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# Cortical Stimulation Associated with Tabletop Cognitive Activities and the Influence of Self-Perceived Challenge as Measured by Electroencephalography: A Pilot Study

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**Abstract**

***Background:*** *Positive associations are reported between "cognitively stimulating" activities and cortical stimulation and between "cognitively challenging" activities and cortical stimulation. However, the basis for these has been largely subjective. One aim of this pilot study was to determine whether tabletop cognitive activities, believed to be cortically stimulating, are objectively based on left dorsolateral prefrontal cortex (LDLPFC) coherence measured by electroencephalography (EEG). A second aim was to compare LDLPFC coherence associated with Sudoku, perceived by most study participants to be the most cognitively challenging activity they completed, with LDLPFC coherence associated with the activity each perceived to be the least cognitively challenging.*

***Methods:*** *Participants engaged for five minutes in an "at rest" condition and each of five presumptively "cognitively stimulating" tabletop activity conditions. EEG data were collected throughout. Participants then ranked the cognitive challenge they experienced completing each tabletop activity.*

***Results:*** *Based on EEG LDLPFC coherence, not all activities were cortically stimulating. Sudoku, the activity rated "most cognitively challenging" by most participants (n = 13/25), was the most cortically stimulating condition in Beta, High Beta, Theta, Delta, and High Delta frequency bands.*

***Conclusion:*** *With a growing body of evidence supporting the benefits of ongoing engagement in challenging cognitive exercise for individuals across their lifespans, identifying cognitive activities that stimulate beneficial cortical activation and, ultimately, cognitive function is needed.*

## Introduction

Researchers describe cognitively stimulating tabletop activities as purposeful tasks that individuals engage in for education or entertainment, requiring some level of thought or effort and excluding gross motor movement (Foubert-Samier et al., 2012; O'Neil-Pirozzi, 2021). Such activities include reading, writing, and playing computerized/non-computerized games. Consistent with the neuroplasticity principle "Use It or Lose It," growing evidence supports the importance of regular engagement in such cognitive activities – also known as "thinking exercises" and "mental exercises" – to brain health (Mackinnon et al., 2003; O'Neil-Pirozzi et al., 2022; Salthouse, 2006). Participating in such environmentally enriching activities—or exercises—may delay cognitive decline in older individuals and decrease the chances of developing Alzheimer's Disease (AD) (Mackinnon et al., 2003; Salthouse, 2006; Wilson et al., 2003). In fact, an extensive body of human and animal literature shows positive correlations between cognitively stimulating activities/exercises and cognitive and neuronal status (Simpson & Kelly, 2011; Yate et al., 2016).

The basis for stating that an activity is cognitively

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stimulating has been largely subjective. Many published studies of cognitively stimulating or environmentally enriching activities have not provided objective evidence that supports their chosen research protocol activities as cognitively stimulating. Others have cited the inclusion of specific activities in previous research on cognitive stimulation as the basis for inclusion in their subsequent studies (Simpson & Kelly, 2011; Wilson et al., 2003; Yate et al., 2016). A few qualitative studies have used self-reports of individuals' engagement in different activities thought to be cognitively stimulating and challenging (Christensen & Mackinnon, 1993; Salthouse et al., 2002). In one of these studies (Salthouse et al., 2002), participants were given a questionnaire listing several everyday activities presumed to be cognitively stimulating and asked to rate how cognitively demanding they perceived each to be. The analyses revealed that participants subjectively rated the activities as cognitively stimulating, but the degree of cognitive demand or challenge varied for each.

Some research suggests that it is only when an activity is experienced as cognitively challenging to complete that it is beneficial (Schooler & Mulatu, 2001). However, the optimum difficulty level needed for a cognitive activity to be beneficial is still not known. Individuals respond differently to what they perceive to be highly challenging cognitive activities – some embrace them, while others reject them (O'Neil-Pirozzi, 2021; Silvestrini & Gendolla, 2019). In the study described above, Salthouse et al. (2002) asked participants to estimate how frequently they performed each listed activity per week. The group's activities were rated as "moderately" (versus "maximally" or "minimally") challenging.

Neurologically, the left dorsolateral prefrontal cortex (LDLPFC) is vital to successful cognitive functioning and is frequently targeted in brain stimulation research to improve cognitive abilities in neurologically typical and atypical individuals (Brunoni & Vanderhasselt, 2014; Teselink et al., 2021). The LDLPFC facilitates cognitive functioning through network connections with cortical and subcortical structures (Gilbert & Burgess, 2008). Cognitive abilities mediated by the LDLPFC include selective attention, inhibition, abstract reasoning, working memory, language processing, and other areas of executive functioning (Baddeley, 1992; Brunoni & Vanderhasselt, 2014; Hertrich et al., 2021; Suchy, 2023).

The primary aim of this pilot study was to determine whether tabletop cognitive activities, believed to be cortically stimulating, are objectively so when measured using electroencephalography (EEG). It was hypothesized that tabletop cognitive activities would be cortically stimulating as indexed by EEG-measured LDLPFC coherence with its surrounding regions, with some activities being more cognitively challenging and, therefore, more stimulating than others. The secondary aim was to compare LDLPFC coherence associated with the tabletop cognitive activity that most study participants perceived to be most cognitively challenging with LDLPFC coherence associated with the activity that they each perceived to be least cognitively challenging. It was hypothesized that the activity most participants perceived to be most cognitively challenging would be associated with greater left dorsolateral prefrontal cortex (LDLPFC) coherence than the activity each perceived as least cognitively challenging. To our knowledge, this is the first EEG study to 1) objectively measure cortical stimulation associated with various tabletop cognitive activities and 2) test for the existence of a relationship between self-perceived challenge associated with activity engagement and cortical stimulation as measured by LDLPFC activation.

## Materials and Methods

### *Study Design*

A prospective, controlled, single-center, single-arm, open-label trial design was used in this pilot study with 25 neurotypical individuals. Hypothesis testing was completed with the data associated with the tabletop cognitive activity that most study participants perceived to be "most cognitively challenging" and the data associated with the activity that each perceived to be "least cognitively challenging." This study conformed to the Declaration of Helsinki guidelines and was prospectively approved by the Northeastern University Institutional Review Board.

### *Participants*

Participants were recruited on the Northeastern University campus. Inclusion criteria for study participation were as follows: 1) male and females 18 years of age and older; 2) right-hand dominant; 3) native English speaker; and 4) full-time college student. Documented acquired brain injury/neurologic/neurobehavioral/psychiatric diagnosis (e.g., attention-deficit/hyperactivity disorder, depression) excluded otherwise eligible individuals from study participation. Most of the 25 participants enrolled in this pilot study were female (76.00%), with an average age of 20.85 years and 14.16 years of education. All were native English speakers, and most described themselves as European American (60.00%), followed by Asian American (24.00%), African American (12.00%), and

mixed (4.00%). Demographic information across participants is summarized in Table 1.

### *Procedures/Experimental Tasks*

After providing written informed consent, each participant completed one study session. The session lasted 60-75 minutes as follows: pre-session demographic questionnaire; pre-activities EEG 5 minutes eyes open "at rest" baseline (not focused on any particular thought or cognitive activity); 5 minutes engagement in each of five tabletop activities previously reported as being "cognitively stimulating" (order randomized across participants using a random online generator); post-activities EEG 5 minutes eyes open "at rest"; and post-session questionnaire probing activity challenge. The five activities, unknown to participants prior to their study engagement and all considered cognitively stimulating in previous studies, were reading an article about air travel; listening to a pop song; completing a 9 x 9 Sudoku puzzle; watching a dramatic television (TV) show episode; and listening to a fictional audio story (Grabbe et al., 2011; Simpson & Kelly, 2011; Wilson et al., 2003; Yate et al., 2016). The stimulus used for each activity was the same across participants. EEG data was collected throughout all activities. Following the completion of the activities, participants were asked to rank their study-specific experience of each activity relative to each other from "'most cognitively challenging"' ('5') to "'least cognitively challenging"' ('1'). Participants' generalized challenge ranking was also obtained to determine whether the challenge ranking of each experimental activity in this study was representative of participants' lifelong experiences.

EEG signals were recorded continuously using Neuroelectric Instrument Controller (NIC) online software and the 32-electrode Enobio EEG WiFi system at a sampling frequency of 500 Hertz (Hz) and with a resolution of 24 bits. Solid gel electrodes were placed following the International 10/10 system for EEG electrode placement (Seeck et al., 2017). Thirty-two channels were recorded in all registers, and the reference and ground electrodes were located on the right earlobe. EEG data were low-pass filtered at 40 Hz and high-pass filtered at 0.5 Hz during recordings. NIC software (https://www.neuroelectrics.com/wiki/index.php/Neuroelectrics%27_Wiki website) recorded and analyzed the electrophysiologic data.

### *Data Analysis*

Self-reported challenge rankings were tallied per activity within and across participants. The Sudoku puzzle was the experimental activity rated 'most cognitively challenging' by the most significant number of study participants (n = 13/25, 52%). To test the hypotheses, the analysis focused on these 13 participants' EEG data for the following three conditions: 1) pre-activities "at rest" baseline, 2) Sudoku, the activity that all participants ranked "most cognitively challenging," and 3) the activity that each participant ranked "least cognitively challenging." Rank-ordering (most to least) of the self-perceived challenge of each study-specific stimulus per experimental activity (e.g., completion of study Sudoku puzzle) compared with the self-perceived challenge of each activity in general (e.g., completion of Sudoku puzzles) was tallied across participants. Because participant's challenge rankings of the five specific experimental activity stimuli in this study and their challenge rankings of each of the five activities, in general, were found to be so similar (92% matched rankings), the relation between EEG cortical activation and activity challenge was examined using experimental activity challenge data only. LDLPFC coherence across delta (>0.9 and <4 Hz), theta (>3.9 and <8 Hz), alpha (>7.9 and <13 Hz), and beta (>12.9 and <30.1 Hz) frequency bands was measured for the 13 participants during 1) at-rest, 2) Sudoku (the "most cognitively challenging" tabletop activity), and 3) "least cognitively challenging" conditions. Additionally, coherence was calculated across the following frequency sub-bands: high delta (> two and <4 Hz), low alpha (>7.9 and <10 Hz), high alpha (>9.9 and <13 Hz), low beta (>12.9 and <20 Hz), high beta (>19.9 and <30.1 Hz). EEG changes within and across participants for the at-rest and two activity conditions (most cognitively challenging and least cognitively challenging) were compared. The 5-minute continuous EEG data per participant activity were cleaned. For this study, the cleaned 5-minute continuous EEG data were then segmented into 10-second signals, averaged across all 30 segments, and analyzed from five EEG electrode positions: F3, AF3, F.Z., FC1, and FC5. Power analysis was obtained at these sites, and coherence analysis was obtained for the following EEG site pairs: F3-AF3, F3-Fz, F3-FC1, and F3-FC5. The EEG data was analyzed from the LDLPFC (F3) and the four electrode positions surrounding it as the region most likely involved in the study activities. Data were low-pass filtered at 50 Hz and high-pass filtered at 1 Hz during analyses.

### *Statistical Analysis*

An intention-to-treat (ITT) analysis was performed. The data were not normally distributed, so we used

| Characteristics | Participants |
|---|---|
| Sex | |
| Male (%) | 6 (24%) |
| Female (%) | 19 (76%) |
| Mean age in years (SD) | 20.85 (2.82) |
| Mean years of education (SD) | 14.16 (1.82) |
| Ethnicity | |
| Hispanic/Latino (%) | 1 (4%) |
| Non-Hispanic/Latino (%) | 24 (96%) |
| Race | |
| African American (%) | 3 (12%) |
| Asian American (%) | 6 (24%) |
| European American (%) | 15 (60%) |
| Mixed (%) | 1 (4%) |

**Table 1:** *Demographic characteristics across study participants.*

the non-parametric Friedman's omnibus test to test for significant differences in coherence among the three conditions ("at rest," "most cognitively challenging" (Sudoku), and "least cognitively challenging)" per frequency band across participants. When significant differences "at rest," "most cognitively challenging" (Sudoku), and "least cognitively challenging)" per frequency band across participants. When significant differences were found, pairwise comparisons were performed using the Wilcoxon Signed-Rank test. Median and interquartile range coherence scores per frequency band were calculated. As a pilot and exploratory study, a p-value of $< 0.05$ was used to determine statistical significance across comparison tests, and no corrections for multiple comparisons were made.

To examine our first aim, whether tabletop cognitive activities believed to be cortically stimulating were so objectively, we compared LDLPFC coherence of "least cognitively challenging" and pre-activities' "at rest" conditions per frequency band using Friedman's test. To examine our second aim, to compare LDLPFC coherence associated with 'most cognitively challenging' and 'least cognitively challenging' activities, we again used Friedman's test for significant differences in LDLPFC coherence of conditions per frequency band, followed by Wilcoxon Signed-Rank test comparisons of significant pairwise differences found.

### *EEG Cleaning and Missing Data*

During manual EEG cleaning on MatLab (EEGLab), data from variable electrodes had to be rejected from individual EEG files before analysis. There was no clear relationship between EEG quality/rejected channels and the three experimental activities. However, 3 out of 4 EEG files rejected belonged to a participant whose only distinguishing factor was thick hair.

When the analysis involved electrodes F3, AF3, Fz, FC1, and FC5, the coherence data for related pairs was also missing. For example, given that EEG data was evaluated using a right ear reference, rejecting AF3 "electrode" data meant that data from the channel AF3-right ear reference was also rejected and that, as a result, coherence data for F3-AF3 was missing. Due to the appearance of equipment-related artifacts in almost all EEG files, an independent component analysis (ICA) was run, and components involving the artifact were rejected as part of the EEG cleaning process. For 31/156 coherence pairs (4 coherence pairs x 3 conditions x 13 participants), missing coherence data had to be imputed for each of the above frequency bands/sub-bands; thus, about 19.9% of missing coherence data was imputed overall. EEGs and channels rejected were related to data quality (affected by technical issues) and did not pertain to experimental activities. For further details on missing and rejected/imputed EEG data, including tabular data (Table S1) for coherence pairs that were rejected and missing/imputed, see the Manuscript Supplement.

## Results

### *Cortical Stimulation of Tabletop Cognitive Activities*

Findings reported in this pilot study focused on EEG-measured cortical stimulation during "at rest" and tabletop cognitive activity conditions as follows: Sudoku, the activity self-ranked as the "most cognitively challenging" activity by the greatest number

| Participant | Most Challenging | Least Challenging |
|---|---|---|
| 1 | Sudoku | Music |
| 2 | Audio | Music |
| 3 | Audio | TV |
| 4 | Audio | Sudoku |
| 5 | Sudoku | Audio |
| 6 | Article | Music |
| 7 | Sudoku | TV |
| 8 | Audio | Music |
| 9 | Audio | TV |
| 10 | Audio | Article |
| 11 | Sudoku | TV |
| 12 | Sudoku | Music |
| 13 | Audio | TV |
| 14 | Audio | TV |
| 15 | Sudoku | TV |
| 16 | Article | Music |
| 17 | Sudoku | TV |
| 18 | Sudoku | TV |
| 19 | Sudoku | TV |
| 20 | Audio | TV |
| 21 | Sudoku | Music |
| 22 | Sudoku | Music |
| 23 | Sudoku | TV |
| 24 | TV | Sudoku |
| 25 | Sudoku | TV |

**Table 2:** *Most and least challenging tabletop cognitive activities per study participant.*

| | Alpha | Low alpha | High alpha | Beta | Low beta | High beta | Theta | Delta | High delta |
|---|---|---|---|---|---|---|---|---|---|
| F3-AF3 | NS | NS | NS | NS | NS | $p$=0.0498 | NS | NS | NS |
| F3-Fz | NS | NS | NS | $p$=0.0498 | NS | NS | $p$=0.0183 | $p$=0.0498 | $p$=0.0231 |
| F3-FC1 | NS | NS | NS | NS | NS | NS | $p$=0.0125 | $p$=0.0062 | $p$=0.0036 |
| F3-FC5 | NS | NS | NS | NS | NS | NS | NS | NS | NS |

Note. NS = not statistically significant (p>0.05)

**Table 3:** *Friedman omnibus test significance results across activity conditions per frequency bandwidth.*

of study participants (n = 13) and the activity that each self-ranked as 'least challenging' (see Table 2). The median LDLPFC coherence and interquartile ranges (IRQ) of each electrode pair per frequency band for each of these three conditions are provided in the Supplement (Table S2). Regarding our first study aim, results of all Friedman's tests comparing LDLPFC coherence of 'least cognitively challenging' and 'at-rest' conditions per frequency band revealed no significant differences between them ($p > 0.05$), suggesting that individuals' engagement in tabletop cognitive activities that they perceive to be 'least cognitively challenging' cognitively may not be any more stimulating, as indexed by LDLPFC coherence, than when they are "at-rest."

### *Comparisons of 'At-Rest,' 'Most Cognitively Challenging,' and 'Least Cognitively Challenging' Study Conditions*

Friedman's test analyses of EEG F3-AF3, F3-Fz, F3-FC1, and F3-FC5 coherence data revealed significant differences for 8 of the 36 frequency band comparisons (22.22%) among the three activity conditions (see Table 3). These differences were found in the F3-AF3, F3-Fz, and F3-FC1 electrode lead pairings.

Regarding our second study aim for all eight frequency band comparisons above that resulted in significant differences using the Friedman's test, pairwise comparisons between the 'most cognitively challenging' and "least cognitively challenging" activity conditions using the Wilcoxon Signed Rank test were also significant. Specifically, as seen in Table 4, there were significant coherence differences between "most cognitively challenging" (Sudoku) and "least cognitively challenging activity conditions at F3-AF3 in high beta ($p = 0.0215$); at F3-Fz in beta ($p = 0.0327$), theta ($p = 0.0012$), delta ($p = 0.0266$), and high delta ($p = 0.0171$); and at F3-FC1 in theta ($p = 0.0105$), delta ($p = 0.0171$); and high delta ($p = 0.0171$). At F3-F5, there were no significant differences in any band/sub-bands ($p > 0.05$). Significant differences were also found at F3-FC1 in theta ($p = 0.0479$), delta ($p = 0.0327$), and high delta ($p = 0.0327$) when comparing Sudoku to 'at rest'. Regarding these significant findings, coherence was higher in Sudoku when compared to either "least cognitively challenging" or "at rest" conditions in all but two to three participants (often the same two participants), suggesting that individuals' engagement in Sudoku, the tabletop cognitive activity perceived by the majority of study participants to be 'most cognitively challenging' cognitively, maybe most cortically stimulating, as indexed by LDLPFC coherence.

## Discussion

An extensive body of research shows positive associations between 'cognitively stimulating activities and cortical stimulation and between 'cognitively challenging' activities and cortical stimulation (Brunoni & Vanderhasselt, 2014; Mackinnon et al., 2003; Salthouse, 2006; Schooler & Mulatu, 2001; Silvestrini & Gendolla, 2019; Wilson et al., 2003). However, the basis for stating that such cognitive activities are cortically stimulating has been largely subjective (Christensen & Mackinnon, 1993; Salthouse et al., 2002; Teselink et al., 2021; Wilson et al., 2003). This pilot study objectively measured the effects of tabletop cognitive activities previously described as subjectively stimulating on cortical stimulation based on EEG coherence between LDLPFC and its surrounding regions. Relationships between the magnitude of the self-perceived challenge of activity engagement and EEG-measured LDLPFC activation were also examined.

### *Cortical Stimulation Associated with Tabletop Cognitive Activities*

We hypothesized that tabletop cognitive activities previously believed to be cortically stimulating subjectively would be so objectively, as measured by EEG LDLPFC coherence with its surrounding regions, and that some activities would be more stimulating than others. This pilot study's findings only partially support this hypothesis, with some activities (i.e., listening to a pop song, watching a TV show, and listening to an audio story) associated with no greater LDLPFC coherence than when participants were at rest.' Sudoku, comparatively, was associated with greater LDLPFC coherence than when "at rest" and when engaged in other tabletop cognitive activities. More specifically, Sudoku induced greater LDLPFC coherence than other activities in beta, high beta, theta, delta, and high delta frequency bands. These findings support the ability of Sudoku to stimulate LDLPFC activation and thereby engage the executive functions that this cortical area oversees, including working memory and problem-solving (Brunoni & Vanderhasselt, 2014; Grabbe et al., 2011; Hertrich et al., 2021; Suchy, 2023). Regarding the song, TV, and audio story activity findings in this study, it is essential to remember that the LDLPFC is part of networks that consist of other brain regions engaged during cognitive activities (e.g., auditory cortex regions when listening to audiobooks or songs; visual and auditory cortex regions when watching TV) (Chien & Chan, 2015; Hakonen et al., 2022; Rothschild et al., 1988; Shestyuk et al., 2019). Based on the cognitive abilities required

| | Alpha | Low alpha | High alpha | Beta | Low beta | High beta | Theta | Delta | High delta |
|---|---|---|---|---|---|---|---|---|---|
| F3-AF3 *At-rest – Most challenging* | - | - | - | - | - | NS | - | - | - |
| F3-AF3 *At-rest – Least challenging* | - | - | - | - | - | NS | - | - | - |
| F3-AF3 *Most – Least challenging* | - | - | - | - | - | $p$=0.0215 | - | - | - |
| F3-Fz *At-rest – Most challenging* | - | - | - | NS | - | - | NS | NS | NS |
| F3-Fz *At-rest – Least challenging* | - | - | - | NS | - | - | NS | NS | NS |
| F3-Fz *Most – Least challenging* | - | - | - | $p$=0.0327 | - | - | $p$=0.0012 | $p$=0.0266 | $p$=0.0171 |
| F3-FC1 *At-rest – Most challenging* | - | - | - | - | - | - | $p$=0.0479 | $p$=0.0327 | $p$=0.0327 |
| F3-FC1 *At-rest – Least challenging* | - | - | - | - | - | - | NS | NS | NS |
| F3-FC1 *Most – Least challenging* | - | - | - | - | - | - | $p$=0.0105 | $p$=0.0171 | $p$=0.0171 |
| F3-FC5 *At-rest – Most challenging* | - | - | - | - | - | - | - | - | - |
| F3-FC5 *At-rest – Least challenging* | - | - | - | - | - | - | - | - | - |
| F3-FC5 *Most – Least challenging* | - | - | - | - | - | - | - | - | - |

**Table 4:** *Pairwise comparison significance results between activity conditions per frequency bandwidth.*

(e.g., attention and memory processing when watching a TV show), perhaps other brain regions play a more primary role during these activities than the LDLPFC (Shestyuk et al., 2019). Alternatively, it may be that, in contrast to Sudoku, these activities were not cognitively demanding enough to engage the LDLPFC in this study's healthy participants, but for some individuals with and without brain impairment, they may be (Ohad et al., 2023).

### *Self-Perceived Challenge of Tabletop Cognitive Activities and LDLPFC Activation*

We also hypothesized that Sudoku, the tabletop cognitive activity in this pilot study perceived as "most cognitively challenging," would be associated with greater LDLPFC coherence than activities perceived as 'least cognitively challenging.' Study findings largely support this hypothesis as evidenced by: a) the greater LDLPFC coherence associated with Sudoku than with the activities perceived as 'least cognitively challenging' in beta, high beta, theta, delta, and high delta frequency bands using EEG F3-AF3 and F3-FZ electrode site comparisons and b) the significant differences between the 'at rest' and 'most cognitively challenging' conditions in slow activity theta, delta, and high delta frequency bands in the F3-FC1 pair of EEG coordinates. These findings support the positive association between individuals' self-perception of challenges associated with their tabletop cognitive activity completion and LDLPFC activation during activity engagement. Also supported is the importance of individuals' engagement in tabletop cognitive activities that they perceive as significantly challenging to facilitate LDLPFC stimulation that is greater than that associated with unchallenging tabletop cognitive activities or being "at rest."

While increases in LDLPFC beta, high beta, and theta coherence during a significantly challenging cognitive activity are not surprising findings, simultaneous increases in delta and high delta coherence are. The reason for increased delta coherence is unclear. It raises the question of whether highly cognitively challenging activities may contribute to subclinical fatigue or periods of slow EEG activity in addition to faster activity and whether the 5-minute EEG recording of each study activity captured this. In future studies, it would be interesting to continue examining whether 1) cognitively challenging activities are followed by increased LDLPFC connectivity in the delta range (slow activity); 2) this phenomenon is a time- and dose-dependent finding (with greater delta coherence being associated with highly challenging activities for more extended periods), and 3) interleaved periods of rest reduce LDLPFC delta connectivity and increase higher frequency band connectivity.

Another interesting finding is that, in some cases, "least cognitively challenging" activities had lower coherence than the pre-activity's at rest' condition in this study. This might relate to "non-tabletop cognitive activity" thought components. Turnbull et al. (2019) found that DLPFC neural activity was high when experimental task demands were high and experimental task demands were low in a whole-brain analysis study using functional magnetic resonance imaging data. Individuals had spontaneously switched to self-prioritized, non-experimental-task thoughts. Perhaps, in the current study, participants utilized their LDLPFC in a self-generated, focused way during the "at rest" condition to a greater extent than when engaged in those tabletop cognitive activities that were 'least cognitively challenging' to them. Alternately, perhaps participants were anxious or tense at the start of the study, not knowing what would be asked of them, thereby biasing the validity of the 'at rest' EEG data collected (Phan et al., 2005; Požar et al., 2022).

### *Clinical Implications of Study Findings and Future Directions*

The World Health Organization defines brain health as "the state of brain functioning across cognitive, sensory, social-emotional, behavioral, and motor domains, allowing a person to realize their full potential over the life course, irrespective of the presence or absence of disorders" (2024). Ongoing engagement in challenging cognitive exercise activity is a crucial pillar of brain health, with a growing body of evidence supporting the benefits of such activity engagement to individuals across the lifespan, with and without such medical diagnoses such as A.D., Mild Cognitive Impairment (MCI), and Traumatic Brain Injury (TBI) (Global Council on Brain Health, 2017; Frank et al., 2023; O'Neil-Pirozzi & Hsu, 2016; Petrella et al., 2023).

As stated, the basis for determining that cognitive activities are cortically stimulating has been largely subjective. Based on their 2021 systematic review and meta-analysis of EEG power spectral measures of cognitive workload, Chikhi et al. (2022) concluded that continued neurophysiologic study of the effects of cognitive workload on brain activation (for example, coherence and functional connectivity) is needed. Using another neuroimaging technology, functional near-infrared spectroscopy (fNIRS), Ashlesh et al. (2020) identified medial and lateral prefrontal cortex activation while participants completed a Sudoku activity. The use of EEG and fNIRS to inform the development of individualized cognitive activity 'prescriptions' that maximize individuals' cognitive health and function during rehabilitation and post-rehabilitation shows promise and warrants future study.

Given the importance of individuals' engagement in tabletop cognitive activities that they perceive as challenging to facilitate LDLPFC stimulation, the association between subjective self-perception and objective LDLPFC activation during activity engagement found in this pilot study with young adults is intriguing and warrants further investigation with adults of all ages (Global Council on Brain Health, 2017; Schooler & Mulatu, 2001). With further study, if this association holds up, querying adults regarding those tabletop cognitive activities that they find most challenging may be a cost-effective, efficient, and universal approach to generate individualized cognitive activity 'prescriptions' that maximize their cognitive function longitudinally. Furthermore, perhaps of most significant potential impact for adults with medical diagnoses such as A.D., MCI, and TBI, pairing the tabletop cognitive activities that they find most challenging with non-invasive brain stimulation techniques targeting the DLPFC as the hub of higher-order cognitive functions and network connections may result in delayed decline, maintenance, or improvement in executive functioning and other cognitive abilities (Cai et al., 2019; Chu et al., 2020; O'Neil-Pirozzi et al., 2017).

These findings highlight the significance of engagement in cognitively challenging activities, with broader implications for cognitive health interventions and long-term brain health. The alignment between self-perceived challenge and objective cortical activation, particularly in the LDLPFC in this study, suggests that interventions should prioritize individualized cognitive tasks that are appropriately challenging to enhance brain activation and cognitive function. This approach is especially relevant for developing cognitive training programs to prevent or mitigate age-related cognitive decline and neurodegenerative diseases, such as Alzheimer's (Bahar-Fuchs et al., 2013). Such tailoring of interventions to ensure sustained engagement in cognitively stimulating activities may offer a promising strategy for maintaining or even improving brain health over time. Further research should explore how these principles can be applied across different populations, including older adults and individuals with cognitive impairments, to develop long-term cognitive health interventions that maximize efficacy and personal relevance.

### *Study Limitations*

Participants for this pilot study were recruited on a university campus. With one inclusion criterion being "full-time college student," the range of ages and education levels was limited. Expanding these inclusion criteria will enhance the generalizability of study findings. The impact of the sex imbalance in this study is not known. Given reported cognitive EEG coherence differences between males and females (Ramos-Loyo et al., 2022), enrollment of similar male and female participants in future studies will be necessary. Additionally, either as exclusion criteria or controlled for statistically, alcohol and other substance use, medications, and sleep issues, which were not considered in this study, should be in the future as these may bias study findings (Aiyer et al., 2016 Prashad et al., 2018; Shenfield et al., 2020).

As stated, some EEG data had artifacts that had to be cleaned and removed by manual cleaning and ICA. Overall, 19.9% of data were missing, with AF3 data missing more than twice as often as Fz and FC5, which appeared to be related to technical factors. Typically, the 20-30% range of missing data is considered acceptable for valid ITT analysis, assuming that the data is randomly missing, which was the case in this study (Frølich & Dowding, 2018; Hu & Du, 2020). Relatedly, the effects of EEG artifacts on data analysis are possible. For example, increased muscle tension can lead to artifactually elevated beta, especially high beta (Frølich & Dowding, 2018). Although 1) data was cleaned and 2) electrodes were in central locations that tend to have less muscle artifact, muscle tension was not measured by electromyography (EMG) lead and, theoretically, could have affected high beta coherence differences between various activity conditions at F3-AF3. Using EMG leads to future studies that may help control for confounding muscle artifacts. As another example, while we do not believe that having to reject some of the EEG files of a participant with thick hair affected this study's results, future studies involving populations that may have different hair types/thicknesses (e.g., different ethnic groups, young versus elderly) should consider its possible influence (Lees et al., 2024). Other common limitations to EEG studies are possible confounding effects of volume conduction and low spatial resolution (Michel & Brunet, 2019). However, this study's objective tabletop cognitive activities and our analytic approach to the high temporal resolution EEG data obtained provide valuable insights into cortical activation associated with such activities.

An "at rest" condition may not be the best control for cognitive activity cortical stimulation comparisons. It is difficult to understand how some participants' engagement in activities like listening to an audiobook was not more cortically stimulating than being "at rest." However, perhaps being 'at rest' cognitively is unattainable, and mind wandering and other cognitive activities/intrusions/interferences make an 'at rest' condition impossible (Garrison et al., 2015; Vago & Zeidan, 2016). Asking participants to include the "at-rest" study condition when rank ordering their perceived challenge of study activities would have informed this possibility. Alternatively, as previously discussed by Turnbull et al. (2019), participants may have activated their LDLPFC more during the "at rest" condition than during the least challenging tabletop cognitive activities. Future studies could address this by asking participants what they thought during the "at rest" conditions.

## Conclusion

While previous research shows positive associations between "cognitively stimulating" activities and cortical stimulation and between "cognitively challenging activities and cortical activation, the basis for considering cognitive activities as cortically stimulating has been subjective. As indexed by EEG-measured left dorsolateral prefrontal cortex (LDLPFC) coherence with surrounding regions in this pilot study, Sudoku was the most cortically stimulating tabletop cognitive activity examined. Based on participants' rankings of the extent of cognitive challenge associated with multiple tabletop cognitive activities, Sudoku was also the most cognitively challenging. With engagement in challenging cognitive stimulation being a key pillar of brain health, developing personalized cognitive exercise programs for individuals to engage in continually is warranted. More work needs to be done to develop accessible, efficient methods of combining individuals' subjective perceptions of tabletop activities that are cognitively challenging to them with objective measures of LDLPFC activation associated with their engagement in those challenging activities. To that end, and informed by this pilot, future studies should utilize experimental designs with combined neuroimaging techniques (e.g., EEG and fNIRS) to provide a more comprehensive understanding of engagement in various levels of challenge completing targeted cognitive activities, cognitive processes, and associated neural correlates by larger and more diverse samples.

## Abbreviations

AD: Alzheimer's Disease
EEG: Electroencephalography
fNIRS: functional near-infrared spectroscopy
Hz: Hertz
ICA: Independent Component Analysis

ITT: Intention-to-treat
LDLPFC: Left Dorsolateral Prefrontal Cortex
MCI: Mild Cognitive Impairment
NIC: Neuroelectrics Instrument Controller
TBI: Traumatic Brain Injury

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## Supplementary Materials

Manuscript Supplement

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## Conflicts of Interest

The authors declare no conflict of interest.

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