water?” We assessed the statistical significance of this effect modification by including a multiplicative interaction term in the models, with p < 0.05 as the criterion for significance.

2.7. Sensitivity analyses

Although models investigating the associations between inhalation and skin contact exposures to crude oil and neurological conditions were adjusted by environmental heat exposure and stratified analyses carried out to evaluate the potential modifying effect of heat exposure, to further account for the potential influence of heat on our findings, we carried out a sensitivity analysis among all responders, excluding responders in the highest category of heat exposure, assessed via the metric of median heat index described above.

To account for the potential influence of pre-existing conditions on the symptoms evaluated, we carried out additional sensitivity analyses in which we re-ran the same models for oil inhalation and oil skin contact exposures among active duty members only and then excluded those with relevant pre-existing conditions. Among the active duty responders in our study we have data on prior relevant diagnoses (e.g., pre-DWH), as captured in the Military Health System Data Repository (MDR), a previously described comprehensive database of all active duty health encounters. (Rusiecki et al., 2017) We did these analyses among active duty members only because we have complete health encounter data on active duty members in our study from the MDR, dating back to October 2007. This is not the case for Select Reserve members, as they do not typically have full coverage healthcare via the Coast Guard. In the MDR, health encounters are coded using the International Classification of Diseases, 9th edition (ICD-9), and our query of pre-existing conditions/prior diagnoses was carried out on data from October 1, 2007 until the date of a responder’s
start of DWH response in 2010. We identified diagnoses of conditions related to headaches (ICD-9 codes 339, 346, 784), lightheadedness/dizziness (386, 780.2, 780.4, 781.3), difficulty concentrating (780.97), numbness/tingling sensation (350–359), blurred/double vision (360–379), and memory loss/confusion (780.93). Supplementary Table 1 lists these codes and their definitions. A diagnosis of each condition was defined as having either one inpatient or two outpatient health encounters with the relevant code for that condition. To address concerns about possible diabetic neuropathy, we also carried out a sensitivity analysis among active duty members, excluding responders with a prior diagnosis of diabetes, since it can cause neuropathy, particularly peripheral neuropathy (of greatest concern for numbness/tingling and blurred/double vision).

Finally, to account for the potential for misclassification of dispersant exposure, we carried out a sensitivity analysis of the combined effects of crude oil and dispersant, excluding those responders reporting missions which had a low probability of exposure to dispersants - air operations and administrative missions - as well as those reporting being involved in equipment/vessel decontamination missions.

All analyses were carried out using SAS Version 9.3.

3. Results

The analyses included 4855 responders who had completed the exit survey. Given the total number of USCG responders in the DWH Coast Guard Cohort Study (N = 8696), this is a response rate of 56%. Table 1 provides descriptive statistics on the demographic characteristics, and oil spill-related exposures reported among the study population. The median age of responders was 32, with 44% (n = 2128) of responders being 25–34 years of age and 36% (n = 1738) being 35–50 years of age. The majority of the responders were male (n = 4127, 85%), white (n = 3741, 77%), active duty (n = 3102, 64%), and enlisted (n = 3530, 73%). More than half of the responders reported ever being exposed to oil (n = 2651, 55%), of whom 2478 (51%) reported exposure via inhalation and 1696 (35%) by direct contact with skin. There were 252 (5%) responders who reported being exposed to both crude oil and oil dispersant and 2136 (44%) who reporting being exposed to neither. A high proportion of responders (75%) also reported being exposed to exhaust fumes.

Prevalence ratios for associations between crude oil exposure and neurological symptoms are presented in Table 2. Symptoms are listed from most frequently reported to least. There was evidence of a statistically significant, increasing trend of symptoms with increasing levels of inhalation exposure for headaches (PR_{most/all vs. never} = 1.80; p-trend ≤ 0.01), lightheadedness/dizziness (PR_{most/all vs. never} = 3.36; p-trend ≤ 0.01), difficulty concentrating (PR_{most/all vs. never} = 1.72; p-trend = 0.04), numbness/tingling sensation (PR_{most/all vs. never} = 3.32; p-trend ≤ 0.01), and blurred vision (PR_{most/all vs. never} = 2.87; p-trend ≤ 0.01). Memory loss/confusion showed a significant test of trend, but no apparent monotonic trend (PR_{most/all vs. never} = 2.03; p-trend = 0.05). Although there were small counts of responders in the highest exposure group (e.g., most or all of the time exposed) for some of these symptoms, most of the PRs were statistically significant and increasing with increasing exposure categories. Prevalence ratios were elevated, but showed less clear
exposure-response trends, in relation to skin contact with crude oil. The exception was lightheadedness/dizziness, for which there was a clear monotonic increase and exposure-response trend (PR\textsubscript{most/all vs. never} = 3.21, p-trend < 0.01). Results based on duration of deployment also showed that with increasing duration, there were moderately elevated PRs for most neurological symptoms, though tests for interaction did not indicate a significant difference between those whose deployment started pre-capping and those whose deployment started post-capping (Supplementary Fig. 1.)

To further investigate the relationship between oil exposure and neurological symptoms and given that a high proportion of people who reported skin exposure also reported inhalation exposure (87%), we carried out additional analyses for inhalation exposure (4 levels), stratified by ever/never skin contact exposure (Supplementary Table 2). Most PRs for inhalation exposure were higher in the ever skin contact exposure group than in the never skin contact exposure group, though there were no significant tests for interaction. Of note, for the symptom, numbness/tingling the PRs in the “sometimes” and “most/all of the time” categories were markedly higher in the skin contact ever group, however there were only three individuals in the reference group, resulting in very imprecise estimates in this stratum.

In a sensitivity analysis, when we excluded responders in the highest heat category from these analyses, results did not differ appreciably (Supplementary Table 3). In another sensitivity analysis, we restricted to active duty members and further excluded those with pre-existing conditions relevant to each symptom. Results from analyses restricted to active duty members are presented in Table 3. Active duty members had similar PRs and trends across exposure categories for both metrics as the total population of active duty plus Select Reservists (i.e., those presented in Table 2). Excluding active duty responders with pre-existing conditions related to each symptom, we found similar patterns for most symptoms, though estimates were modestly attenuated for both the inhalation and skin contact metrics. Excluding responders with a prior diabetes diagnosis (N = 25) did not appreciably impact our results (data not shown).

Results for stratified analyses are presented in Table 4. In these analyses, ever/never exposed to crude oil was the exposure metric. Prevalence ratios appeared to be consistently higher for males than for females; PRs were significant in both strata and tests for interaction (p-interaction ≤0.05) significant for only headaches and lightheadedness/dizziness, though the number of females in some of these analyses was rather small. There were no significant differences by exhaust exposure, except for headaches, with a stronger PR among those without exhaust exposure (PR\textsubscript{exhaust} = 1.39, PR\textsubscript{no exhaust} = 1.86, p-int < 0.01). Prevalence ratios appeared to be consistently higher among those reporting PPE use compared to those reporting no PPE use, though they were significantly different for only blurred/double vision (PR\textsubscript{PPE} = 2.45, PR\textsubscript{noPPE} = 1.15, p-int = 0.02). Analyses stratified by heat exposure resulted in stronger PRs for each of the symptoms in the higher heat strata than in the lower heat strata. These analyses indicated the potential for effect modification by heat for associations between oil exposure and lightheadedness/dizziness, and blurred/double vision (p-interactions = 0.01, 0.02, respectively). For headaches approached significance (p-interaction = 0.09).
Adjusted comparisons of responders who reported both crude oil and oil dispersant to those who reported neither yielded PRs of higher magnitude than comparisons of responders who reported only crude oil exposure versus neither (Fig. 1, Supplementary Table 4). Oil plus dispersant appears to be substantially more strongly associated than oil alone with all neurological symptoms except headaches, for which the PR was only slightly larger than for the oil only group. A sensitivity analysis excluding responders who reported dispersant exposure, but were involved in missions/tasks with a low likelihood of dispersant exposure, indicated similar, but generally more pronounced effects. (Supplementary Table 4).

4. Discussion

This cross-sectional study identified acute neurological symptoms associated with self-reported exposure to crude oil exposure as well as combined crude oil and dispersant exposure experienced by oil spill responders. We found exposure-response relationships for all the neurological symptoms we evaluated – headaches, lightheadedness/dizziness, difficulty concentrating, numbness/tingling sensations, blurred/double vision, and memory loss/confusion – in relation to oil exposure via inhalation. Similar exposure-response relationships were observed for skin contact with crude oil, with the exception of difficulty concentrating, and patterns for several of the symptoms suggested a possible threshold effect. A series of sensitivity analyses carried out, excluding responders in the highest heat exposure category and excluding responders with pre-existing conditions, indicated the stability of these findings. Additionally, analyses based on duration showed increasing PRs with increasing duration of deployment. It appeared that self-reported exposure via both inhalation and skin contact resulted in higher PRs for numbness/tingling sensations and blurred/double vision, in particular. It should be pointed out that the six neurological symptoms studied here tended to be moderately to strongly correlated with each other, thus the elevated risks seen across these symptoms may reflect a possible common underlying neurological phenomenon.

There is a paucity of literature on acute neurological symptoms potentially associated with oil spill clean-up exposures. The neurological symptoms reported in previous studies in populations responding to or living near oil spills have been mainly headaches, (Carrasco et al., 2006; Cheong et al., 2011; Ha et al., 2008; Kim et al., 2009; Lee et al., 2010; Lyons et al., 1999; Na et al., 2012) with a few reporting dizziness (Carrasco et al., 2006; Lee et al., 2010; Peres et al., 2016) and one reporting memory loss. (Ha et al., 2008). Most of these studies relied on exposed/non-exposed comparisons, responder/non-responder comparisons, or job task during spill clean-up to investigate associations with exposure to crude oil, though one study finding an association with headaches did present results for duration of clean-up work and frequency of skin exposure. (Cheong et al., 2011)

We also report here that exposure to both crude oil and oil dispersant was more strongly associated with the battery of acute neurological symptoms we evaluated than was exposure to oil alone. The group of responders who reported being exposed to both crude oil and dispersant was small (n = 252), so this must be considered when interpreting these findings. However, a large proportion of them reported headache (65%) and nearly 40% reported lightheadedness/dizziness. The estimates of association became stronger for most
symptoms when we attempted to reduce exposure misclassification by excluding responders who reported dispersant exposure but had a low likelihood of such exposure, including those on missions with a low probability of dispersant exposure and those engaged in decontamination of vessels or equipment. To further explore our findings for combined oil/dispersant exposure, we investigated whether this exposure group acted as a proxy for people in the highest categories of oil exposure. To do this, we identified the level of the original 5 point Likert scale crude oil inhalation and skin contact metrics for the responders in the combined oil/dispersant group. We found that for the inhalation metric the distribution was: never (3%), rarely (13%), sometimes (33%), most of the time (27%), and all of the time (24%); for the skin contact metric, it was even less weighted toward the higher crude oil exposure levels: never (15%), rarely (23%), sometimes (39%), most of the time (15%), and all of the time (9%). These findings suggest that the combined oil/dispersant metric was not likely to be simply a proxy for high exposure to crude oil.

We are unaware of other human studies which have evaluated acute neurological symptoms in relation to combined oil and dispersant exposure, though a previous analysis from the Coast Guard cohort study indicated similar patterns for respiratory symptoms. (Alexander et al., 2018) A recent report from the GuLF STUDY cohort found increased respiratory symptoms among responders who were likely exposed to dispersant, but that analysis did not focus on combined oil and dispersant exposures nor examine neurological symptoms. (McGowan et al., 2017) In the experimental literature, however, exposure to chemical ingredients in oil dispersants caused neurotoxicity and subsequent neuronal damage in rat models, suggesting greater risks for potential neurological health effects (Sriram et al., 2011). Another study investigated the effects of a mixture of oil and dispersants on mammalian hippocampal cells and found this mixture to induce aberrant expressions of genes associated with neurological functions, again suggesting potential neurotoxicity. (Zheng et al., 2014).

A recent study which investigated the effects of wave energy and slick properties on the temporal evolution of emissions, measured aerosol size distribution, total particle-bound aromatic hydrocarbons (pPHA), and volatile organic compounds (VOCs) in three different experimental scenarios in a tank: seawater plus slicks of (1) Louisiana Light Sweet crude oil (a surrogate of the M252 oil released in the DWH oil spill), (2) crude oil-dispersant mixture, and (3) dispersant only. (Afshar-Mohajera et al., 2018) The dispersant used in these experiments was Corexit 9500A (Nalco Environmental Solutions, Inc.), the primary dispersant used in the DWH oil spill clean-up. The investigators reported that the total particulate concentration from the oil-dispersant mixture was 1–2 orders of magnitude higher than those of crude oil alone across the entire nano-scale range, though not in the micron range. They indicated that this drastic increase in ultrafine particle concentrations may raise concerns about effects of inhalation by cleanup workers and downstream communities and that their study indicates the extent to which the spray of dispersant may change the ratio of airborne particulate matter, although they found a decreased concentration of VOCs. The authors hypothesized this decrease in VOC may be due to suppression of organic diffusion across interfaces coated with the dispersant or because of an increase in the dissolution rate of organic compounds into the water column, thus reducing the partitioning to the atmosphere. (Afshar-Mohajera et al., 2018) The results of
this study are of relevance to human populations involved in oil-spill cleanup scenarios in which dispersant application is used, and the DWH oil spill cleanup relied heavily on the Corexit 9500A dispersant.

Much of the most intense clean-up efforts from the DWH oil spill response occurred during the summer months of 2010, which were reported to be one of the three hottest summers for the southern United States in 117 years of recording. (National Oceanic and Atmospheric Administration National Centers for Environmental Information, 2011) Heat was an important exposure during these responders’ deployments, and the acute neurological symptoms we studied could also have potentially been associated with heat exposure. We attempted to control for environmental heat exposure in our models, first by adjusting for environmental heat as previously assessed for our study population, (Erickson et al., 2018) and then by carrying out a sensitivity analysis excluding responders in the highest heat category of this metric. We did not find any appreciable differences after excluding them, but we cannot rule out residual confounding by heat. We also evaluated the potential for effect modification by heat and found that those experiencing higher heat exposure had stronger associations between oil exposure and neurological symptoms than those experiencing lower heat exposure. These findings indicate a potential synergistic effect between oil exposure and heat, particularly for headaches, lightheadedness/dizziness, and blurred/double vision and should be considered in future oil spill responses by the leadership for force health protection.

Our other stratified analyses of oil exposure-neurological symptom associations indicated that the most consistent differences were by sex and by reported use of oil PPE, such that associations between crude oil exposure and neurological symptoms were stronger for males than females and for those reporting ever using oil PPE than for those never reporting use, though the strata for females had small counts. Similar to our findings, a study on Hebei Spirit oil spill cleanup showed increased prevalence of neurological symptoms, such as headache and dizziness, among cleanup workers who wore PPE. (Gwack et al., 2012) Although this appears counter-intuitive, it could be that ever use of oil PPE in this cross-sectional analysis is not a specific enough metric to be able to evaluate the potentially protective effects of PPE use and that rather it is a proxy for oil exposure, since, as expected, those never reporting oil PPE included a large number of responders who also reported not being exposed to oil. Another possible explanation is that responders wearing certain types of PPE such as Tyvek suits became hotter and experienced neurological symptoms as a result. Future studies will need to capture more detailed information on PPE use, together with exposure opportunity among oil spill clean-up workers.

The survey response rate among all responders in the cohort (N = 8696) was 56%. We have previously compared survey completers to non-survey completers among the Coast Guard responders and found the two groups to be similar with respect to most baseline characteristics, (Rusiecki et al., 2017) although there was a higher proportion of responders deploying prior to the July 15th well-capping among the non-survey completers and a higher proportion of this group who were stationed aboard Coast Guard cutters during their response. These differences indicate the potential for the non-survey responders to have
experienced greater exposure to crude oil. The sample of responders who completed the survey used in this study, may therefore be a somewhat lower exposed group.

A strength of this study is that we have access to pre-existing medical conditions for active duty personnel. In an attempt to further refine our analyses, we excluded responders who had prior medical encounters relevant to the symptoms we were studying. Interpretation of results did not change after these exclusions. Other strengths of this study include a large study population, providing adequate power to detect associations in categorized exposure variables and for stratified analyses. Additionally, it enabled us to carry out multiple sensitivity analyses, which indicated the robustness of our results. Unlike most prior studies from other oil spills, this study queried self-report of exposure based on frequency of exposure, rather than a more crude ever/never. Additionally, Coast Guard responders are generally healthy, reducing the impact of comorbidities, although as mentioned we had the ability to investigate this potential directly. Finally, recall of the deployment experience is likely to be accurate, as more than two-thirds of responders completed the exit survey within the month of their deployment, with the majority of the responders completing prior to or at the end of their deployment (57%).

Limitations of this study should be pointed out, though. Assessment of exposure to crude oil, oil dispersants, and exhaust exposure were based on self-report and may be subject to reporting bias. In this study we do not have information on where responders were, when. This is information we have encouraged disaster response leadership to obtain in future disaster responses in order to more adequately capture the exposure experiences of responders. In the current study, we attempted to address, to the extent possible, differences in exposure by considering timing of deployment with respect to the well capping. Additionally, although Corexit 9527A and 9500 were widely used in the DWH oil spill response, the survey instrument did not explicitly ask for oil dispersant product names. However, most participants are unlikely to have known, and there was substantial temporal overlap of use of the two dispersants. Also, reporting of exposure to oil and oil dispersants was highly concordant among these responders; therefore, the effect of only dispersant exposure in the absence of oil could not be meaningfully assessed. While the neurological symptoms we investigated may have been affected by oil spill clean-up exposures, some of the findings we report here, particularly those with a threshold effect, rather than an exposure-response effect, may be attributable to non-specific medical symptoms frequently described as medically unexplained physical symptoms (MUPS), which are common in survivors of disasters. (van den Berg et al., 2005) Finally, because this study is cross-sectional, the timing of the exposure and health effects in relation to each other are unknown.

Our findings indicate that exposures of Coast Guard responders to various chemical hazards such as crude oil and combined exposure to crude oil and dispersants were associated with an increased prevalence of acute neurological symptoms. Since the six neurological symptoms studied here tended to be moderately to strongly correlated, the elevated risks seen across these symptoms may reflect a common underlying neurological phenomenon. Given the lack of information, particularly regarding the adverse effects of oil dispersants and combined effects of oil and dispersant exposures on humans, it warrants future
investigations. Given the cross sectional nature of this study, these findings should be interpreted with caution and should be replicated in other studies. While the focus of this study was on acute symptoms, in future analyses, we plan to examine long-term neurological effects using longitudinal health encounter data. Better understanding of both the short and long term health effects of oil spill clean-up work as well as the potential influence from PPE use and the influence of environmental heat will enable disaster response planners to optimize the protection of the responder population.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.
Associations between exposure to a combination of crude oil and dispersant vs. neither and crude oil only vs. neither and acute neurological symptoms, estimated by adjusted prevalence ratios (PRs) and 95% confidence intervals (CIs) among entire study population.
Table 1

Distribution of demographics, exposures, and neurological symptoms of surveyed responders of the Deepwater Horizon oil spill.

| Characteristic                                      | N     | (%)  |
|-----------------------------------------------------|-------|------|
| Age group (median age = 32 yrs)                     |       |      |
| Less than 25 years old                              | 827   | (17) |
| 25–34 years old                                     | 2128  | (44) |
| 35–50 years old                                     | 1738  | (36) |
| Older than 50                                       | 162   | (3)  |
| Gender                                              |       |      |
| Male                                                | 4127  | (85) |
| Female                                              | 728   | (15) |
| Race/ethnicity                                      |       |      |
| White                                               | 3741  | (77) |
| Black or African American                           | 203   | (4)  |
| Asian/Al/AN/NH/PI                                   | 182   | (4)  |
| Other                                               | 242   | (5)  |
| Unknown                                             | 487   | (10) |
| Employee class                                      |       |      |
| Active duty                                         | 3102  | (64) |
| Selected reserve                                    | 1753  | (36) |
| Employee type                                       |       |      |
| Enlisted                                            | 3530  | (73) |
| Officer                                             | 1311  | (27) |
| Other/unknown                                       | 14    | (< 1)|
| Crude oil/oily water exposure                       |       |      |
| Ever                                                | 2651  | (55) |
| Inhalation                                          | 2478  | a    |
| Direct contact with skin                            | 1696  | a    |
| Never                                               | 2204  | (45) |
| Dispersant exposure                                 |       |      |
| Sometimes/most of the time/all of the time          | 258   | (5)  |
| Rarely/never                                        | 4597  | (95) |
| Oil and dispersant exposure, combined               |       |      |
| Exposed to both crude oil and dispersant            | 252   | (5)  |
| Exposed to neither crude oil nor dispersant         | 2136  | (44) |
| Exhaust inhalation                                  |       |      |
| Ever                                                | 3660  | (75) |
| Never                                               | 1195  | (25) |
| Smoking status during deployment                    |       |      |
| Ever                                                | 908   | (19) |
| Never                                               | 3947  | (81) |
| Characteristic                | N    | (%)  |
|------------------------------|------|------|
| **Sleep status**             |      |      |
| Less than 6 h of sleep       | 1730 | (36) |
| At least 6 h but < 8 h       | 2743 | (57) |
| 8 or more hours              | 382  | (8)  |
| **Use of oil PPE**           |      |      |
| Ever                         | 3135 | (65) |
| Never                        | 1720 | (35) |
| **Deployment period**        |      |      |
| Started before 15 July 2010  | 3356 | (69) |
| post-capping                 |      |      |
| Started on or after 15 July  | 1499 | (31) |
| 2010 (post-capping)          |      |      |
| **Deployment length**        |      |      |
| Less than 30 days            | 1313 | (27) |
| Greater than or equal to 30  | 3542 | (73) |

*a* Responders could have reported both, so there is overlap between these indicators.
Table 2

Associations between exposure to crude oil/oily water and acute neurological symptoms, estimated by adjusted prevalence ratios (PRs) and 95% confidence intervals (CIs).

| Neurologic symptom                  | Exposure level | Ever/never | Inhalation exposure | Skin contact exposure |
|-------------------------------------|----------------|------------|---------------------|-----------------------|
|                                     |                | (95% CI)   |                     |                       |
|                                     |                | PR (adj.)  |                     |                       |
|                                     |                |            |                     |                       |
|                                      | Never          | 580/2204   | 1.00                | 637/1740              | 971/2188 |
|                                      | Ever           | 1311/2651  | 1.45 (1.32–1.60)    | 526/538               | 1.34 (1.24–1.46) |
|                                      | Rarely         | 483/679    | 1.27 (1.56–1.40)    | 302/193               | 1.54 (1.40–1.68) |
|                                      | Sometimes      | 461/388    | 1.60 (1.45–1.76)    |                       | 1.53 (1.38–1.70) |
|                                      | Most/all times | 310/157    | 1.80 (1.61–2.01)    | ≤0.01                 | 1.53 (1.38–1.70) |
|                                      | Ever           | 511/2651   | 1.83 (1.49–2.26)    | 143/352               | 2.52 (2.07–3.08) |
|                                      | Rarely         | 149/1013   | 1.55 (1.24–1.95)    | 185/879               | 1.69 (1.40–2.03) |
|                                      | Sometimes      | 179/670    | 2.38 (1.91–2.96)    | 143/352               | 2.52 (2.07–3.08) |
|                                      | Most/all times | 165/302    | 3.36 (2.66–4.25)    | ≤0.01                 | 3.21 (2.50–4.12) |
|                                      | Ever           | 159/204    | 1.00                | 168/2209              | 1.00                 |
|                                      | Rarely         | 117/1045   | 1.16 (0.92–1.47)    | 115/949               | 1.26 (1.01–1.56) |
|                                      | Sometimes      | 105/744    | 1.46 (1.14–1.86)    | 85/410                | 1.92 (1.50–2.47) |
|                                      | Most/all times | 78/389     | 1.72 (1.28–2.30)    | 0.04                  | 19/118               |
|                                      | Ever           | 57/204     | 1.00                | 60/2317               | 1.00                 |
|                                      | Rarely         | 53/1109    | 1.36 (0.93–1.99)    | 63/1001               | 1.50 (1.09–2.07) |
|                                      | Sometimes      | 62/787     | 2.20 (1.51–3.22)    | 51/444                | 2.43 (1.70–3.50) |
|                                      | Most/all times | 54/413     | 3.32 (2.19–5.05)    | ≤0.01                 | 14/123                |
|                                      | Ever           | 71/204     | 1.00                | 78/2299               | 1.00                 |
|                                      | Rarely         | 53/1109    | 1.36 (0.93–1.99)    | 63/1001               | 1.50 (1.09–2.07) |
|                                      | Sometimes      | 62/787     | 2.20 (1.51–3.22)    | 51/444                | 2.43 (1.70–3.50) |
|                                      | Most/all times | 54/413     | 3.32 (2.19–5.05)    | ≤0.01                 | 14/123                |
|                                      | Ever           | 147/2651   | 1.32 (0.93–1.87)    | 106/3053              | 1.00                 |
| Neurologic symptom                  | Exposure level   | Ever/never | Inhalation exposure | Skin contact exposure |
|------------------------------------|------------------|------------|--------------------|-----------------------|
|                                    |                  |            | (95% CI)           |                       |
|                                    |                  | N<sup>b</sup> | PR (adj.)<sup>c</sup> | p-Trend |
|                                    |                  | N<sup>b</sup> | PR (adj.)<sup>c</sup> |                       |
|                                    |                  | N<sup>b</sup> | PR (adj.)<sup>c</sup> | (95% CI) | p-Trend |
| Rarely                             |                  | 49          | 1.16 (0.80–1.69)   | 46                    | 1.29 (0.90–1.84) |
| Sometimes                          |                  | 39          | 1.32 (0.87–1.99)   | 51                    | 3.03 (2.11–4.37) |
| Most/all times                     |                  | 52          | 2.87 (1.90–4.33)   | ≤0.01                 | 2.92 (1.59–5.39) |
| Memory loss/confusion              | Never            | 34/2204     | 1.00               | 57                    | 1.00               |
|                                    | Ever             | 93/2651     | 1.55 (0.97–2.48)   |                       |                     |
| Rarely                             |                  | 26          | 1.10 (0.65–1.86)   | 34                    | 1.52 (0.98–2.36) |
| Sometimes                          |                  | 42          | 2.44 (1.50–3.96)   | 29                    | 2.61 (1.58–4.32) |
| Most/all times                     |                  | 22          | 2.03 (1.10–3.75)   | ≤0.01                 | 2.09 (0.87–5.03) |

<sup>a</sup> Adjusted for: age, sex, dispersant exposure, exhaust exposure, smoking, environmental heat, and hours of sleep per night during deployment.

<sup>b</sup> Count of responders reporting the symptom for the corresponding exposure level.

<sup>c</sup> Count of responders not reporting the symptom for the corresponding exposure level.
Table 3
Sensitivity analysis of association between crude oil exposures and acute neurologic symptoms, excluding responders with pre-existing specific neurologic conditions.

| Acute neurological symptom | Exposure level | Inhalation | | | Skin contact | | |
|---------------------------|----------------|------------|-----------------|---|-----------------|---|
|                           |                | All active duty (N = 1638) | Active duty - no pre-existing conditions (N = 1626) | | All active duty (N = 1117) | Active duty - no pre-existing conditions (N = 1107) |
|                           |                | N | PR (adj.) | (95% CI) | p-Trend | N | PR (adj.) | (95% CI) | p-Trend | N | PR (adj.) | (95% CI) | p-Trend |
| Headaches                 |                |   |          |          |          |   |          |          |          |   |          |          |          |
| Never                     | 368            | 1.00 |          |          |          | 338 |          |          |          | 530 | 1.00 |          |          |          |
| Rarely                    | 282            | 1.30 | (1.14–1.47) |          |          | 258 | 1.22 | 1.10–1.36 |          | 312 | 1.28 | 1.16–1.37 |          |          |
| Sometimes                 | 297            | 1.62 | (1.43–1.84) |          |          | 277 | 1.48 | 1.36–1.67 |          | 181 | 1.41 | 1.30–1.53 |          |          |
| Most/all times            | 244            | 1.81 | (1.59–2.08) | < 0.0001 |          | 219 | 1.61 | 1.44–1.80 | < 0.0001 | 69  | 1.36 | 1.22–1.57 | < 0.0001 |          |
| Light-headedness/dizziness|                |   |          |          |          |   |          |          |          |   |          |          |          |
| Never                     | 85             | 1.00 |          |          |          | 83  |          |          |          | 146 | 1.00 |          |          |          |
| Rarely                    | 84             | 1.52 | (1.12–2.04) |          |          | 82  | 1.51 | 1.19–1.90 |          | 105 | 1.54 | 1.28–1.86 |          |          |
| Sometimes                 | 106            | 2.25 | (1.69–3.00) |          |          | 96  | 2.15 | 1.71–2.70 |          | 90  | 2.19 | 1.79–2.68 |          |          |
| Most/all times            | 129            | 3.60 | (2.70–4.80) | < 0.0001 |          | 125 | 2.78 | 2.17–3.56 | < 0.0001 | 45  | 2.59 | 2.00–3.36 | < 0.0001 |          |
| Difficulty concentrating  |                |   |          |          |          |   |          |          |          |   |          |          |          |
| Never                     | 74             | 1.00 |          |          |          | 73  |          |          |          | 127 | 1.00 |          |          |          |
| Rarely                    | 61             | 1.27 | (0.91–1.78) |          |          | 61  | 1.10 | 0.87–1.39 |          | 60  | 1.16 | 0.93–1.44 |          |          |
| Sometimes                 | 66             | 1.66 | (1.19–2.33) |          |          | 66  | 1.23 | 0.96–1.58 |          | 58  | 1.65 | 1.29–2.11 |          |          |
| Most/all times            | 61             | 1.96 | (1.36–2.83) | 0.0001   |          | 61  | 1.36 | 1.36–1.83 | < 0.0001 | 16  | 1.11 | 0.69–1.77 | 0.0001   |          |
| Numbness/tingling sensation|                |   |          |          |          |   |          |          |          |   |          |          |          |
| Never                     | 29             | 1.00 |          |          |          | 26  |          |          |          | 48  | 1.00 |          |          |          |
| Rarely                    | 25             | 1.29 | (0.74–2.23) |          |          | 22  | 1.27 | 0.85–1.89 |          | 30  | 1.35 | 0.97–1.87 |          |          |
| Sometimes                 | 35             | 2.20 | (1.30–3.71) |          |          | 35  | 1.89 | 1.27–2.82 |          | 33  | 2.10 | 1.46–3.02 |          |          |
| Most/all times            | 38             | 3.20 | (1.86–5.51) | < 0.0001 |          | 37  | 2.53 | 1.64–3.90 | < 0.0001 | 9   | 1.82 | 1.00–3.32 | 0.0002   |          |
| Acute neurological symptom | Exposure level | All active duty (N = 1638) | Active duty - no pre-existing conditions (N = 1626) | All active duty (N = 1117) | Active duty - no pre-existing conditions (N = 1107) |
|----------------------------|----------------|-----------------------------|---------------------------------------------------|-----------------------------|---------------------------------------------------|
|                            |                | N<sup>a</sup> | PR<sup>b</sup> (adj.) | (95% CI) | p-Trend | N<sup>a</sup> | PR<sup>b</sup> (adj.) | (95% CI) | p-Trend | N<sup>a</sup> | PR<sup>b</sup> (adj.) | (95% CI) | p-Trend |
| Blurred/double vision       | Never          | 33 | 1.00 |          |          | 27 | 1.28 | 0.84–1.95 |          |          | 38 | 1.17 | 0.78–1.74 |          |          |
|                            | Rarely         | 23 | 1.13 | 0.65–1.96 |          | 17 | 1.28 | 0.84–1.95 |          |          | 19 | 2.69 | 1.81–3.99 |          |          |
|                            | Sometimes      | 24 | 1.48 | 0.84–2.58 |          | 18 | 1.32 | 0.83–2.09 |          |          | 27 | 2.69 | 1.81–3.99 |          |          |
|                            | Most/all times | 38 | 3.17 | 1.86–5.42 | <0.0001 | 33 | 2.41 | 1.51–3.86 | <0.0001 |          | 11 | 2.25 | 1.16–4.34 | <0.0001 |          |
| Memory loss/ confusion     | Never          | 18 | 1.00 |          |          | 18 | 1.00 |          |          |          | 30 | 1.00 |          |          |          |
|                            | Rarely         | 14 | 1.15 | 0.56–2.35 |          | 14 | 0.97 | 0.57–1.65 |          |          | 18 | 1.31 | 0.85–2.04 |          |          |
|                            | Sometimes      | 25 | 2.52 | 1.32–4.81 |          | 25 | 1.90 | 1.15–3.11 |          |          | 22 | 2.11 | 1.28–3.49 |          |          |
|                            | Most/all times | 19 | 2.35 | 1.12–4.95 | 0.004 | 19 | 1.45 | 0.78–2.69 | 0.0037 |          | 6 | 1.66 | 0.69–4.00 | 0.0015 |          |

<sup>a</sup>With the outcome and exposure.

<sup>b</sup>Adjusted for: age, sex, dispersant contact, exhaust exposure, smoking, heat index and hours of sleep per night during deployment.
Table 4

Stratified analyses of associations between ever exposure to crude oil/oily water and acute neurological symptoms, compared to never exposure, estimated by adjusted prevalence ratios (PRs) and 95% confidence intervals (CIs).

| Neurologic symptom                  | N<sup>a</sup> | N<sup>b</sup> | PR (adj.) | 95% CI          | N<sup>a</sup> | N<sup>b</sup> | PR (adj.) | 95% CI          | Interaction p-value |
|-------------------------------------|---------------|---------------|-----------|----------------|---------------|---------------|-----------|----------------|---------------------|
|                                     | Males         | Females       |           |                |               |               |           |                |                     |
| Headaches                           | 1538          | 2589          | 1.87      | (1.69–2.07)    | 353           | 375           | 1.34      | (1.14–1.58)    | < 0.01              |
| Lightheadedness/dizziness           | 507           | 3620          | 3.00      | (2.37–3.80)    | 136           | 507           | 2.07      | (1.44–2.96)    | 0.02                |
| Difficulty concentrating           | 372           | 3755          | 1.81      | (1.44–2.26)    | 96            | 632           | 1.28      | (0.86–1.90)    | 0.01                |
| Numbness or tingling sensations     | 193           | 3934          | 2.41      | (1.68–3.42)    | 36            | 692           | 1.82      | (0.88–3.80)    | 0.30                |
| Blurred/double vision               | 175           | 3952          | 1.96      | (1.38–2.78)    | 43            | 685           | 1.31      | (0.69–2.49)    | 0.05                |
| Memory loss/confusion               | 109           | 4018          | 2.58      | (1.60–4.16)    | 18            | 710           | 1.03      | (0.37–2.87)    | 0.02                |
|                                      | With exhaust exposure | Without exhaust exposure |               |                |               |               |           |                |                     |
| Headaches                           | 1649          | 2011          | 1.39      | (1.27–1.52)    | 242           | 953           | 1.86      | (1.51–2.29)    | < 0.01              |
| Lightheadedness/dizziness           | 586           | 3074          | 2.23      | (1.80–2.77)    | 57            | 1138          | 2.30      | (1.32–4.02)    | 0.88                |
| Difficulty concentrating           | 403           | 3257          | 1.32      | (1.09–1.68)    | 65            | 1130          | 1.29      | (0.71–2.33)    | 0.92                |
| Numbness or tingling sensations     | 206           | 3454          | 1.68      | (1.20–2.37)    | 23            | 1172          | 3.48      | (1.44–8.42)    | 0.21                |
| Blurred/double vision               | 181           | 3479          | 1.63      | (1.15–2.33)    | 37            | 1158          | 1.26      | (0.54–2.92)    | 0.68                |
| Memory loss/confusion               | 112           | 3548          | 1.78      | (1.11–2.86)    | 15            | 1180          | 2.04      | (0.56–7.41)    | 0.74                |
|                                      | With oil-PPE   | Without oil-PPE |               |                |               |               |           |                |                     |
| Headaches                           | 1379          | 1756          | 1.71      | (1.53–1.92)    | 512           | 1208          | 1.45      | (1.25–1.68)    | 0.14                |
| Lightheadedness/dizziness           | 501           | 2634          | 2.59      | (2.01–3.35)    | 142           | 1578          | 2.50      | (1.79–3.48)    | 0.94                |
| Difficulty concentrating           | 307           | 2828          | 1.71      | (1.30–2.25)    | 161           | 1559          | 1.50      | (1.10–2.06)    | 0.60                |
| Numbness or tingling sensations     | 164           | 2971          | 3.06      | (1.87–5.00)    | 23            | 1172          | 1.37      | (0.82–2.28)    | 0.06                |
| Blurred/double vision               | 147           | 2988          | 2.45      | (1.54–3.91)    | 71            | 1649          | 1.15      | (0.68–1.96)    | 0.02                |
| Memory loss/confusion               | 89            | 3046          | 2.55      | (1.35–4.81)    | 38            | 1682          | 1.72      | (0.88–3.36)    | 0.22                |
|                                      | Pre-capping    | Post-capping  |               |                |               |               |           |                |                     |
| Headaches                           | 547           | 952           | 1.80      | (1.62–2.00)    | 1344          | 2012          | 1.54      | (1.33–1.77)    | 0.09                |
| Lightheadedness/dizziness           | 155           | 1344          | 2.35      | (1.87–2.96)    | 488           | 2868          | 3.30      | (2.27–4.79)    | 0.25                |
| Difficulty concentrating           | 129           | 1370          | 1.61      | (1.27–2.03)    | 339           | 3017          | 1.66      | (1.17–2.35)    | 0.90                |
| Numbness or tingling sensations     | 59            | 1440          | 2.38      | (1.63–3.47)    | 170           | 3186          | 1.73      | (0.97–3.08)    | 0.95                |
| Blurred/double vision               | 55            | 1444          | 1.82      | (1.27–2.61)    | 163           | 3193          | 1.40      | (0.80–2.45)    | 0.52                |
| Neurologic symptom               | N<sup>a</sup> | N<sup>b</sup> | PR (adj.)<sup>c</sup> | 95% CI         | N<sup>a</sup> | N<sup>b</sup> | PR (adj.)<sup>c</sup> | 95% CI         | Interaction p-value |
|---------------------------------|---------------|---------------|------------------------|----------------|---------------|---------------|------------------------|----------------|----------------------|
| Memory loss/confusion           | 35            | 1464          | 1.55                   | (0.96–2.52)    | 92            | 3264          | 5.09                   | (2.29–11.30)   | 0.07                 |
|                                 |               |               | Low heat               |                |               |               | High heat              |                |                      |
| Headaches                       | 825           | 1573          | 1.65                   | 1.48–1.84      | 1066          | 1391          | 1.73                   | 1.50–1.99      | 0.09                 |
| Lightheadedness/dizziness       | 220           | 2178          | 2.18                   | 1.68–2.82      | 423           | 2034          | 3.22                   | 2.29–4.54      | 0.01                 |
| Difficulty concentrating        | 261           | 2137          | 1.49                   | 1.19–1.86      | 207           | 2250          | 1.99                   | 1.30–3.06      | 0.45                 |
| Numbness or tingling sensations | 106           | 2292          | 2.12                   | 1.45–3.10      | 123           | 2334          | 2.34                   | 1.29–4.24      | 0.80                 |
| Blurred/double vision           | 115           | 2283          | 1.43                   | 1.00–2.07      | 103           | 2354          | 3.13                   | 1.51–6.46      | 0.02                 |
| Memory loss/confusion           | 67            | 2331          | 2.00                   | 1.24–3.22      | 60            | 2397          | 2.43                   | 0.97–6.13      | 0.45                 |

<sup>a</sup> Count of responders reporting the symptom for the corresponding exposure level.

<sup>b</sup> Count of responders not reporting the symptom for the corresponding exposure level.

<sup>c</sup> Adjusted for: age, sex, dispersant contact, exhaust exposure, smoking, environmental heat and hours of sleep per night during deployment; note each model is adjusted for all of these co-variates, with the exception of what they are stratified by.