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Subcortical surface morphometry in substance dependence: An ENIGMA addiction working group study


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ABBREVIATIONS: AlcD, alcohol dependence; CbD, cannabis dependence; CocD, cocaine dependence; ICV, intracranial volume; JD, log of the Jacobian determinant; NicD, nicotine dependence; MetD, methamphetamine dependence; RD, radial distance
Abstract

While imaging studies have demonstrated volumetric differences in subcortical structures associated with dependence on various abused substances, findings to date have not been wholly consistent. Moreover, most studies have not compared brain morphology across those dependent on different substances of abuse to identify substance-specific and substance-general dependence effects. By pooling large multinational datasets from 33 imaging sites, this study examined subcortical surface morphology in 1628 nondependent controls and 2277 individuals with dependence across alcohol, nicotine, cocaine, methamphetamine, and/or cannabis. Subcortical structures were defined by FreeSurfer segmentation and converted to a mesh surface to extract two vertex-level metrics—the radial distance (RD) of the structure surface from a medial curve and the log of the Jacobian determinant (JD)—that, respectively, describe local thickness and surface area dilation/contraction. Mega-analyses were performed on measures of RD and JD to test for the main effect of substance dependence, controlling for age, sex, intracranial volume, and imaging site. Widespread differences between dependent users and nondependent controls were found across subcortical structures, driven primarily by users dependent on alcohol. Alcohol dependence was associated with localized lower RD and JD across most structures, with the strongest effects in the hippocampus, thalamus, putamen, and amygdala. Meanwhile, nicotine use was associated with greater RD and JD relative to nonsmokers in multiple regions, with the strongest effects in the bilateral hippocampus and right nucleus accumbens. By demonstrating subcortical morphological differences unique to alcohol and nicotine use, rather than dependence across all substances, results suggest substance-specific relationships with subcortical brain structures.

KEYWORDS

addiction, structural MRI, substance dependence
1 | INTRODUCTION

Substance dependence is characterized by compulsive substance-seeking, and a loss of control over intake, despite negative social, interpersonal, and occupational consequences. Substance use disorder can be related to any of a number of licit and illicit substances, including alcohol, cannabis, opioids, stimulants, and tobacco. While not all substance users will experience problems related to use, a significant number will become dependent, although the proportion differs between substances. Within the United States alone, over 1.5 million substance users are admitted to treatment facilities every year for problems related to substance use, reflecting a huge personal cost, and a severe toll on social and economic development. Substance dependence accounts for over 37.6 million disability-adjusted life years (DALYs; ie, number of years lost due to disability and premature mortality) globally. Disability (mental health, social and emotional functioning) also increases with dependence severity among users. Identifying biomarkers associated with dependence across different substances (ie, alcohol, tobacco, cannabis, opioids, and stimulants) may greatly help our understanding of dependence and its consequences and improve the identification of individuals most vulnerable to dependence-related harm.

Neuroimaging research over the years has attempted to elucidate brain-based biomarkers (ie, structure, function, and neurochemistry) that may indicate aberrant processes in dependence on various substances. Separately, these studies have demonstrated volumetric differences in common subcortical structures, including the hippocampus, amygdala, striatum, and thalamus, in opioid, stimulant, alcohol, tobacco, and cannabis use disorders. Such findings are consistent with the proposed role of these striatal and limbic structures in supporting processes (eg, planning and decision-making, reward, and memory) crucially involved in the etiology of substance use and dependence. However, studies have yet to compare subcortical structure across multiple substances using the same methods, making it difficult to infer substance-specific versus substance-general neural alterations characterizing dependence. Furthermore, gross volumetric measures commonly employed by structural imaging studies may be unable to capture more localized subcortical differences (ie, focal differences on the vertices or triangular mesh that make up the subcortical surface, as opposed to a single volumetric value across the entire structure) that can either be generalizable across substances of abuse or specific to particular substances. This is relevant as structures such as the hippocampus, amygdala, and striatum may be functionally segregated across their subregions or topology, given differences in gene expression, receptor distributions (eg, GABA<sub>A</sub>, dopamine, and cannabinoid receptors), and innervation along the structure. Different regions of these subcortical structures may therefore be differentially associated with substance use and dependence. For example, the basolateral and central amygdala are differentially recruited over the course of cocaine-seeking in rats. The former is suggested to be relevant for the development of substance-seeking "habit," while the latter is thought to be responsible for its long-term maintenance, reflecting unique but complementary roles in the etiology of substance use. The dorsal and ventral regions of the hippocampus are also differentially implicated in context- and cue-induced reinstatement of substance use due to their greater involvement in cognitive and affective functions, respectively. Different substances of abuse are further thought to have differing cellular and molecular pathways to dependence, raising the potential of substance-specific dependence effect. These observations motivated us to consider more fine-grained shape differences in subcortical morphology when delineating individual substance dependence-related effects on the brain.

This study was conducted by the Addiction working group of the Enhancing Neuroimaging Genetics through Meta-Analysis (ENIGMA) Consortium, which leverages already collected neuroimaging datasets to overcome limitations of sample size and statistical power in identifying biomarkers of substance dependence. Our previous study examining FreeSurfer-segmented subcortical volumes across a combined sample of 23 research sites identified substance-specific effects of alcohol dependence in the amygdala, hippocampus, nucleus accumbens, and putamen. A nonlinear support vector machine was further able to classify alcohol dependence and nicotine dependence above chance levels (despite there being no significant nicotine dependence effects on individual subcortical volumes), suggesting that there may be nonlinear or multivariate patterns of effects across multiple brain areas not captured by standard univariate analysis of regional volumes. Building on this result, this study sought to characterize substance-general and substance-specific shape variation across the subcortical surfaces, which might better identify fine-grained regional effects not captured by a single volumetric measure (ie, as was the limitation of our previous paper, Mackey et al, 2018). This study contained pooled neuroimaging data from 33 research sites, adopting a surface-based approach used to quantify subcortical shape variability (a) between all dependent users and nondependent controls, (b) across dependence groups (alcohol, nicotine, cocaine, methamphetamine, or cannabis) and nondependent controls, and (c) across nicotine use status. This will provide insight into whether dependence on different substances of abuse may be associated with unique and localized effects on the brain, specifically on subcortical structures. In turn, such brain effects may have the potential to serve as useful biomarkers for risk factors or evidence of recovery from substance dependence.

2 | MATERIALS AND METHODS

Case and control data were contributed from 33 scanning sites from the ENIGMA addiction working group (http://enigmaaddiction.com). This included a total of 1535 nondependent controls and 2270 individuals with a primary substance dependence diagnosis (according to DSM-IV criteria) on one of five substances: alcohol (AlcD), nicotine (NicD), cocaine (CocD), methamphetamine (MetD), and cannabis (CbdD), although approximately 8% of dependent users met criteria for dependence on more than one substance. Cases were excluded if criteria were met for any lifetime history of central nervous system...
disease, or a current axis I diagnosis apart from substance dependence, mood and anxiety disorders. Nondependent controls may have used these substances (ie, mainly alcohol and nicotine) but did not meet diagnostic criteria or were not assessed for substance dependence. Individual site information and diagnostic instrument is provided in Table S1. All subjects provided written informed consent, and all procedures were in accordance with the Declaration of Helsinki.

2.1 MRI data processing

Site-specific scanner and acquisition details for T1-weighted MR images are available in Table S1. All scans were prepared (either centrally at the University of Vermont or at the respective individual sites) using the FreeSurfer image analysis environment (http://surfer.nmr.mgh.harvard.edu/) version 5.3.0 to segment 14 subcortical regions (ie, bilateral accumbens, amygdala, caudate, hippocampus, pallidum, putamen, and thalamus) from surrounding brain tissue. All FreeSurfer output underwent quality control at each site, according to an established protocol (http://enigma.ini.usc.edu/protocols/imaging-protocols/), which included outlier detection and visual inspection of all data. A second level of quality control was also performed on a random selection of participants from each site, centrally at the University of Vermont.

Morphometric analysis on the FreeSurfer-segmented subcortical regions was performed at the University of Vermont. This entailed converting subcortical boundaries to a mesh surface using the Medial Daemons method27,28 (http://enigma.ini.usc.edu/ongoing/enigma-shape-analysis/). This step includes registration of the FreeSurfer-segmented subcortical structures to a master template based on brain images from 200 young adults created by the University of Southern California’s Imaging Genetics Center team. By matching their shape curvatures and medial features to a master template, mesh representations of the subcortical boundaries were generated. All resulting mesh reconstructions were visually inspected by Y.C. for quality control. Reconstructions that had significant artifacts (eg, spikes and holes) or were grossly inaccurate upon visual inspection (2.19% of generated structures) were excluded. Finally, two vertex-level metrics were derived from the mesh surface to quantify subcortical shape. This included (a) the radial distance (RD), which is the distance between each surface vertex and a skeleton core created along the long axis of the structure, and (b) the natural logarithm of the Jacobian determinant (JD), which represents the surface dilation ratio necessary to map corresponding vertices on the subject-specific surface to the surface of the master template. The logarithm is used to obtain a distribution that is closer to Gaussian. RD and JD capture surface measures akin to “thickness from a central skeleton” and “area,” respectively,29 and are only weakly correlated (ie, correlation coefficient from our sample, $r = .0228$, CI, 0.0226-0.0230). They thus complement each other in providing information on localized grey matter changes across subcortical structures. The number of vertices per structure was consistent across subjects, as defined by the master template (accumbens $= 930$; amygdala $= 1368$; caudate $= 2502$; hippocampus $= 2502$; putamen $= 2502$; thalamus $= 2502$; pallidum $= 1254$). See Figure 1 for an overview of the vertex-wise shape metrics employed.

2.2 Statistical analysis

Three sets of tests examined substance-general and substance-specific correlates of dependence, using an optimized split-half strategy, described in the later paragraph. The first set (model I: substance-general model) assessed the main effect of dependence on any substance (ie, dependent users vs nondependent control). In these analyses, individuals reporting dependence on one or more substances were included.

The second set (model II: substance-specific model) assessed the main effect of individual substances of dependence (ie, AlcD, NicD, CocD, MetD, and Cbd versus nondependent controls as a fixed factor with six levels). In the second set of analyses, individuals who were dependent on more than one substance were excluded to clarify the association between dependence on individual substances and subcortical morphology. However, nondependent occasional substance use (eg, recreational alcohol use in either group) was not excluded. Effect of AlcD was further validated in a post hoc analysis with a subsample of 171 AlcD participants versus nondependent controls to ensure that any observed AlcD effects were not due to their comparatively larger sample (n = 830) relative to other substance-user groups in this study ($n = 171-565$). The subsample of 171 AlcD participants were created by systematically selecting one in five AlcD participants, ordered by site, sex, and age, to ensure that these covariates were matched across selected and nonselected samples.

The third set of analyses (model III: nicotine-disambiguation model) investigated nicotine use effects. The large number of nondependent controls and individuals diagnosed with dependence who use nicotine may have affected the search for nicotine-related results in the second model. This is particularly important as individual studies that recruited users on AlcD, CocD, MetD, and Cbd may not necessarily screen for nicotine use or dependence. Consequently, the third set of analyses compared three groups: individuals with NicD, nondependent controls who use nicotine, and nondependent controls who do not use nicotine.

Similar to the method in our previous paper,26 for the three models were analyzed using an optimized split-half strategy whereby the data were first split into two halves matched for site, age, sex, and intracranial volume. Subsequently, the series of linear models were tested on each separate half, on the RD and JD measures of each subcortical structure, controlling for participants’ age, sex, and intracranial volume (ICV, to account for premorbid head size), and imaging site. All outputs were corrected using a regional searchlight false discovery rate (FDR) method30 at $q = .05$, conservatively treating the 14 subcortical structures (ie, bilateral accumbens, amygdala, caudate, hippocampus, pallidum, putamen, and thalamus) and two metrics (RD and JD) in each model as a single family of tests. Lastly, the
corresponding outputs across the split halves were overlaid to identify common regions of significance (ie, vertices that were significant across both splits, henceforth referred to as “overlap”).

3 | RESULTS

Demographic information for the full sample is presented in Table 1. In general, dependent samples included more males, were older, and exhibited greater ICV than nondependent controls. Association between sex, age, and ICV are also presented graphically in Figures S1 and S2. To control for these factors, sex, age, and ICV were included as covariates in the linear models. The effects of sex, age, and ICV on RD and JD are also presented graphically in Figure S3.

3.1 | Model I: Substance-general model

Dependent users were compared with nondependent controls. On average, dependent users exhibited lower RD and JD values relative to nondependent controls in the hippocampus and amygdala, diffuse areas of the thalamus, and the right nucleus accumbens (Figure 2).

3.2 | Model II: Substance-specific model

For this model, individuals with dependence on multiple substances (~8%) were excluded, resulting in a reduced sample size of 1535 nondependent controls and 2085 dependent users. No significant differences emerged from comparisons of NicD vs nondependent controls, CocD vs nondependent controls, MetD vs nondependent controls, or CbD vs nondependent controls. However, AlcD demonstrated significantly smaller RD and JD values, particularly across bilateral hippocampus and putamen and the right amygdala and thalamus (Figure 3). These regions of significance roughly correspond to regions identified in Model I. Post hoc analysis on a smaller subsample of 171 AlcD participants (ie, the sample size of the smallest substance dependence group in our study) similarly showed significantly smaller RD and JD values relative to nondependent controls, suggesting that the observed alcohol-specific effect was not due to the comparatively larger AlcD sample relative to other substance-user groups in our study (n = 171-565).

3.3 | Model III: Nicotine-disambiguation model

Finally, model III was run to clarify the potential effect of NicD by minimizing the potential confounding influence of cigarette smoking in nondependent controls. Control participants recruited from all sites were separated into 918 nonsmoking controls, 189 smoking controls, after excluding participants without information on smoking status. These groups, and the group of 565 NicD participants that were originally recruited by sites that tested for smoking effects, were compared. NicD participants demonstrated significantly higher RD and JD values relative to nonsmoking controls, indicating greater volume and surface area across bilateral regions of the hippocampus, thalamus, putamen, and the right nucleus accumbens (Figure 4).

Similarly smoking controls (who were not assessed for nicotine dependence by the recruiting sites) demonstrated inflated structures relative to nonsmoking controls, across the hippocampus, thalamus, diffuse regions of the putamen, and the right nucleus accumbens (Figure 5). There was no significant difference between NicD and smoking controls.

Common regions of significance across both splits (ie, overlap) are reported in Table 2 as the percentage of significant vertices relative to the total number of vertices across each structure.

FIGURE 1 Overview of the vertex-wise shape metrics employed. A, 3D model of subcortical structures within the brain space. B, The radial distance (RD) of a structure corresponds to the distance between each surface vertex and the structure's medial skeleton. C, The Jacobian determinant (JD) corresponds to the deformation necessary to match the subject-specific structure to a template. A higher JD reflects a larger “surface area” relative to the template.
The striking alcohol-specific effect on subcortical structures (in particular, the striatal and limbic structures) is consistent with our previous ENIGMA study on gray matter volume in substance dependence, which demonstrated lower volume in widespread cortical and subcortical regions specific to alcohol dependence.26 The absence of a subcortical association with cocaine, methamphetamine, and cannabis is interesting given the literature implicating striatal and limbic structures in the development of dependence toward these substances.7,31 To ensure that the observed alcohol-specific effect was not due to the comparatively larger alcohol dependence sample (n = 830) relative to other substances (n = 171-565) in our study, we reran the substance-specific model with a subsample of 171 alcohol dependence users. Results remained consistent and significant, suggesting that alcohol dependence effect was robust, even across a much smaller sample. The individual effects of other illicit substances on brain morphology may be subtler than previously assumed.6,7,10 Alternatively, various moderating influences such as quantity of substance use and timed developmental exposure may be relevant in considering brain morphology as alcohol use typically starts earlier than the other illicit drugs (eg, 50% of those who ever used alcohol starts at age 14-21 years, compared with age 16-28 years for cannabis and cocaine32). Unfortunately, comparison of use level across different substances was not possible in the present samples, as similar substance use histories were not obtained on all subjects at the participating sites. An important goal for future studies will be to examine the impact of age of onset and lifetime quantity of use on morphological measures in alcohol dependence.

While nicotine dependence effects were not observed in model II when segregating users into their substance of choice, differences were observed in model III when comparing nicotine-dependent users to nonsmoking controls. The lack of effect of the former model may be due to the confounding influence of smoking status within the nondependent control sample. Control samples collected by sites that seek due to the confounding influence of smoking status within the nondependent control sample. Control samples collected by sites that seek
and methamphetamine) often do not account for smoking status in their samples or deliberately seek to match groups on cigarette use levels. By segregating nonsmoking and smoking controls, model III sought to tease apart the influence of occasional cigarette smoking relative to dependence. Finding greater RD and JD in nicotine-dependent users relative to nonsmoking controls in the hippocampus, putamen, and thalamus was in agreement with studies linking greater putamen volume with cigarette smoking, but in contrast to previous evidence of smaller thalamus and hippocampus in chronic cigarette smokers relative to nonsmokers. Some studies have also reported no thalamic or hippocampal volume difference in smokers relative to nonsmokers, reflecting the inconsistency of current evidence on nicotine dependence. By pooling a combined sample of 1672 subjects, adopting a more sensitive measure of vertex-level morphology, and requiring split-half replication, this study provides evidence for a reinterpretation of cigarette smoking-related effects on brain morphology.

FIGURE 2 Subcortical difference between individuals with substance dependence and nondependent controls. Bottom and top view of (a) local surface thickness (radial distance, RD) and (b) local area (natural logarithm of the Jacobian determinant, JD) differences across subcortical structures in the left (left) and right hemispheres (right), in individuals with substance dependence compared to nondependent controls. All effects controlled for imaging site, sex, and age. Heat maps represent beta-values of the significant regions in each split half (SPLIT 1 and SPLIT 2). Overlap in significance across both splits are colored in blue in the last column (OVERLAP).
The smoking-related effect was not only observed between nicotine dependence and nonsmoking controls but also between smoking controls (who were not diagnosed with a nicotine dependence) and nonsmoking controls, suggesting structural differences associated with use rather than dependence. The proposed exposure-related effect (as opposed to dependence-related effect) of cigarette smoking is supported by a study demonstrating a dose-dependent relationship between nicotine use and enlarged putamen volume. Nicotinic receptors, which are particularly densely located along regions where effects were observed (ie, hippocampus, thalamus, basal ganglia), and are paradoxically upregulated in response to chronic nicotine exposure, may underlie the observed morphological differences.

It is interesting to note that similar cigarette-smoking-related effects (ie, greater RD and JD in the hippocampus, thalamus, and putamen) are not apparent in other substance-dependent users in our sample, given the high comorbidity between cigarette smoking and...
and other substance use, particularly cannabis.\textsuperscript{42,43} Subcortical morphometry may be subject to an interactive effect between nicotine and other substance use. For example, the typically observed subcortical differences in users dependent on methamphetamine, cocaine, or cannabis\textsuperscript{6,7,10} may have been counteracted by an opposing cigarette-smoking effect. Unfortunately, the low number of methamphetamine-, cocaine-, or cannabis-dependent subjects who are also nonsmokers, and the lack of well-characterized smoking level information within these substance-dependent users prevents an interrogation of the interactive effect between cigarette smoking and other substance use/dependence in brain structural effects.

A key structure emerging from this comprehensive examination of substance-related subcortical morphology is the hippocampus, being notably implicated (up to >40\% of the structure’s surface) across the examined models. The hippocampus is a crucial structure for learning...

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**FIGURE 4** Subcortical difference between individuals with nicotine dependence and nonsmoking controls. Bottom and top view of (a) local surface thickness (radial distance, RD) and (b) local area (natural logarithm of the Jacobian determinant, JD) differences across subcortical structures in the left (left) and right hemispheres (right) in individuals with a nicotine dependence (NicD) compared with nonsmoking controls. All effects controlled for imaging site, sex, and age. Heat maps represent beta-values of the significant regions in each split half (SPLIT 1 and SPLIT 2). Overlap in significance across both splits are colored in blue in the last column (OVERLAP).
and memory—its function is central to substance-related memory processes including reinforcement learning and reinstatement of substance use. The observed hippocampal effect was mostly confined to the hippocampal head and inferior body of the left hippocampus, roughly coinciding with the cornu ammonis (CA1) and subicular regions. The CA1 is thought to be important for input integration and contains a high density of N-methyl-D-aspartate (NMDA) receptors that are modulated by substance use, in particular alcohol. Alcohol-associated NMDA effects are further thought to contribute to alcohol tolerance and dependence. The subiculum receives input from the CA1, and along with the CA1, provides the main hippocampal outflow to a range of cortical and subcortical sites. Both the CA1 and subiculum are particularly affected in neurodegenerative disorders such as Alzheimer’s disease, reflecting regional vulnerability to age-related atrophy, that may further be amplified by chronic alcohol abuse. Further, the anterior thalamic subregion was also found in
this study to be preferentially affected relative to other sub-regions of the thalamus. The anterior thalamus is primarily connected to the hippocampus and frontal cortex, with reduced thalamo-frontal projections and anterior thalamic volume being particularly associated with increased age and cognitive (attention and memory) decline. The anterior thalamus is primarily connected to the hippocampus, implicated in our study, is also argued to be important for reward learning, motivation, and decision-making, and therefore relevant in the early stages and acquisition of substance dependence (whereas the central amygdala is thought to be more involved in stress, negative reinforcement, and maintenance of dependence). The selective vulnerability of the anterior thalamus may further extend to alcohol dependence, as demonstrated by this study.

While effects observed in the amygdala were relatively small and diffuse, across both the lateral and basal regions, they were observed mostly in the right amygdala. This laterality effect is in line with previous studies demonstrating a stronger association between the right (vs left) amygdala with substance dependence, and risk for developing alcohol dependence. Findings from the latter study also suggest that an amygdala effect may precede dependence. The basolateral amygdala, implicated in our study, is also argued to be important for reward learning, motivation, and decision-making, and therefore relevant in the early stages and acquisition of substance dependence (whereas the central amygdala is thought to be more involved in stress, negative reinforcement, and maintenance of dependence). However, it should be noted that the cross-sectional nature of this study prevents us from confirming a causal role of subcortical differences across the trajectory of substance dependence. Large-scale, longitudinal studies that track the trajectory of brain development and substance use, such as the ABCD study (https://abcdstudy.org/), will be beneficial in clarifying the direction of association between substance use, dependence, and brain morphology.

The current findings should be interpreted in the light of several limitations. First, the datasets from multiple sites were collected under institutional review board (IRB) approval. Second, the datasets from multiple sites were collected under institutional review board (IRB) approval.
differing protocols and scanner sequences. The diagnostic instruments adopted by the imaging sites for segregating dependence from controls also differ. While these instruments are all validated and reliable, the inter-site differences may limit the specificity of study findings. This study attempted to mitigate the site issues in scanning and diagnosis by having a single rater visually inspect all subcortical reconstructions and by incorporating site factors in all the statistical models. Conversely, a benefit of making inference from multisite data is that findings might have greater generalizability to the wider population due to the collation of larger samples. A second concern of adopting a multisite approach is in the interpretability of findings, particularly in relation to the spectrum of dependence severity, lifetime use quantity, or other clinical variables of interest such as those that index quality of life and wellbeing. The latter is particularly relevant for their potential confounding influence on observed brain differences. For example, depressive symptoms and mood disorders, which are highly comorbid in substance dependence, have also been associated with alterations of subcortical volumes (e.g., reduction in hippocampal volume). However, as not all sites in the current study collected information on depressive symptoms, or adopted common instruments in measuring them, their confounding influence on the current study findings cannot be ruled out. Moving forward, a standardized approach to recruiting and testing future samples (i.e., wherein all future substance dependence studies should collect information on duration, frequency, and quantity of substance use, and mood and anxiety symptoms, at the minimum) will be beneficial to allow for standardization and comparisons across datasets. This approach may in turn facilitate collaboration and crosstalk across studies, in clarifying substance-general and substance-specific brain correlates.

To conclude, our comprehensive examination of subcortical morphology in the largest dependent user sample to date revealed significant alcohol and nicotine-specific effects on subcortical structures, in particular the hippocampus, thalamus, and putamen. By contrast, the effect of illicit substance dependence on brain volume was found to be minimal. Such findings might warrant a revised understanding of the structural correlates of addiction. It is possible that the brain-based effects of illicit substances may not be evident with morphological measurements, but may instead be confined to functional or connectivity-related differences.

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CONFLICT OF INTERESTS

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DATA ACCESSIBILITY

The summary data on which the analyses were performed are available from the corresponding author upon reasonable request.

AUTHORS CONTRIBUTION

PMT, PC, HG, and SM designed the study. BG and CRKC designed the study’s method. AB, SB, SB, EC, JC, AD, JF, AEG, RH, KH, NJ, AMK, OK, CSRL, EDL, VL, ML, RMS, SM, RM, AM, CO, MPP, GP, LR, LS, RS, NS, DJS, EAS, DT, AU, RVH, DJV, AVG, RWW, and MY collected the study’s method. AB, SB, SB, EC, JC, AD, JJF, AEG, RH, KH, NJ, AMK, AUTHORS CONTRIBUTION

The first draft with close input from SM and HG. All other authors provided intellectual feedback on the final draft.

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REFERENCES


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