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Chronic radon exposure is associated with developmental alterations to neural and behavioral indices of cognitive control

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Abstract

Radon is a prevalent, naturally occurring gas which contributes to radiation within the environment and is the second-leading cause of lung cancer worldwide. Although many environmental toxins have been linked to maladaptive neurodevelopmental outcomes in children and adolescents, radon has seldom been examined for its effects on the developing brain. This study aimed to investigate the effects of chronic home radon exposure on top-down neural processes of cognitive control in youths. Fifty-nine participants (aged 6–14 years) completed a Simon interference task during magnetoencephalography (MEG), and radon levels were measured in their homes. MEG data were transformed into time-frequency space and significant oscillatory responses relative to baseline were imaged condition-wise and then subtracted to isolate the Simon interference effect (i.e., Simon-control). Whole-brain linear regressions indicated that children with greater radon exposure exhibited aberrant oscillatory activity in widespread networks related to attentional control. We also found that radon exposure moderated the developmental trajectory of theta and gamma oscillations underlying selective attention in frontoparietal cortices and other regions. Further, mediation analyses showed that the neural interference effects within cerebellar and extended motor cortices mediated the relationship between radon exposure and behavioral outcomes. Additionally, we found the mediating effects of neural interference within the left superior frontal

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Declaration of competing interest

The authors declare that they have no competing interests.

CRediT authorship contribution statement

Haley R. Pulliam: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Christine M. Embury:** Writing – review & editing, Software. **Maggie P. Rempe:** Writing – review & editing, Software. **Hannah J. Okelberry:** Writing – review & editing, Data curation. **Danielle L. Rice:** Writing – review & editing, Data curation. **Anna T. Coutant:** Writing – review & editing, Data curation. **Ryan Glesinger:** Writing – review & editing, Data curation. **Tony W. Wilson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Brittany K. Taylor:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

gyrus and precuneus on the relationship between age and task accuracy were dependent on radon exposure. These data are among the first to demonstrate radon-related disruptions to the normative development of the neural substrates supporting cognitive control processes. Further, these disruptions have direct implications on observable behavior.

Keywords

Neurotoxicology; Radon; Neurodevelopment; Magnetoencephalography; Cognitive control; Simon effect

1. Introduction

Cognitive control is a broad umbrella term capturing a myriad of neurocognitive abilities that are integral to everyday functioning. These cognitive abilities, including selective attention and conflict resolution, and the neural substrates that support their efficacy rapidly mature throughout childhood and adolescence (Konrad et al., 2005; Petersen and Posner, 2012; Rueda et al., 2004). Various paradigms have been used to investigate cognitive control across development (Eriksen and Eriksen, 1974; Forstmann et al., 2008; Lanssens et al., 2019; Peterson et al., 2002; Simon and Rudell, 1967; Stroop, 1935; Wang et al., 2014; Yi and Kim, 2020), including the Simon task, which probes stimulus-response interference (Simon and Rudell, 1967). As stimuli are presented in different locations, participants must overcome interference from the spatial information of the stimulus (task-irrelevant) and the spatially mapped behavioral response (task-relevant). Through childhood and adolescence, youths mature from utilizing diffuse brain areas to more refined neural networks to support conflict resolution during selective attention (Abundis-Gutiérrez et al., 2014; Konrad et al., 2005). As these systems mature, there is also a decrease in behavioral and neural interference effects (Brodeur and Enns, 1997; Taylor et al., 2021).

Past research using the Simon interference task and others that probe selective attention has identified key neural regions serving the development and refinement of interference control. Notably, networks spanning lateral prefrontal, posterior parietal, premotor, and cingulate cortices, as well as the supplementary motor area (SMA) and frontal eye fields (FEFs) have been shown to support developmental improvements in processing and adapting to interference (Bush and Shin, 2006; Lanssens et al., 2019; McDermott et al., 2017; Peterson et al., 2002; Yi and Kim, 2020). Functional imaging studies using magnetoencephalography (MEG) during a Simon task have identified theta and alpha activity in attentional networks as well as interference effects in both oscillatory bands in a sample of adults (Son et al., 2023). They have also noted that interference-related changes in multispectral dynamics are robustly associated with increasing age in youths. In a developmental sample, condition-wise differences were found in the alpha and gamma bands. Specifically changes in connectivity interference effects with increasing age were identified in the cerebellum, occipital cortex, and left temporoparietal junction (TPJ; (Son et al., 2024)). P-Importantly, these developmentally sensitive neural dynamics supporting cognitive control are also modulated by numerous other individual differences, including sex and variability in

neurobehavioral health domains like impulsivity and hyperactivity (Killanin et al., 2020; Picci et al., 2023; Taylor et al., 2021).

The developmental sensitivity of these neural processes and the substrates that support them are of critical interest when considering the acute sensitivity of youth to the dangerous consequences of chronic environmental toxin exposures (Bearer, 1995; Perera et al., 2006). Environmental exposures, ranging from inhaled air pollutants (Chiu et al., 2016; Peterson et al., 2015) to heavy metals (e.g., lead, manganese; Sanders et al., 2015; Silver et al., 2016) have been connected to a breadth of neurocognitive decrements in children and adolescents. Exposure to these toxins is associated with atypical development of brain structure and sensory systems (Silver et al., 2016), increased risk for anxiety and mood disorders (Bornschein et al., 2006), and impaired cognitive functioning, including detriments to attentional control and memory processes (Chiu et al., 2016; Liu and Lewis, 2014; Perera et al., 2006; Sanders et al., 2015). Further, increased risk for learning and neurocognitive disorders, including ADHD, has been broadly reported in youths with greater toxic exposure (Myhre et al., 2018; Sanders et al., 2015). Despite clear links in the literature between numerous toxic environmental exposures and neurodevelopmental aberrations, the effects of some extremely common toxins are relatively unknown. One particularly understudied toxin is radon gas.

Radon is a ubiquitous, odorless, and colorless gas that originates from naturally occurring uranium decay (Clement et al., 2010; Darby et al., 2005; Kang et al., 2019; Vogeltanz-Holm and Schwartz, 2018). It can seep into buildings where its concentration can reach hazardous levels over time (Sethi et al., 2012; Vogeltanz-Holm and Schwartz, 2018). Of particular importance is its accumulation in homes, where people spend most of their time (Laquatra and Laquatra, 2018; Riudavets et al., 2022). This is especially true for children and adolescents, a group who are already more susceptible to the dangerous effects of environmental toxins (Kendall et al., 2021). In fact, 1 in 15 homes within the United States are estimated to have an indoor radon concentration which exceeds 4.0 pCi/L, the action limit recommended by the Environmental Protection Agency (EPA; United States Environmental Protection Agency, 2016). Despite its prevalence and recommendations from the EPA and Department of Health and Human Services, public knowledge of the dangers of radon exposure is severely lacking (Novilla et al., 2021; Vogeltanz-Holm and Schwartz, 2018).

Radon exposure is associated with numerous health consequences ranging from lung cancer (Sethi et al., 2012; Vogeltanz-Holm and Schwartz, 2018) to neurodegenerative diseases in adulthood (Gómez-Anca and Barros-Dios, 2020; Zhang et al., 2022). Importantly, recent work in youth found radon-related increases in certain inflammatory biomarkers (Taylor et al., 2022) commonly linked to decrements in neurocognitive development (Ehrlich et al., 2021; Loftis et al., 2020; Miller et al., 2009). Further, elevated levels of radon exposure have been associated with difficulties in the domains of self-and emotion-regulation in children and adolescents (Taylor et al., 2024), as well as critical differences in the developmental trajectory of gross brain structure (Smith et al., 2024) and neural oscillatory dynamics serving attentional reorienting (Pulliam et al., 2024). Although numerous studies have linked radon exposure to concerning health outcomes, there is a lack of investigation

into the breadth of possible deleterious effects of home radon exposure on neurocognitive functioning in youths.

The present study investigated how chronic home radon exposure impacts the developmental trajectory of the neural oscillatory dynamics underlying cognitive control, and more specifically, Simon-type interference. A sample of typically-developing children and adolescents completed a modified Simon task during high-density MEG. Radon test kits were used to measure the radon concentration within their homes to derive a total radon exposure index. We predicted there would be multispectral aberrations in task-related neural dynamics that scale with exposure given their broad developmental sensitivity. We further hypothesized that children with higher radon exposure would exhibit detectable decrements in neural and behavioral interference effects compared to their lesser-exposed peers, and that these differences would change as a function of age in this developing sample.

2. Methods and materials

2.1. Participants

We studied 59 healthy youth aged 6- to 14-years-old (mean: 10.62 ± 2.59 years, 30 females) who were recruited from the local community. The sample was comprised of a subset of participants recruited for an ongoing NIH-funded longitudinal study (R01-MH121101), which aims to characterize the development of neural dynamics in high-order cognitive networks across the sensitive period of childhood and adolescence. All participants were typically developing, without any history of head trauma, neurological or psychiatric disorders, or other disorders affecting brain function. Participants were excluded according to general MEG/MRI exclusionary criteria such as the presence of metal implants, dental braces, permanent retainers, and/or any type of ferromagnetic non-removable devices. Inclusion/exclusion were confirmed through participant interviews involving the child and parent. After a complete description of the study, written informed consent was obtained from the legally authorized representative of each participant, and participants provided assent. All procedures were approved by the Institutional Review Board.

2.2. Radon data collection

Families were provided with a commercial short-term home radon testing kit (<https://www.radon.com/>). This test kit is a standard carbon-based envelope that hangs on an interior wall on the lowest livable level of the home for three to seven days. After the testing period, the envelope is sealed and dropped in the mail for processing at a commercial lab. Parents were given the test kit along with instructions from the commercial vendor for proper deployment. We instructed families to leave the kit exposed for approximately four days. Our lab and the family each received a copy of the home radon results. In the case that a result exceeded the EPA action limit for mitigation (4 pCi/L), the principal investigator (BKT) called the family to ensure they understood the results and provided additional information on radon safety and local resources.

In addition to completing the radon test kit, parents completed a questionnaire probing information about how long the child had lived in the home, the construction of their

home, and other details to help characterize home radon exposure. We used the information about how long the child had lived in the home to compute a radon exposure index. Specifically, each child's individual radon exposure index was computed as the natural log of the measured home radon concentration multiplied by the duration that the child had lived in the home (in years), plus one to account for the natural log transform (see Eq. (1) below; (Pulliam et al., 2024; Smith et al., 2024; Taylor et al., 2022, 2024). This radon exposure index (REI) was used in subsequent analyses exploring the associations between chronic home radon exposure and neural dynamics. The decision to utilize this metric of cumulative exposure, as opposed to simply using the home radon concentration as a more instantaneous measure of exposure, is aligned with recommendations from the literature exploring the impacts of ionizing radiation on multiple aspects of health, including neurocognitive impacts (e.g., (Azizova et al., 2020; Dinocourt et al., 2017; Duan et al., 2015)).

$$\text{Radon exposure index} = \ln([\text{time lived in home}] * [\text{home radon concentration}]) + 1 \quad (1)$$

2.3. Experimental paradigm

Participants completed a number-based version of a modified Simon task (Fig. 1; (Son et al., 2023, 2024; Wiesman et al., 2020; Wiesman and Wilson, 2020b) during MEG recording. Participants were instructed to maintain fixation on a centrally presented crosshair throughout the task. Each trial began with the presentation of only the crosshair on a grey background for 2200 ms (± 200 ms). Next, a row of three equally-spaced integers between 0 and 3 appeared for 1500 ms. Two of these integers were identical (task-irrelevant zeros), while the other integer was different (i.e., the target). Participants pressed buttons representing the numbers 1, 2, and 3, using their index, middle, and ring finger, respectively. Upon appearance of the stimulus (i.e., row of three integers), they were instructed to press the button corresponding to the numerical identity of the “odd-number-out,” *not* its spatial location. Youths were also instructed that speed and accuracy were important during this task. Each participant completed two blocks, one of each task condition: a control condition without spatial interference (e.g., “0 2 0”) and a Simon condition with spatial interference (e.g., “2 0 0”). Each block contained 100 trials of a single condition, resulting in a combined recording time of ~12 min. Conditions were counterbalanced across the sample. Custom stimuli were programmed in MATLAB (MathWorks Inc.) using *Psychophysics Toolbox Version 3* (Brainard, 1997) and projected onto a nonmagnetic screen. To assess behavioral results, we computed accuracy as a percentage (correct trials/total trials), as well as reaction time (RT) for each correct trial.

2.4. MEG data acquisition

Recordings were conducted in a one-layer magnetically shielded room with active shielding engaged. With an acquisition bandwidth of 0.1–330 Hz, neuromagnetic responses were sampled continuously at 1 kHz using a MEGIN MEG system with 306 magnetic sensors (Helsinki, Finland). MEG data from each participant were individually corrected for head motion and subjected to noise reduction using the signal space separation method with a temporal extension (Taulu et al., 2005; Taulu and Simola, 2006).

2.5. Structural MRI acquisition, processing, and coregistration with MEG data

Preceding MEG recording, four coils were attached to the participant's head and localized, together with the three fiducial points and scalp surface, with a 3D digitizer (Fastrak; Polhemus Navigator Sciences, VT). Once the participant was positioned for MEG recording, an electric current with a unique frequency label (i.e., 322 Hz) was fed to each of the coils. This induced a measurable magnetic field and allowed each coil to be localized in reference to the sensors throughout the recording session. Since coil locations were also known in head coordinates, all MEG measurements could be transformed into a common coordinate system. With this coordinate system, each participant's MEG data were coregistered with their structural T1-weighted neuroanatomical data prior to source space analyses using BESA MRI (Version 2.0; BESA GmbH, Gräfelfing, Germany). Structural T1-weighted MR images were acquired using a Siemens Prisma 3T MRI scanner with a 32-channel head coil and a MP-RAGE sequence with the following parameters: TR = 2400 ms; TE = 1.94 ms; flip angle = 8°; FOV = 256 mm; slice thickness = 1 mm (no gap); voxel size = 1 × 1 × 1 mm. All structural MRI data were aligned parallel to the anterior and posterior commissures and transformed into standardized space, along with the functional images, after beamforming.

2.6. MEG time–frequency transformation and statistics

Cardiac and ocular artifacts (e.g., blinks, eye movement) were removed from the data using signal-space projection (SSP), which was accounted for during source reconstruction (Uusitalo and Ilmoniemi, 1997). MEG data were then analyzed with respect to the target stimulus to evaluate the oscillatory dynamics associated with attentional processing. To evaluate the higher order responses involved in attention, the continuous magnetic time series was divided into epochs of 3500 ms duration, with the onset of the stimulus being defined as 0 ms and the baseline being defined as −500 to 0 ms. Note that the baseline period was selected to prevent motor responses from the prior trial from “contaminating” the baseline. Epochs containing artifacts were rejected based on a fixed threshold method, supplemented with visual inspection. In brief, for each individual, the distribution of amplitude and gradient values was computed across all trials, and those trials containing the highest amplitude and/or gradient values relative to the full distribution were rejected by selecting a threshold that excluded extreme values. Importantly, these thresholds were set individually for each participant, as interindividual differences in variables such as head size and proximity to the sensors strongly affects MEG signal amplitude. Additionally, we visually inspected the data to identify trials contaminated with other types of artifacts, such as those produced by muscle tension, and rejected such trials. On average, 78.38 ± 8.56 control trials and 68.60 ± 9.98 Simon trials per participant remained after artifact rejection. We determined whether the number of trials remaining varied as a function of condition or any of our predictors of interest (i.e., age, radon exposure, and their interaction) using a repeated measures ANCOVA (2-way within-person factor of Condition: control, Simon). There were no significant main effects or interactions ($ps = 0.25$ to 0.91).

Artifact-free epochs were transformed into the time-frequency domain using complex demodulation with a resolution of 1 Hz and 50 ms, and the resulting spectral power estimations per sensor were averaged across all trials to generate time-frequency plots of mean spectral density. These sensor-level data were then normalized with respect to baseline

power, which was calculated as the mean power between -500 and 0 ms prior to target onset. Of note, this normalization was performed separately for each 1 Hz by 50 ms bin within each spectrogram using the corresponding baseline data.

The time-frequency windows used for imaging were determined by statistical analysis of the sensor-level spectrograms across all trials (control and Simon), gradiometers, and participants. Each data point (i.e., 1 Hz by 50 ms bin) in the spectrogram was initially evaluated using a mass univariate approach based on the general linear model. To reduce the risk of false positive results while maintaining reasonable sensitivity, a two-stage procedure was followed to control for Type 1 error. In the first stage, paired-sample t -tests against baseline were conducted on each data point and the output spectrogram of t values was thresholded at $p < .05$ to define time-frequency bins containing potentially significant oscillatory deviations across all participants. In stage two, time-frequency bins that survived this threshold were clustered with temporally and/or spectrally neighboring bins that were also significant, and a cluster value was derived by summing all the t values of all data points in the cluster. Nonparametric permutation testing was then used to derive a distribution of cluster values and the significance level of the observed clusters (from stage one) were tested directly using this distribution (Ernst, 2004; Maris and Oostenveld, 2007). For each comparison, 1000 permutations were computed to build a distribution of cluster values. Based on these analyses, only the time-frequency windows that contained significant oscillatory events across all trials were subjected to the beamforming (i.e., imaging) analysis. Thus, a data-driven approach was utilized for selecting the time-frequency windows to be imaged. See Wiesman and Wilson [2020a] for a complete description of this approach.

2.7. MEG source imaging and statistics

Cortical dynamics were imaged through an extension of the linearly constrained minimum variance vector beamformer (Gross et al., 2001; Hillebrand et al., 2005; Van Veen et al., 1997), which applies spatial filters to time-frequency sensor data to calculate voxel-wise source power for the entire brain volume. Such images are typically referred to as pseudo- t maps, with units (pseudo- t) that reflect noise-normalized power differences (i.e., active vs. passive) per voxel. Following convention, the source power in these images was normalized per participant using a separately averaged pre-stimulus noise period (i.e., baseline) of equal duration and bandwidth (Hillebrand et al., 2005). MEG preprocessing and imaging used the Brain Electrical Source Analysis (version 7.0) software.

Normalized source power was computed for the selected time-frequency bands over the entire brain volume per participant at $4.0 \times 4.0 \times 4.0$ mm resolution. Each participant's functional images were transformed into standardized space using the transform that was previously applied to the structural images and then spatially resampled. The resulting 3D maps of brain activity were derived separately for control and Simon conditions. Within each condition, maps were averaged across participants to assess the anatomical basis of the significant oscillatory responses identified through the sensor-level analysis. To identify the effect of Simon-type interference on oscillatory responses, we subtracted the control

condition maps from the Simon maps voxel-by-voxel per participant and the resulting interference maps were used in our primary analyses.

To assess associations between chronic home radon exposure, age, and neural oscillatory dynamics, we computed whole-brain linear regressions (one for each of the oscillatory bands of interest) using the radon exposure index, age, and their interaction as predictors of interest, and the Simon effect map of each oscillatory band as the dependent measure of interest. We mean-centered our predictors of interest to account for potential multicollinearity considering the interaction term. To account for multiple comparisons, a significance threshold of at least $p < .005$ was used for the identification of significant clusters in all whole-brain statistical maps, accompanied by a stringent cluster (k) threshold of more than 5 contiguous voxels of $4 \times 4 \times 4$ mm (i.e., $> 320 \text{ mm}^3$). These analyses, performed in SPM 12, yielded F maps showing significant clusters with main effects of age, radon exposure, and their interaction. We report the standardized beta coefficients for significant associations identified in the F maps for interpretability of the effects. Pseudo- t values were extracted from the peak voxels of each significant cluster per participant to further probe effects of interest, which were FDR corrected. In particular, we used the Interactions (Long, 2019) and JTools (Long, 2023) packages in R (version 4.3.3) to probe age-by-radon interactions. Of note, because the current investigation is focused on the effects of radon exposure, only the main effects of radon and the radon-by-age interaction are reported in the main text. Main effects of age are reported in the Supplementary Materials.

Finally, we performed mediation analyses to test the degree to which radon-related aberrations in the neural oscillatory dynamics serving attentional processing were functionally relevant. Specifically, for clusters identified with main effects of radon, we examined whether oscillatory activity measured at the peak of each identified cluster in the primary analysis mediated the relationship between chronic radon exposure and task performance (i.e., reaction time and accuracy). For clusters exhibiting radon-by-age interactions, we modeled moderated mediations and probed whether activity in the cluster mediated age-to-behavior relationships, with radon exposure moderating the relationship between age and neural activity. Because traditional tests of indirect effects (e.g., the Sobel test) often violate the assumption of normality, we utilized asymmetrical confidence intervals which best represent the true distribution of the indirect effect (i.e., the product of coefficients from the “a” and “b” paths). Thus, we examined the 95 % confidence intervals of bias-corrected bootstrapped confidence intervals based on 1000 bootstrapped samples to more rigorously detect any potential relationships between brain activity and behavior (Austin and Tu, 2004; Efron and Tibshirani, 1986; Fritz and MacKinnon, 2007), which provide a robust estimate of mediation effects and are asymmetrical (Fritz and MacKinnon, 2007). Mediation analyses were conducted in JASP version 18.3.

3. Results

3.1. Behavioral analysis

Twelve participants were excluded from all analyses due to low accuracy (less than 60 % correct in the Simon task). Individuals who were excluded based on poor performance

did not differ from the final included sample on sex ($\chi^2 = 0.004$, $p = .95$), home radon concentrations ($U = 249.00$, $Z = -0.622$, $p = .53$), or radon exposure index values ($t = 1.62$, $p = .11$, Cohen's $d = 0.52$). However, those excluded were generally younger than the final evaluable sample ($t = 4.84$, $p < .001$, Cohen's $d = 1.57$). The remaining 47 participants performed well, responding accurately to an average of 95.10 % ($SD = 6.43$ %) of the control trials and 83.53 % ($SD = 10.66$ %) of the Simon trials (Fig. 2A). Of the evaluable sample, six were left-handed. Children who were left-handed did not differ from those who were right-handed on reaction times or accuracy during the task ($t = -0.627$ to 0.412 , $ps = 0.534$ to 0.808 , Cohen's $ds = -0.274$ to 0.180). The average reaction time was 707.66 ms ($SD = 146.78$ ms) for control trials and 800.81 ms ($SD = 139.21$ ms) for Simon trials (Fig. 2B). Using two repeated measures ANCOVAs (2-level within person factor of Condition: control, Simon), we examined associations between the measures of interest (i.e., age, radon exposure, and their interaction) and both accuracy and reaction time during the task. We found a main effect of age on accuracy ($F(1, 46) = 9.25$, $p = .004$, $\eta^2_p = .16$) and reaction time ($F(1, 46) = 10.11$, $p = .003$, $\eta^2_p = .18$), such that older children were generally more accurate and responded faster than younger children. There were no other main effects or interactions (accuracy: $ps = 0.07$ to 0.50 ; reaction time: $ps = 0.51$ to 0.99).

3.2. Home radon exposure

The raw result of the radon tests ranged from 0.3 to 33.3 pCi/L with an average of 6.28 pCi/L ($SD = 7.32$). Every family also reported how long the children had lived in their current home. Each child had been exposed to the recorded radon level for an average of 3.92 years ($SD = 3.22$, $range = 0$ to 12.4 years). As stated in the Methods, we computed a radon exposure index for each participant by combining the recorded home radon concentration and the duration of time that the child had lived in their home. The resultant radon exposure index had an average of 2.38 ($SD = 1.29$), ranging from 0 to 5.94.

3.3. Sensor-level analysis

Statistical analysis of the time-frequency spectrograms revealed significant clusters of theta (3–6 Hz), alpha (8–12 Hz), beta (14–18 Hz), and gamma (78–96 Hz) oscillatory activity primarily in posteriorly-positioned gradiometers across all participants and conditions ($p < .05$, corrected; Fig. 3). Significant theta activity began shortly after the onset of the target stimulus (0 ms = target onset) and tapered off about 400 ms later (i.e., from 150 to 550 ms). In the alpha range, significant activity emerged roughly 400 ms after target onset and continued for about 200 ms before dissipating (i.e., from 400 to 600 ms). Significant beta activity emerged earlier and lasted about 250 ms (i.e., from 200 to 450 ms). Lastly, significant activity in the gamma range emerged shortly after target presentation and dissipated after about 200 ms (i.e., from 100 to 300 ms).

3.4. Beamformer analysis

To identify the brain regions generating the significant sensor-level oscillations, these time frequency windows were imaged using a beamformer for each condition (Simon, control). The resulting whole-brain images were examined, and outliers with significant artifactual activity were excluded. The resulting maps were grand averaged across participants, and these responses are shown in Figure 3. Strong oscillations were observed across all trials in

gamma activity (78–96 Hz) from 100–300 ms in the bilateral visual cortices. Strong beta (14–18 Hz, 200–450 ms) and alpha (8–12 Hz, 400–600 ms) responses were also evident in the bilateral visual cortices, with alpha activity extending up into parietal cortices as well. Lastly, a strong cortical network of theta oscillations (3–6 Hz) appeared across the frontal and parietal lobes during the 150 to 550 ms window.

To determine the effect of home radon exposure on the oscillatory activity underlying selective attention, subtraction maps were calculated by subtracting the whole-brain voxel-wise control condition maps from the Simon condition maps. The resulting “Simon effect” interference maps for each participant were then subjected to whole-brain linear regressions with age, radon, and the radon-by-age interaction as predictors of interest. In the following sections, we report the main effects of radon and the radon-by-age interaction effects. Main effects of age are reported in the Supplementary Materials.

3.5. Main effects of radon

Our whole-brain linear regressions revealed multiple main effects of radon exposure on the neural oscillatory dynamics supporting Simon-type cognitive control, accounting for the effects of age (Table 1). In the theta band, there was a main effect of radon in the left inferior occipital gyrus (IOG), left lateral occipital cortex (LOC), right cerebellum, right middle frontal gyrus (MFG), and right parahippocampal gyrus (Fig. 4). Within these regions, greater radon exposure was associated with a reduced Simon effect compared to those with lower exposure. Generally, youths with greater radon exposure exhibited stronger theta oscillations for control trials (β s = 0.178 to 0.510) and weaker for Simon trials (β s = -0.271 to -0.342).

Within the alpha band (Fig. 4D–F; Table 1), there was a main effect of radon exposure on the neural Simon effect in the left posterior cingulate cortex (PCC), left inferior temporal gyrus (ITG), right precentral gyrus, right middle temporal gyrus (MTG), and three clusters in the right dorsolateral prefrontal cortex (dlPFC). Above and beyond the effect of age, youths with greater radon exposure exhibited a reduced Simon effect with weaker (i.e., less negative) alpha oscillations for the Simon trials compared to control trials. Specifically, alpha responses during the control trials became stronger as a function of increasing radon exposure in the right precentral gyrus and two of the dlPFC clusters (labelled “B” and “C” in Table 1; β s = -0.376 to -0.580, $p_{FDRS} < 0.001$ to 0.024). In the rest of the regions, there was no change in alpha responses during control trials as radon exposure increased ($p_{FDRS} = 0.13$ to 0.769). In contrast, alpha responses during Simon trials became weaker with greater radon exposure (β s = 0.343 to 0.628, $p_{FDRS} < 0.001$ to 0.050), nearing negligible levels during these trials, or did not change as a function of radon, as in the right precentral gyrus and one cluster in the dlPFC (labeled “B” in Table 1; β s = 0.244 and 0.248, $p_{FDRS} = 0.156$).

Lastly, main effects of radon were revealed within the gamma band (Fig. 4G–I; Table 1) in the right supplementary motor area (SMA), right ventromedial prefrontal cortex (vmPFC, Fig. 4H), left precentral gyrus, and left calcarine sulcus (Fig. 4G, H). In these regions, youths with greater radon exposure exhibited an increased neural Simon effect, accounting for effects of age. In the left precentral gyrus, right vmPFC, and right SMA, this effect was driven by weaker gamma responses as a function of radon exposure during control trials (β s = -0.461 to -0.600, $p_{FDRS} < 0.001$ to 0.010). In all regions, there was no significant change

in gamma activity during Simon trials ($\beta_s = 0.250$ to 0.325 , $p_{FDRs} = 0.080$ to 0.169) as radon exposure increased. Finally, we did not detect any significant main effects of radon exposure in the beta band.

3.6. Radon-by-Age interaction

We also found multiple brain regions where radon exposure modulated the effect of age on the theta and gamma oscillatory dynamics serving selective attention (Table 2). These interactions were unpacked using the interactions pack in R, using mean and $\pm$ one standard deviation of the radon exposure index to examine the relationships further. In the theta band, our whole-brain linear regression revealed significant radon-by-age interactions in the left TPJ and MTG (Fig. 5). In the left TPJ, youths with the lowest exposure exhibited a weaker Simon effect with increasing age, whereas those with the greatest radon exposure showed significantly stronger Simon effects with greater age. Individuals with only moderate levels of radon exposure showed no change in Simon interference activity across development (Fig. 5D–F). In contrast, the developmental trajectory of the neural Simon effect in the left MTG was significantly moderated by moderate-to-high levels of radon exposure. Specifically, among individuals with low levels of radon exposure, there was minimal change in the Simon effect as a function of age, whereas those with moderate-to-high levels of radon exposure exhibited significantly stronger Simon effects across development (Fig. 5A–C).

In the gamma band, there were significant radon-by-age interaction effects in the left middle occipital gyrus (MOG) near primary visual cortex, left superior frontal gyrus (SFG), right SMA, left precuneus, and right superior parietal lobule (SPL). Across all clusters except for the right SPL, youth with lower levels of radon exposure tended to show a stronger Simon effect as a function of age. However, with increasing radon exposure, there was a reversal in the developmental trajectory such that youth with the greatest exposure exhibited a decreased, or even inversed Simon effect with increasing age (Fig. 6A–C). The right SPL showed the opposite pattern. Youths with lower levels of radon exposure tended to show decreases in their neural Simon effect with increasing age, whereas those with greater radon exposure exhibited stronger interference effects over time (Fig. 6D–F).

3.7. Relationships to behavior

Lastly, we performed a set of mediation analyses to examine the relationships between home radon exposure, the neural Simon effect, and behavioral metrics of task performance. Specifically, we investigated whether the neural Simon effects in regions demonstrating radon-related aberrations mediated the relationship between radon exposure or the radon-by-age interaction and task reaction time (RT) and accuracy Simon effects (i.e., RT for Simon – RT for control trials; accuracy for Simon – accuracy for control trials). For each time-frequency band of interest, we tested a separate model including all significant clusters of response-related activity as mediators with RT and accuracy Simon effects as outcomes (Fig. 7).

We found multiple significant indirect effects on behavior, all of which are detailed in Table 3. Notably, radon-related aberrations in theta interference effects measured in the right

cerebellum, as well as gamma interference effects in the right SMA and left precentral gyrus, were all related to improved behavioral performance (i.e., smaller differences in performance between control and Simon trials). We also detected two instances of moderated mediation, such that radon exposure modulated the indirect effect of age on task performance via gamma responses. In the left SFG, the indirect effect of age on behavior became progressively more negative as a function of increasing radon exposure. Younger children with greater radon exposure tended to show robust neural Simon effects in the SFG, which progressively decreased as a function of age. These age-related decreases in neural Simon effects predicted more similar performance across task conditions. In contrast, the indirect effect of age on task behavior via the precuneus was only present among youth with relatively low levels of radon exposure. Specifically, younger children with relatively low exposure tended to show an inverse Simon effect (i.e., control > Simon), which reversed with age. The age-related emergence of a "traditional" neural Simon effect (i.e., Simon > control) was associated with a lesser behavioral Simon effect among these youth.

4. Discussion

The present study investigated the impact of chronic indoor radon exposure on the developmental trajectory of the neural oscillatory dynamics serving aspects of cognitive control, namely selective attention and conflict resolution, during Simon-type interference. We found multispectral aberrations related to radon exposure in this sample of children and adolescents within regions involved in early sensory processes, as well as more eloquent cortices involved in higher order cognition. Within the theta and gamma oscillatory bands, radon exposure also moderated the typical development of these neural processes within a distributed network imperative for attentional control. Further, the interference-related neural dynamics in many of these regions mediated the relationship between radon exposure and behavioral outcomes, and in several instances, radon exposure moderated the indirect effect of age on task behavior via neural aberrations. We discuss each of these findings and their implications below.

We found main effects of radon exposure on the neural oscillations within theta, alpha, and gamma bands across distributed network. Many of these aberrations were present in areas of cortex involved in the early processing of stimuli or motor planning. For instance, we noted radon-related changes in neural interference effects within occipital and motor cortices, suggesting that radon exposure may have important impacts on processes critical for properly deciphering stimuli and making a motor plan to overcome Simon-type interference and execute an accurate response. These radon-related aberrations are noteworthy given past research, which has detailed the association between interference-resolution and oscillations occurring within occipital cortices (Proskovec et al., 2018; Wiesman and Wilson, 2020b), precentral gyri (Forstmann et al., 2008; Yi and Kim, 2020), and the SMA (Peterson et al., 2002; Proskovec et al., 2018). The SMA is of particular interest in the context of the stimulus-response interference involved in the Simon task (Wiesman et al., 2020). This region is critical in resolving conflict between multiple responses that compete for activation, overriding the prepotent response, and executing a motor plan which reflects the accurate response (Forstmann et al., 2008; Yi and Kim, 2020). Importantly, in the present study, neural interference effects in the right SMA and left precentral gyrus mediated

the relationship between radon exposure and task behavior, suggesting that radon-related aberrations in neural processes within sensory and motor systems directly impact efficient motor planning and observable behavior. These exposure-related changes in neurobehavioral relationships may have lasting consequences to downstream neurocognitive functioning and abilities for these youths.

In addition to impacts on sensory and motor systems, we noted several main effects of radon exposure across a myriad of regions critical for attentional control and higher order cognitive processes. Specifically, we found radon-related changes in neural Simon interference effects spanning frontal and temporal cortices. Impacted regions included the right MFG, vmPFC, and multiple clusters in the dlPFC, all which have been implicated in executive control processes within both children and adults (Konrad et al., 2005) and are expected to show interference-related activity during the Simon task and similar paradigms (Bush and Shin, 2006; Peterson et al., 2002). Studies have shown that these areas of the prefrontal cortex are critical in top-down modulation of selective attention (McDermott et al., 2017; Son et al., 2023), attentional orienting (Petersen and Posner, 2012; Picci et al., 2023), and inhibition of prepotent responses (Aron et al., 2004, 2014; Wiesman and Wilson, 2020b), guiding behavior accordingly.

In alpha and theta bands, youths with greater radon exposure exhibited a decreased or reverse Simon effect across frontal cortices which may point to a depletion of resources when compensating for the increased cognitive load of the harder condition. These findings are in line with the compensation-related utilization of neural-circuits hypotheses (i.e., CRUNCH), which explains neural processes in older adults that support compensation to match performance of their younger counterparts (Reuter-Lorenz and Cappell, 2008). More specifically, older adults are able to improve performance under instances of low cognitive load through increased recruitment of key neural substrates, but under higher cognitive demand, they reach a resource ceiling and thus are unable to efficiently process the more difficult stimuli and act accordingly (Reuter-Lorenz and Cappell, 2008). A similar explanation may apply to our sample of youths with greater radon exposure. Despite no differences in task behavior, children with more exposure are dedicating more neural resources to cognitive control. This could have implications for their ability to complete real-world tasks that are more complex and/or cognitively demanding. Further, these indications of developmental delay may impact overall cognitive reserve across a lifetime in which they may continue to be exposed to radon.

In contrast to our findings of weaker/reversed Simon effects in the theta and alpha bands, findings in the gamma band demonstrated stronger interference effects. More specifically, youths with greater radon exposure exhibit weaker gamma activity in the right vmPFC during the control condition than their lesser exposed peers, which may point to altered inhibitory function in this critical region for attentional control given the relationship between gamma oscillations and local inhibitory circuits (Bryson et al., 2020; Kelsom and Lu, 2013; Köster and Gruber, 2022). These findings could suggest that youths with greater exposure may have aberrant cortical inhibition in higher order cortices during the easier control condition. Future work could implement spectroscopy to probe neurotransmitter concentrations in these critical cortical areas.

Beyond the main effects of radon, our whole brain linear regressions revealed a distributed network of eloquent cortical areas showing radon-by-age interactions in the theta and gamma bands. In other words, within the identified regions, the developmental trajectory of the neural oscillatory dynamics underlying selective attention was moderated by the degree of radon exposure experienced by our sample of youths. The substrates which exhibited this interactive effect have been implicated in higher order cognitive processes including orienting to visual stimuli, interference resolution, and overriding prepotent responses (Forstmann et al., 2008; Lanssens et al., 2019; Peterson et al., 2002; Yi and Kim, 2020). Radon-related deviations from normative development of the regions underlying these critical processes are of particular interest given the developmental sensitivity of theta and gamma oscillations through childhood and adolescence and the coupling which occurs between oscillatory activity within these two bands. Theta and gamma oscillations undergo extensive development throughout this period (Rempe et al., 2023; Uhlhaas et al., 2010), and many developmental changes are related to attentional control and interference resolution (Killanin et al., 2020; Picci et al., 2023; Taylor et al., 2021). Additionally, cross-frequency coupling between theta and gamma oscillations has been proposed as a process underlying numerous cognitive processes, including interference resolution and attentional control (Bramson et al., 2018; Fries et al., 2013; Köster and Gruber, 2022; Lisman and Jensen, 2013; Spooner and Wilson, 2022; Tort et al., 2009). Further investigations could consider exploring potential radon-related aberrations in cross-frequency coupling patterns to determine whether these spectrally-specific findings are functionally linked.

Interestingly, activity within several of the brain regions showing age-by-radon interactions were directly related to behavioral outcomes. Within the left SFG and precuneus, the mediating effect of gamma-based Simon interference on the relationship between age and behavior was dependent on the level of radon exposure. It appeared that younger children exposed to greater degrees of radon were recruiting the left SFG more than their less-exposed peers and were still performing worse on the task, but with age, the impact of radon exposure diminished and performance “normalized.” Additionally, differential developmental trajectories were observed within the precuneus such that its maturation supported efficacious processing under conditions of higher cognitive load, as well as better performance, but only among individuals with lesser toxic exposure. These impacts of radon exposure on behavioral metrics of attention and their development are in line with studies detailing how numerous other environmental toxins influence behavioral outcomes such as impaired attention and memory function, lowered intelligence, and increased risk for neurocognitive and learning disorders (Chiu et al., 2016; Perera et al., 2006; Sanders et al., 2015). Our findings provide evidence that the brain processes underlying cognitive control are a potential pathway by which chronic radon exposure may lead to measurable behavioral decrements.

It is worth noting that in the present study, we identified significant windows of oscillatory activity related to the task in the theta, alpha, beta, and gamma ranges. Prior works using this task design in various age groups have found more limited patterns of neural dynamics confined primary to the theta and alpha ranges (e.g., (Son et al., 2023, 2024)). It is possible that our detection of additional windows of oscillatory activity may be the result of differences in preprocessing between projects, or that there was something unique about the

current study sample that resulted in greater visibility/power to detect additional oscillatory windows. Future investigations should consider taking a longer developmental approach to examining the maturational trajectory of neural dynamics serving cognitive control. In tandem, exploration into the potential modulatory effects of chronic radon exposure on these neural dynamics would be highly informative to the field and to the broader public.

Before concluding, we must acknowledge several limitations of the current study. Firstly, the test kits we used only measured the participants' current home radon concentrations. Although we estimated cumulative exposure by accounting for how long youths had lived in their current residence, there may be better ways to assess lifetime exposure, including exposures in prior dwellings. Future studies could approximate past exposure from other residences by using average radon concentrations from the zip codes of the child's prior homes, though the overall variability in radon concentrations that we have measured between homes would suggest that this is perhaps not the most rigorous path forward. Glass-based measures could also improve accuracy of lifetime exposure if the family could provide a sample of glass which has been in the home for the duration of the child's lifetime (Mahaffey et al., 1993; Samuelsson, 1988), though these measurements are not as precise as individual home measurements. Secondly, the radon test kits employed to assess home radon concentrations in this study were short-term kits which measure for a three- to seven-day period. While generally providing reliable measurements, these test kits are susceptible to inaccuracies due to changes in the environment during the test period, such as adverse weather conditions, open doors or windows, or damp conditions in the location of the test. Studies suggest longer-term kits with a testing period of at least 30 days provide more accurate measurements of home radon concentrations which are more robust against any variations in weather or seasons (Novilla et al., 2021). One other limitation is that we only measured radon concentrations within homes. Although, the greatest source of exposure for most people is their home (Kendall et al., 2021), future studies may consider testing other commonly occupied spaces (i.e., schools) or accounting for the average time each child spends in their home per day. Finally, the current study employed a cross-sectional design using a relatively small sample. Future works using a longitudinal design with a larger study sample would support the ability to examine clearer linkages between chronic radon exposure and individual trajectories of changes in the neural dynamics serving cognitive control.

5. Conclusion

To conclude, the present investigation discovered substantial changes in the neural oscillatory dynamics supporting cognitive control, as well as their development through childhood and adolescence, as a function of chronic home radon exposure. These aberrations were further implicated in direct measures of behavioral outcomes related to attentional control. Adding to an extensive literature detailing decrements to cognitive domains related to increased exposure to a myriad of toxins, these findings provide new evidence that chronic home radon exposure has impacts on developing youth beyond the commonly noted increases in lifetime risk for lung cancer. These data provide key insight into how radon exposure may impact the development of effective cognitive control, and more specifically the capability of youths to attend to their environment and adapt accordingly, even in a

sample of typically-developing children and adolescents. As such, future works should explore the potential implications of radon exposure on other domains of cognition, as well as clinically-relevant symptomatology of disorders such as ADHD.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data and code availability

All data are publicly available via the Collaborative Informatics and Neuroimaging Suite (COINS; <https://coins.trendscenter.org/>) on request.

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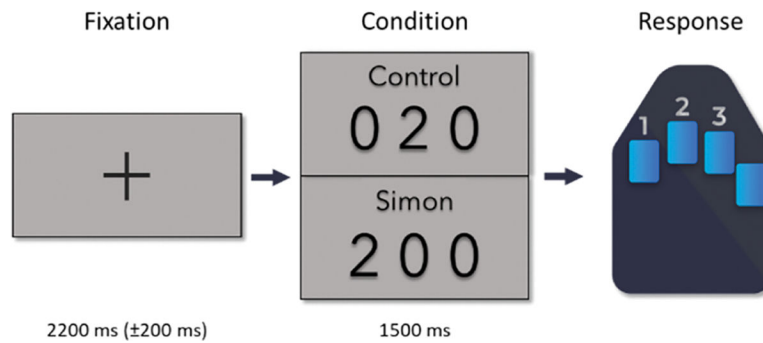
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Further reading

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**Fig. 1.**

Modified Simon task and epoch definition. A fixation cross was presented for 2200 (± 200) ms. Next, the target stimulus (row of three integers) appeared for 1500 ms. Participants responded as to the numerical identity of the “odd-number-out” with their index, middle, and ring fingers, corresponding to numbers 1, 2, and 3, respectively. Two blocks of 100 trials were completed, one for each trial type (control, Simon). To evaluate the responses involved in selective attention, the neuromagnetic data were defined with the onset of the target stimulus as 0 ms and the baseline was defined as -500 to 0 ms preceding stimulus onset.

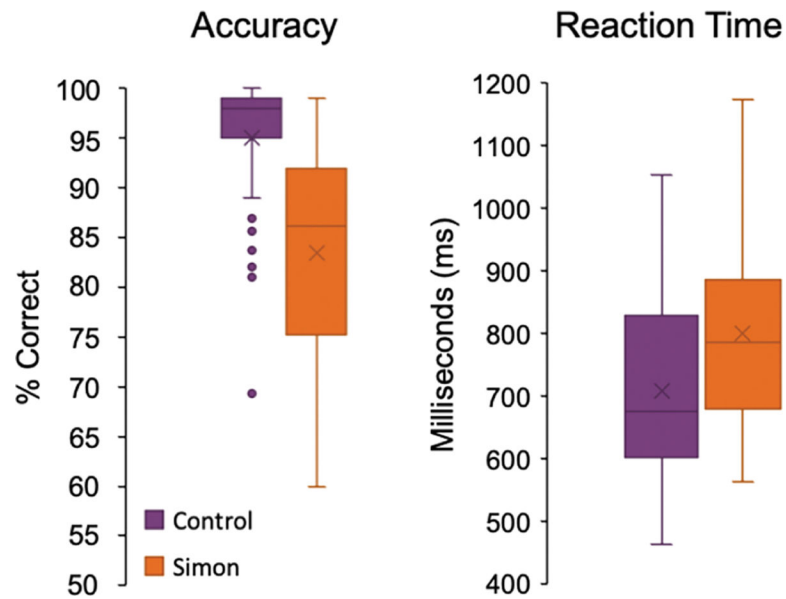


Fig. 2.

Box and whiskers plots displaying accuracy and reaction time data for both Simon and control trials. A: Average accuracy is shown as the percent of trials answered correctly during the Simon task with data divided between Simon and control trials. B: Reaction time is shown in milliseconds from onset of target stimulus (0 ms) to participant button press.

Note: "X"s represent means, center lines represent medians.

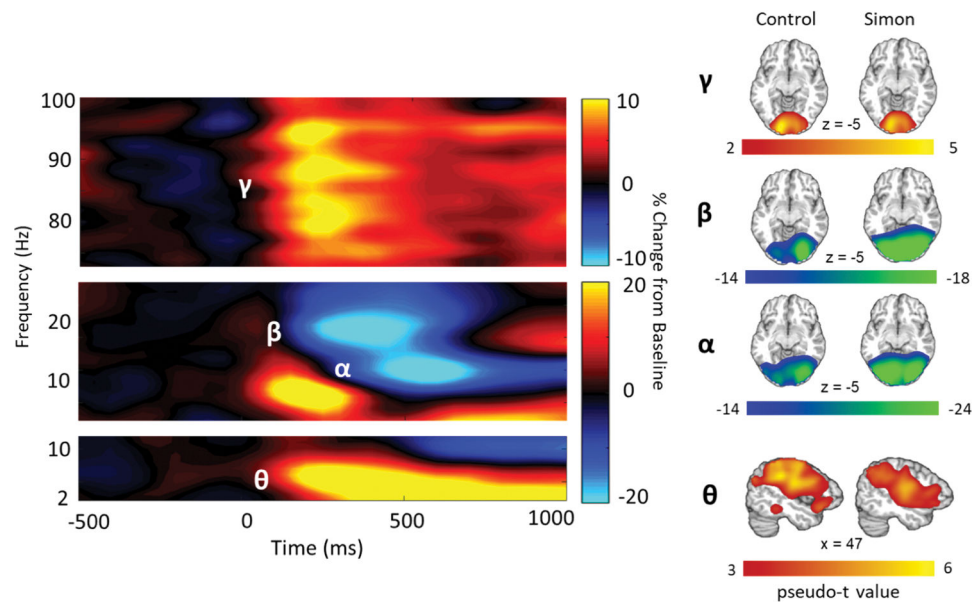


Fig. 3. Spectrograms across all trials (Simon and control) and average source reconstructions of each trial type. Left panel: Time-frequency decomposition and permutation-corrected statistical analyses indicated four time-frequency bins with significant responses ($p < .05$, corrected) relative to baseline. These included gamma activity (78–96 Hz) from 100–300 ms, beta activity (14–18 Hz) from 200–450 ms, alpha activity (8–12 Hz) from 400–600 ms, and theta activity (3–6 Hz) from 150–550 ms. The statistical analyses included all 204 gradiometers, but for visualization, we display the sensors most clearly showing the significant responses (i.e., MEG2113 for gamma, MEG1913 for alpha and beta, and MEG1312 for theta). Right panel: Grand-averaged source reconstructions per task condition were made for each time-frequency bin across all participants. As shown, theta oscillations were detected across a widespread frontoparietal network, while alpha, beta, and gamma oscillations were largely confined to occipital and parietal cortices.

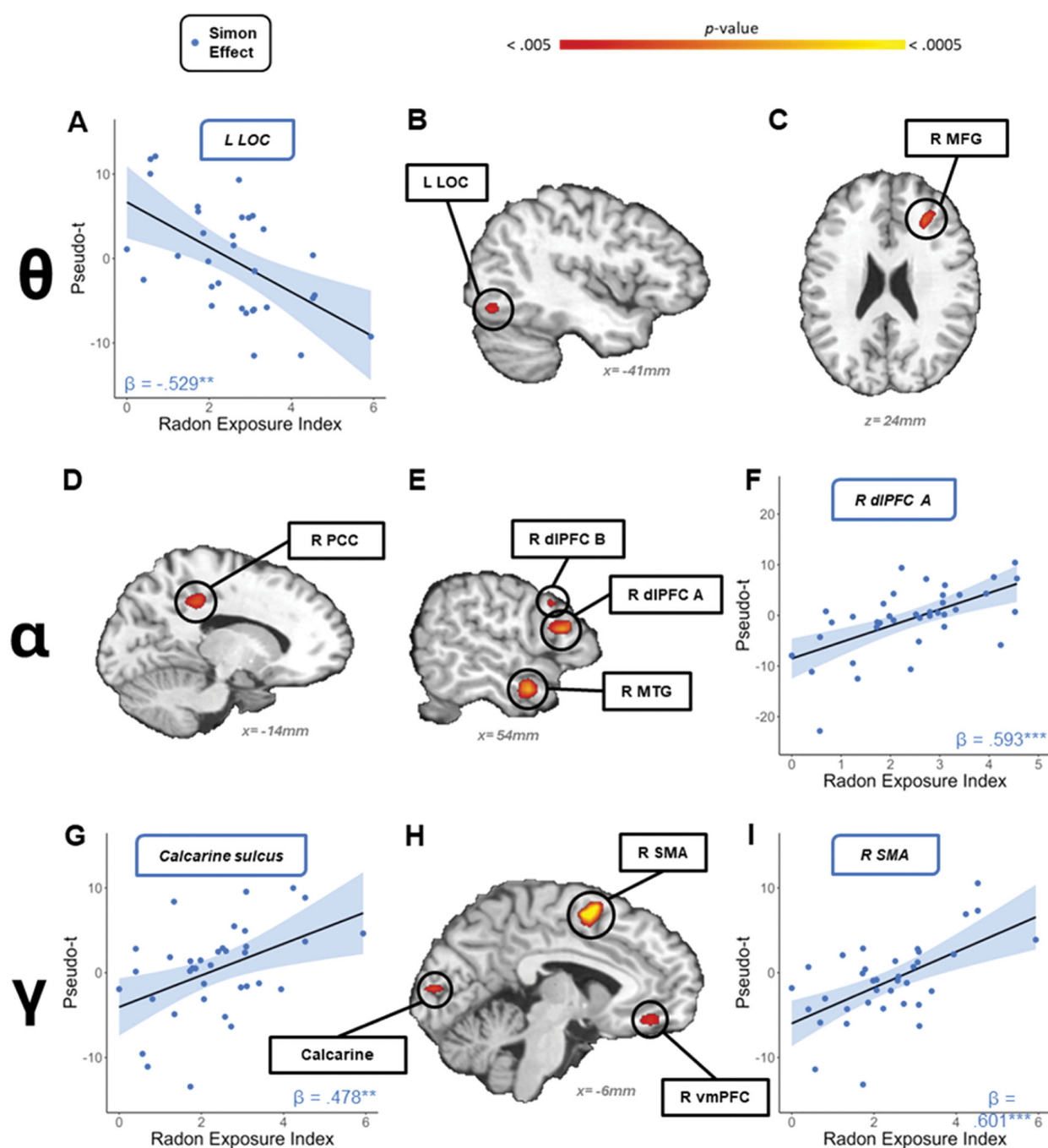


Fig. 4. Main effects of radon exposure on the neural Simon effect within the theta (top row), alpha (middle row), and gamma (bottom row) bands. In the theta band, radon exposure was significantly related to the neural Simon effect in the left LOC and right MFG (A: scatterplot of peak LOC voxel values and B, C: statistical F map). In the alpha band, radon exposure was significantly related to the Simon interference effect in multiple clusters (D, E: statistical F map showing example clusters and F: scatterplot of peak voxel values in one of the right dlPFC clusters, labelled “dlPFC A”). In the gamma band, radon exposure related

to the Simon effect in the calcarine sulcus, right SMA, and right vmPFC (G: scatterplot of peak voxel values in the calcarine sulcus, H: statistical F map showing example clusters, I: scatterplot of peak voxel values in right SMA. All reported β values are standardized; $**p < .005$, $***p < .001$. Note: “dlPFC” = dorsolateral prefrontal cortex; “L” = left; “LOC” = lateral occipital cortex; “MFG” = middle frontal gyrus; “MTG” = middle temporal gyrus; “PCC” = posterior cingulate cortex; “R” = right; “SMA” = supplemental motor area, “vmPFC” = ventromedial prefrontal cortex.

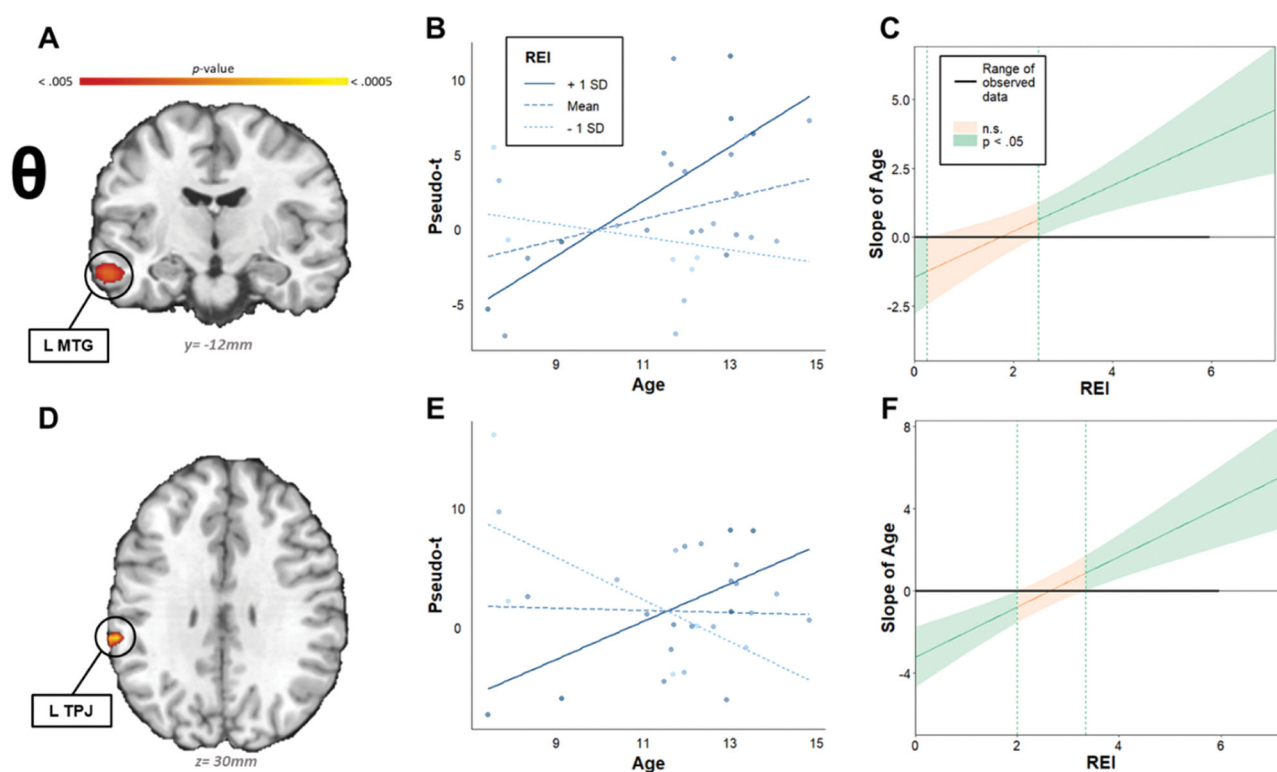


Fig. 5.

Age-by-radon interactions on the neural Simon effect within the theta band. **A, D:** Statistical *F*-maps showing clusters for which there was a statistically significant age-by-radon exposure interaction. **B, E:** Scatterplots showing the differential association between age and the neural validity effect for the mean ± 1 SD radon exposure index. **C, F:** Johnson-Neyman plots showing the levels of radon exposure index for which there is a significant interaction effect. Notes: “L” = left; “MTG” = middle temporal gyrus; “REI” = radon exposure index; “TPJ” = temporoparietal junction.

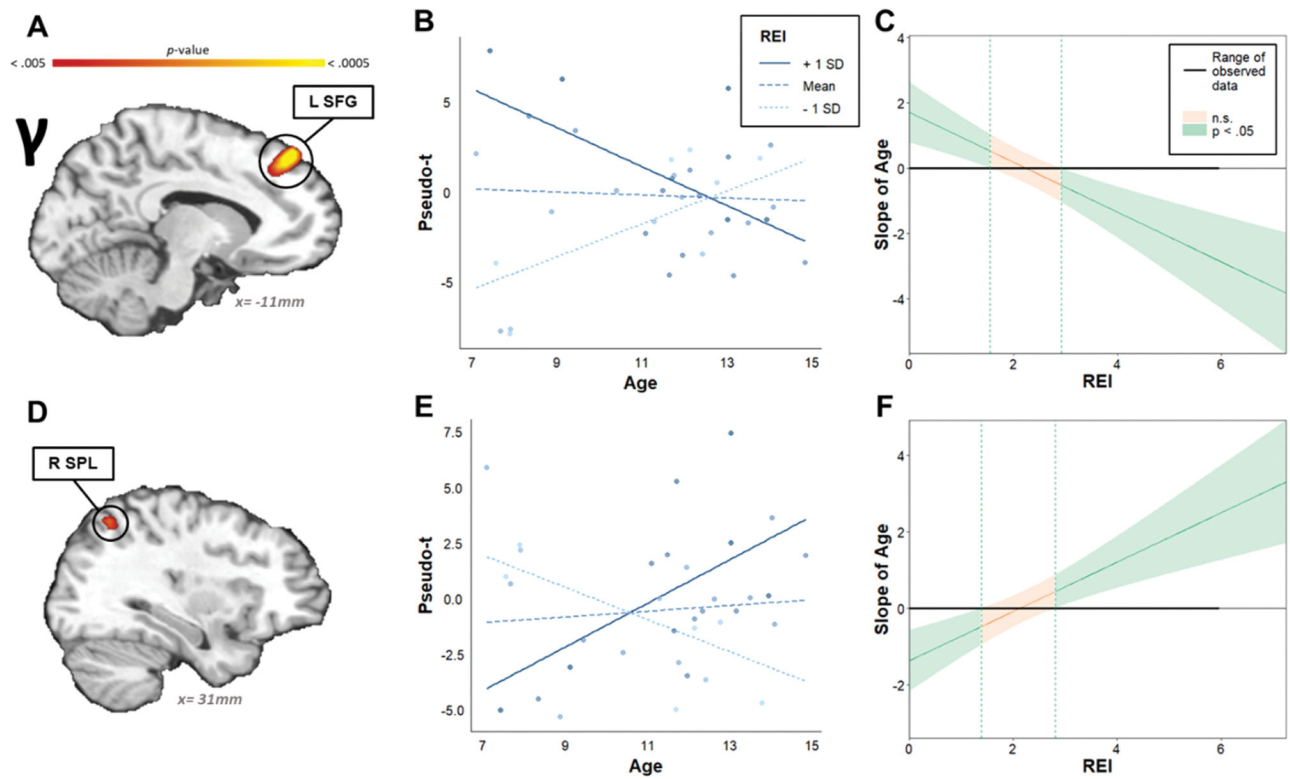


Fig. 6. Age-by-radon interactions on the neural Simon effect within the gamma band. **A, D:** Statistical F maps showing representative clusters for which there was a statistically significant age-by-radon exposure interaction. **B, E:** Scatterplots showing the differential association between age and the neural validity effect for the mean ± 1 SD radon exposure index. **C, F:** Johnson-Neyman plots showing the levels of radon exposure index for which there is a significant interaction effect. Notes: “L” = left; “SFG” = superior frontal gyrus; “SPL” = superior parietal lobe; “R” = right; “REI” = radon exposure index.

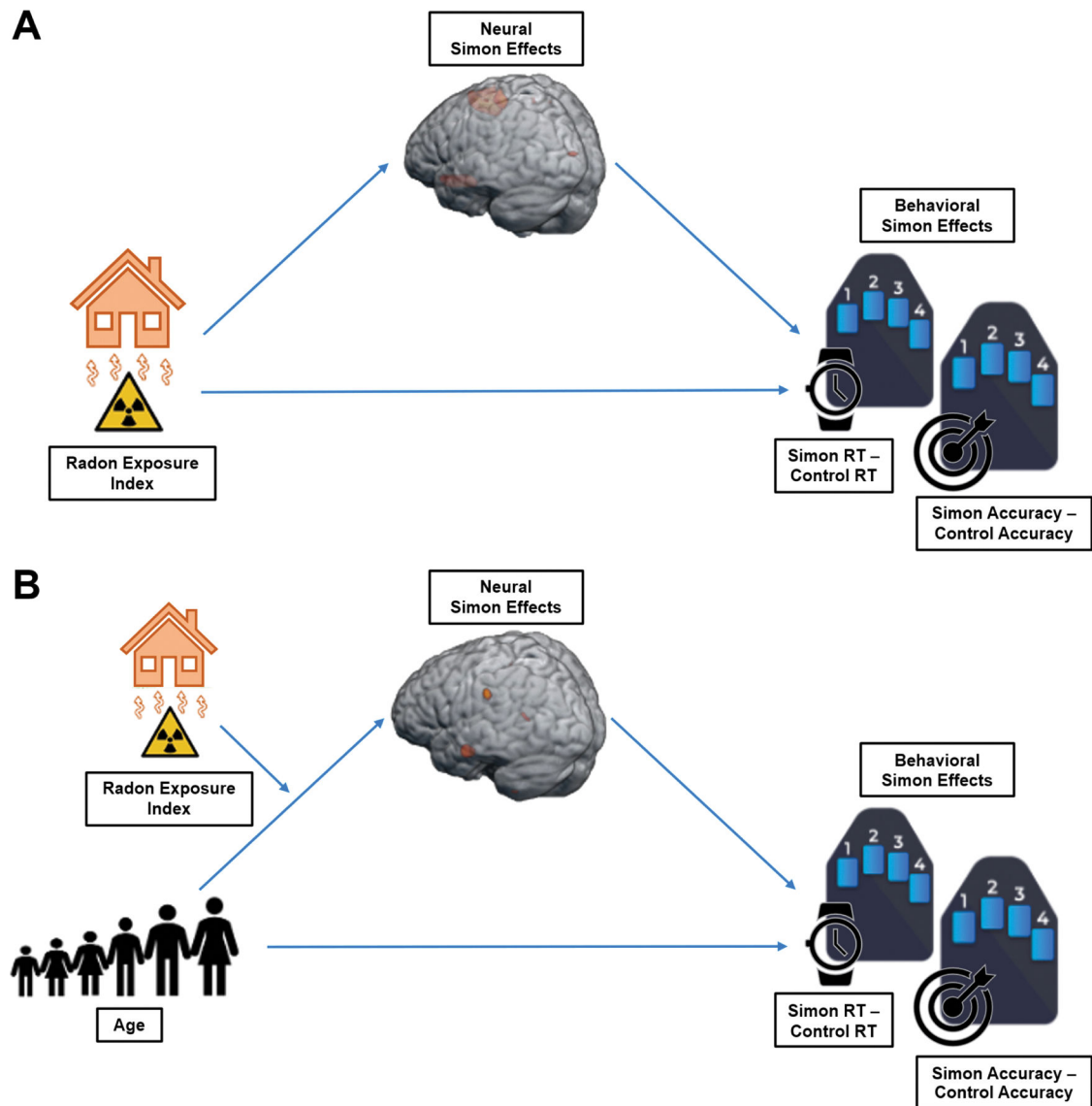


Fig. 7.

Conceptual representations of mediation and moderated mediation models. **A:** Mediation model of indirect effect of radon exposure index on behavioral Simon effects (i.e., accuracy and RT Simon effects) via neural Simon interference effects. Not pictured, the effect of age was modeled as a control variable on all other variables within the model. **B:** Moderated mediation model wherein radon exposure is a modulator of the indirect effect of the radon exposure index on behavioral Simon effects via neural Simon interference effects.

Table 1

Main effects of radon on oscillatory dynamics serving selective attention.

Oscillatory Band/Region	<i>F</i>	<i>p</i>	η_p^2	X	Y	Z
<i>Theta</i>						
L LOC	12.59	.001390	0.31	-46	-72	-11
R parahippocampal gyrus	12.44	.001469	0.31	26	-44	9
R MFG	12.29	.001553	0.31	30	36	25
L IOG	12.16	.001630	0.30	-18	-96	-15
R cerebellum	11.68	.001952	0.29	46	-72	-23
<i>Alpha</i>						
L ITG	18.53	.000128	0.35	-10	-0	-27
R MTG	15.38	.000319	0.31	58	-0	-19
L PCC	13.49	.000795	0.28	-18	-36	37
R dlPFC A	12.95	.000979	0.27	54	20	17
R dlPFC B	11.99	.001429	0.26	50	16	37
R dlPFC C	12.06	.001390	0.26	26	44	41
R precentral gyrus	10.68	.002431	0.23	2	-24	69
<i>Gamma</i>						
R SMA	21.72	.000053	0.40	10	4	53
R vmPFC	17.70	.000195	0.36	18	36	-11
L precentral gyrus	15.26	.000455	0.32	-26	-28	57
L calcarine sulcus	10.97	.002304	0.26	-6	-88	9

Notes: Peak coordinates are in Talairach space; “dlPFC” = dorsolateral prefrontal cortex; “IOG” = inferior occipital gyrus; “ITG” = inferior temporal gyrus; “L” = left; “LOC” = lateral occipital cortex, “MFG” = middle frontal gyrus; “MTG” = middle temporal gyrus; “PCC” = posterior cingulate cortex; “R” = right; “SMA” =supplemental motor area; “vmPFC” = ventromedial prefrontal cortex.

Table 2

Radon x age interaction effect on oscillatory dynamics serving selective attention.

Oscillatory Band/Region	<i>F</i>	<i>p</i>	η_p^2	X	Y	Z
<i>Theta</i>						
L TPJ	16.14	.000401	0.37	-58	-32	29
L MTG	12.26	.001571	0.30	-58	-12	-15
<i>Gamma</i>						
L SFG	18.07	.000172	0.36	-14	40	45
L MOG	16.44	.000300	0.34	-18	-88	17
L precuneus	14.69	.000559	0.31	-30	-72	41
R SPL	13.40	.000899	0.30	34	-60	49
R SMA	10.06	.003334	0.24	2	4	53

Notes: Peak coordinates are in Talairach space; “L” = left; “MTG” = middle temporal gyrus; “MOG” = middle occipital gyrus; “R” = right; “SFG” = superior frontal gyrus; “SPL” = superior parietal lobule; “TPJ” = temporoparietal junction.

Table 3

Statistically significant indirect effects detected in brain-behavior mediation analyses.

Effect of Interest / Brain Region	a	b	direct (c')	indirect	95 % CI
<i>Radon → Brain → Accuracy</i>					
θ R cerebellum	−0.56 ^{***}	−0.54 [*]	−0.072	.30	.041, 0.77
γ R SMA	.58 ^{***}	.72 ^{**}	−0.28	.42	.088, 0.97
<i>Radon → Brain → Reaction Time</i>					
γ L precentral gyrus	.55 ^{***}	−0.52 [*]	−0.080	−0.29	−0.76, −0.061
<i>Radon × Age → Brain → Accuracy</i>					
γ L SFG	−0.20 ^{***}	.65 ^{***}	.059	−0.13	−0.30, −0.029
γ L precuneus	−0.19 ^{***}	−0.41 [*]	.059	.078	.018, 0.18

Notes: “a” = *a* path of the mediation analysis (predictor of interest → brain); “b” = *b* path of the mediation analysis (brain → behavior); “direct (c’)” = direct effect of predictor of interest on outcome behavior after accounting for indirect effects (predictor of interest → behavior); “L” = left; “R” = right; “SFG” = superior frontal gyrus; “SMA” = supplementary motor area; “θ” = theta band response; “γ” = gamma band response; “95 % CI” = 95 % bias-corrected boot-strapped confidence interval used to determine statistical significance of indirect effects (values represent lower and upper bound of the confidence interval).

*
 $p < .05$

**
 $p < .01$

 $p < .001$, denoted only for a, b, and c’ path effects (indirect effect significance determined via 95 % CI). All effects listed are standardized estimates.