rijksuniversiteit groningen

Frontal Midline Theta Power and Behavioural Performance in Working Memory Updating in Subjective Cognitive Decline, Mild Cognitive Impairment, and Healthy Older Adults

Ryan Kooi

Masterthese – Klinische Neuropsychologie

S3981746
April 2026
Vakgroep Psychologie
Rijksuniversiteit Groningen
Thesebegeleider: Nido Wardana

AI usage statement

During the preparation of this master thesis, I used ChatGPT to help structure the outline of my paper, and improve the fluency of the text, specifically regarding grammar, vocab, and punctuation. After using this tool, I reviewed and edited the content as needed and take full responsibility for the content of the final publication.

Abstract

Introduction: Alzheimer's disease (AD) is a leading cause of dementia and is increasingly conceptualized as a continuum that includes preclinical stages with subtle cognitive changes. Subjective cognitive decline (SCD) reflects self-reported cognitive decline without having objective cognitive impairment, whereas mild cognitive impairment (MCI) involves measurable cognitive deficits with relatively preserved daily functioning. Both groups are important regarding research to AD. Executive functions may be sensitive to early AD-related changes. Hence, investigating how SCD operates as a possible predictor/precursor of AD seems relevant. Neural markers of cognitive control and compensatory mechanisms could clarify differences within individuals with SCD and MCI. Methods: the present study examined whether frontal midline theta (FMT) power during a high-load working memory executive functioning task, the N-back task, differs between individuals with SCD, individuals with MCI, and healthy older adults. Participants (N = 41) completed different cognitive loads of the N-back task, including a 0 and a 3-back condition, while EEG was recorded. Behavioural performance was assessed using two load-cost variables: Accuracy, and Reaction time. Group differences in FMT power and behavioural load cost measures were expected, suggesting altered compensatory recruitment and cognitive control demands across individuals with SCD, MCI, and healthy older adults. Results: Contrary to expectations, three one-way ANOVAs showed no significant group differences in N-back FMT power ($\eta^2 \approx .05$) or behavioural load-cost measures. Discussion: The present findings did not provide evidence for significant group differences in FMT power, Accuracy, or Reaction time during high-load working-memory updating. The null findings may reflect subtle group differences, limited statistical power, or variability related to group classification. Future studies using more participants and balanced clinical groups and different working memory load-based FMT comparisons are needed to further examine compensatory recruitment in SCD and MCI.

Frontal Midline Theta Power and Working Memory Updating Performance in Subjective Cognitive Decline, Mild Cognitive Impairment, and Healthy Older Adults

Dementia is a major public health challenge and encompasses a broad spectrum of diseases. Within this spectrum, Alzheimer's disease (AD) is the most common aetiology among older adults (Niu et al., 2017). AD is a neurodegenerative condition with a high prevalence among older adults. Worldwide 32 million people have been diagnosed with AD (Gustavsson et al., 2022). In addition to this high prevalence, AD can be conceptualized as a continuum with multiple stages depending on disease progression, including individuals with normal cognition, subjective cognitive decline, and mild cognitive impairment (Parnetti et al., 2019; Gustavsson et al., 2022). The high worldwide prevalence of AD in combination with the broad range of different levels of cognitive functioning within individuals with AD, underscores the clinical importance of this disease. These different levels of cognitive decline associated with AD can be shown by the assessment of clinical and neuropsychological exams (Jessen et al., 2020).

Subjective cognitive decline (SCD) is one level of cognitive functioning and is defined as a subjective self-experienced decline in cognition compared with a previously normal cognitive status (Jessen et al., 2014). This perceived decline may occur across a variety of different cognitive domains, such as language, attention, memory, and executive functioning (Rabin et al., 2015). An important addition to the definition of SCD is that objective cognitive performance remains within the normal range on standardized neuropsychological tests. Subjective cognitive concerns, such as memory complaints, can be assessed using self-report or other report measures, such as the Cognitive Function Index, the Cognitive Change Index, and the Everyday Cognition questionnaire (Farias et al., 2011; Amariglio et al., 2015; Rattanabannakit et al., 2016; Jessen et al., 2020). Thus, individuals with SCD report a subjective decline in cognition, while performing within the normal range on standardized

tests, but still not meeting the criteria for objective cognitive impairment, such as MCI or AD (Jessen et al., 2014). SCD has therefore been proposed as an early clinical condition that may predict and may precede MCI and AD in the future (Jessen et al., 2014; Jessen et al., 2020). In a meta-analysis, Mitchell et al. (2014) showed that, after approximately four years, 10.9% of the individuals with a form of SCD declined into dementia, and 27% progressed into MCI. Similarly, a meta-analysis by Pike et al. (2022), reported that SCD was associated with an approximately doubled risk of developing both MCI and dementia (Pike et al., 2022). Thus, examining individuals with SCD, as a possible precursor of AD, seems clinically relevant for identifying early cognitive and neurophysiological changes before objective impairment becomes clinically detectable. Hence, assessing both groups of individuals, with SCD and with MCI, seems relevant for research into AD.

Executive functioning (EF) is commonly conceptualized in terms of core components such as working memory updating, inhibitory control, and set shifting (Miyake et al., 2000). EF, including working memory updating, is relevant in the context of the AD-continuum, since executive functions support everyday functioning (Vaughan & Giovanello, 2010; McAlister & Schmitter-Edgecombe, 2016). This is important, because difficulties in EF may influence instrumental activities of daily living, everyday functioning, and quality of life in older adults (Willis et al., 1998; Schmitter-Edgecombe, Parsey, & Lamb, 2014; Smit et al., 2023a). Hence, for individuals with MCI and SCD, it is relevant to investigate whether certain executive functions are affected, even when everyday functioning is still largely preserved. However, within the definition of SCD, objective cognitive performance remains within the normal range on standardized cognitive tests (Jessen et al., 2014). For MCI, on the other hand, diagnosis generally involves having objective cognitive impairment, while independence in everyday functioning is relatively preserved, although subtle enough that difficulties in

complex daily activities may already be present (Albert et al., 2011; Dubois et al., 2007; Petersen et al., 1999).

The N-back task was initially created to test intra-individual performance on tasks with different cognitive loads that measures short-term memory retention (Kirchner, 1958). But more specifically, has the N-back task been widely recognized as a useful psychometric tool for identifying working memory (WM) processes when manipulating load, or content updating (Jaeggi et al., 2010). N-back tasks with high loads are particularly relevant when examining intra-individual performance in WM-updating (Schmiedek, Lövden, & Lindenberger, 2014). Still N-back tasks are widely recognized as a measure of WM-updating (Zając-Lamparska et al., 2024). Therefore, WM-updating can serve as an indicator of executive functioning and, by extension, relate to quality of life for individuals with SCD and MCI.

When an individual performs a certain cognitive task, changes in EEG activity can be observed as changes in oscillatory power within specific scalp regions. EEG power reflects the strength of activity of brain waves within a given frequency range, such as the brain wave types of theta, alpha, beta, and gamma activity. Task-related increases or decreases in power are commonly interpreted as changes in neural synchronization or desynchronization (Pfurtscheller & Lopes da Silva, 1999). Theta power has been strongly associated with WM-processes. It is shown that when during a cognitive task, wherein WM is required, then theta power rises and remains elevated during the task, until the task is offset (Raghavachari et al., 2006). Brain activity in the theta band in EEG examination in humans is commonly defined as the oscillatory activity in the range of 4 and 8 Hz of oscillatory neural activity in humans (Raghavachari et al., 2006). This range between 4 and 8 Hz reflects active brain operations across the whole cortex (Cavanagh & Frank, 2014).

Executive functioning can be examined in individuals by measuring their brain activity, particularly frontal midline theta (FMT) activity has been proposed as an EEG marker of cognitive control processes (Cavanagh & Frank, 2014). FMT activity during EF-tasks is suggested to reflect the recruitment of cognitive control mechanisms, for example in tasks that require attention, inhibition, conflict monitoring, or working-memory updating (Cavanagh & Frank, 2014; Eisma et al., 2021). When considering the performance of certain EF-tasks, the midcingulate cortex has been proposed as an important brain region involved in both FMT activity and cognitive control (Enriquez-Geppert et al., 2013; Mitchell et al., 2008). Cognitive control involves executive functions such as conflict monitoring, set shifting, and WM-updating, and these processes are strongly associated with the prefrontal and midline frontal brain regions (Miyake et al., 2000). Increases in theta power over frontal midline regions, during EF-tasks, are thought to reflect increased cognitive control demands and better performance on tasks that measure conflict monitoring, set shifting, and WM-updating (Cavanagh & Frank, 2014; Jensen & Tesche, 2002; Smit et al., 2023). In line with this, FMT power has been shown to increase during WM-tasks, reflecting activity in frontal brain regions (Onton et al., 2005). Furthermore, an increase in frontal theta activity has been associated with successful WM-updating/-manipulation tasks (Itthipuripat et al., 2013). Thus, examining FMT activity, in the frontal brain regions, during the N-back task, may clarify how behavioural performance is linked to the recruitment of cognitive control across groups.

Research shows that increased brain activity in certain brain areas may reflect compensatory recruitment of additional neural resources, particularly in older adults. For example, the Hemispheric Asymmetry Reduction in Older Adults (“HAROLD”) model suggests that older adults often show more bilateral prefrontal activation than younger adults during cognitive tasks, which may support preserved performance (Cabeza, 2002). Similarly, the posterior–anterior shift in ageing (PASA) describes a pattern in which older adults show

reduced posterior activity together with increased frontal activity, which has often been interpreted as reflecting compensatory frontal recruitment (Davis et al., 2008). Specifically, regarding working memory, older adults showed increased activity in prefrontal brain areas during higher working memory processes tasks, in comparison to younger individuals (Cappell et al., 2010; Mattay et al., 2006). Another influential account is the Compensation-related utilization of neural circuits hypothesis, also the "compensation hypothesis" and referred to as CRUNCH (Reuter-Lorenz & Cappell, 2008). This hypothesis proposes that older adults recruit more neural resources at lower or moderate levels of task demand to maintain performance, in a broad range of tasks. Here higher brain activation is seen in the prefrontal brain areas. However, when cognitive load becomes too high, these compensatory resources may reach the limit in older adults, resulting in reduced neural upregulation and poorer performance. (Reuter-Lorenz & Cappell, 2008). Related to CRUNCH, the Scaffolding Theory of Ageing and Cognition proposes scaffolding in older adults during cognitive tasks, called "cognitive scaffolding", as a compensatory mechanism. Cognitive scaffolding regards the recruitment of additional or alternative neural circuits, to counteract age-related neural decline in older adults, showing more bilateral brain activity as opposed to younger individuals (Goh, & Park, 2009; Park & Reuter-Lorenz, 2009).

However, for individuals with MCI a different pattern may be expected. Instead of showing increased neural activity when task demands become higher, individuals with MCI may show reduced neural activation. Research suggested that brain imaging studies show under activation in individuals with MCI compared to cognitively unimpaired adults during working-memory tasks with an increasing load (Kirova et al., 2015). Similarly, it was shown that frontal activation was reduced in individuals with MCI during high working-memory load (Yeung et al., 2016). Therefore, increased neural activity in SCD may reflect compensatory recruitment or greater cognitive effort, whereas reduced activation in MCI may

indicate that compensatory mechanisms are less effective when cognitive demands become too high.

Cognitive effort can be understood as the amount of controlled processing resources that are needed to perform a task, especially when the task is difficult or requires cognitive control (Shenhav et al., 2013; Westbrook & Braver, 2015). This is also relevant when looking at individuals with SCD. For example, previous research showed that individuals with SCD can show increased neural activity during cognitive tasks. This has been interpreted as a possible sign of greater cognitive effort or compensatory recruitment, especially when subtle dysfunction is already present in episodic memory processes (Erk et al., 2011).

When considering both individuals with SCD and MCI, regarding the brain activity in this frontal midline region, there are studies that have shown an increase in theta power during working memory tasks, even when performance on those working memory tasks was within the normal range. An increase in activation in the prefrontal cortex of the left hemisphere in individuals with SCD was found during encoding of working memory (Rodda et al., 2009). Also, an increase in activation in the right dorsolateral prefrontal cortex was found in individuals with SCD, when they were compared with controls during an episodic memory task (Erk et al., 2011). One meta-study showed many neuroimaging studies, including EEG, with an increase in related functional brain activity in individuals with SCD or early AD disease states, while still being cognitively stable (Viviano & Damoiseaux, 2020). However, there are also studies that show other differences between healthy older adults and adults with SCD regarding brain activation prefrontal brain regions. Hayes et al. (2017) showed a decrease in ventromedial prefrontal cortex within older adults with SCD. One suggestion they offer is that individuals with SCD show different neural mechanisms, in comparison to individuals without SCD, possible being due to advanced ageing (Hayes et al., 2017).

More recent research suggests that reduced brain activation reflects fewer executive processing resources available in performing certain working memory tasks (Blake et al., 2025). Accordingly, older adults tend to perform worse on N-back tasks compared to healthy controls, while still outperforming individuals with MCI (Blake et al., 2025). However, when examining N-back task performance in relation to FMT power, compensatory behaviour was not observed in older adults (Zając-Lamparska et al., 2024).

For the present study, the relevant groups examined were individuals with SCD, individuals with MCI, and healthy older adults, the latter serving as the control group. By assessing their behavioural performance during a working memory updating task and by examining FMT power during the 3-back condition, the present study aimed to investigate whether behavioural performance and neurophysiological activity differed across these groups. Behavioural performance was reflected by Accuracy and Reaction time. In the present study, the variable Accuracy was operationalized using "dprime", reflecting the ability to distinguish targets from non-target, whereas reaction time reflected response speed, both calculated as a load-cost between the 0-back and 3-back conditions. Neurophysiological activity was reflected by FMT power spectral density. Based on previous literature, it can be hypothesized that group differences will be present when considering neurophysiological activity and behavioural performance during the N-back task, mainly due to changes in compensatory mechanisms.

First, it was hypothesized that group differences in FMT power during the N-back task will be present. The SCD group was expected to show an increase in FMT power during N-back in comparison with both the healthy older adults control group and MCI group, specifically for the 3-back load condition. This expectation was based on the suggestion that individuals with SCD show greater cognitive effort or compensatory recruitment during cognitive demanding tasks. In contrast, the MCI group was expected to show reduced FMT

power, compared with both the SCD and control groups, specifically for the 3-back task. Because previous literature suggests that individuals with MCI may show reduced frontal neural activation when the load of a task, hence the task demand, becomes higher. Possibly reflecting having less effective compensatory mechanisms in high cognitive demanding tasks. The null hypothesis was that there would be no group differences in FMT power between the SCD, MCI, and healthy older adults control groups.

Second, it was hypothesized that group differences in behavioural performance during the N-back task will be present. Behavioural performance was reflected by Accuracy and reaction time. The SCD group was expected to show similar behavioural performance on the N-back task in comparison with the healthy older adults control group. This expectation was based on the suggestion that individuals with SCD show subjective cognitive complaints while objective cognitive performance remains within the normal range. In contrast, the MCI group was expected to show poorer behavioural performance, compared with both the SCD and control groups. Because previous literature suggests that individuals with MCI may have more difficulty performing tasks with a high working memory load. Hence, individuals with MCI may be less able to recruit neural resources, which may result in poorer task performance. Therefore, group differences were expected in Accuracy and Reaction time during the N-back task. The null hypothesis was that there would be no group differences for behavioural performance, so no differences in both Accuracy and Reaction time between the SCD, MCI, and healthy older adults control groups.

The main question this paper focuses on is the following: Are there group differences in frontal midline theta power during 3-back working memory updating and in behavioural performance, reflected by Accuracy and Reaction time, between individuals with Subjective Cognitive Decline, individuals with Mild Cognitive Impairment, and healthy older adults?

Method

Design

The present study used a cross-sectional, between-subjects design. The independent variable was group status, consisting of three levels: Subjective Cognitive Decline (SCD), Mild Cognitive Impairment (MCI), and healthy older adults (Control). The dependent variables were behavioural performance on the N-back task, measured using Accuracy and Reaction time, and neurophysiological activity, measured using frontal midline theta power. Accuracy was operationalized as a dprime based load-cost measure between the 0-back and 3-back conditions, whereas Reaction time was operationalized as the difference between mean reaction time for correct responses between the 0-back and 3-back conditions. Participants were classified into one of the three groups based on their neuropsychological assessment results. MCI classification was based on performance on the recognition task of the 15-Word test. Participants were classified as MCI when they scored more than 1.5 standard deviations below the normative value. SCD classification was based on participants' responses to two questions concerning subjective memory problems. If a participant met the criteria for SCD but also scored more than 1.5 standard deviations below the normative value on the 15-Word recognition task, the participant was classified as MCI.

Participants

This study involved participants from around Groningen, The Netherlands. Inclusion criteria were: 1) a minimum age of 50 years; 2) Dutch proficiency; 3) partially or fully right-handedness; and 4) participants with or without memory complaints. Exclusion criteria were: 1) current psychiatric and neurological conditions, other than depression and MCI.

Participants were recruited using multiple nonprobability samples, mostly through convenience sampling (e.g., posters and flyers in public spaces, by email and telephone, and through snowball sampling). Firstly, potential participants were identified through a pre-

existing database of volunteers from a prior study (i.e., the COGMAX project). To supplement this sample, additional participants were recruited through the distribution of flyers and posters in the city centre of Groningen, that attract the target audience such as libraries, medical centres, GP offices, an Alzheimer's café, nursery homes, etc.

The study protocol was reviewed and approved by the Medical Ethics Review Committee of the University Medical Centre Groningen (UMCG reference number ABR no. NL86354.042.24). Participants received an information letter, and a written consent form was obtained from them prior to data collection.

While participants were not compensated for their participation, they received reimbursement for travel costs (e.g., public transport, gasoline, parking fee).

Procedure

Data collection took place at two locations across two separate days. The first session concerned a neuropsychological assessment and was held either at the Centre for Clinical Neuroscience and Cognition or at the University Psychiatry Centre, both part of the UMCG in Groningen. The second session concerned the electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) assessments and was held in an EEG-lab at the faculty of Arts in the Harmony building, in Groningen.

Materials and apparatus

Neuropsychological measures

The test battery for neuropsychological examinations consisted of various tests measuring different domains of cognition. The battery consisted of the following tests: The Edinburgh Handedness Inventory, the Mini-Mental State Examination, the 15-Word Test with recall & recognition, the Trail Making Test, the Stroop Color-Word Test, the Digit Symbol Substitution Test, the Geriatric Depression Scale-30, the Digit Span Test, and the Apathy Evaluation Scale. The battery also included two SCD-questions, about memory complaints,

and a structured interview, about spontaneous speech. Regarding this thesis only the data from the questions of SCD and the 15-Word Test was used.

Questions of SCD. Two questions were included in the test battery to identify a SCD-classification. When participants answered "Yes" to both questions, a SCD-classification was obtained. The two questions were: "Do you believe you have memory problems?" & "Do you believe you experience more memory problems compared to individuals of your age?" (translated from Dutch).

The 15-Word Test (part 1). The 15-Word Test was administered to potentially identify MCI-classification. This test assesses verbal learning and immediate memory. Participants were presented with a list of 15 words, without being aware of the number of words, across five learning trials and were asked to recall as many words as possible after each presentation. The 15-Word Test (part 2) was used to assess delayed verbal memory and recognition. Approximately 20 to 30 minutes after initial encoding, participants were asked to freely recall the previously presented words and subsequently complete a recognition task with a list of 30 words, 15 words from part 1 and 15 previously unpresented distractor words. Outcome measures included the number of correctly recalled and recognized words.

Neurophysiological assessment

Participants performed five computerized tasks while EEG and fNIRS signals were recorder. Participants completed the following tasks in this fixed order: resting-state EEG/fNIRS (2 min eyes open; 4 min eyes closed), a sentence comprehension task, the N-back task, object and action picture naming, and an elicited imitation/sentence repetition task. EEG and fNIRS signals were simultaneously measured and connected via the same cap. The fNIRS optodes were positioned over regions associated to Wernicke's and Broca's areas. However, fNIRS was not included in the current thesis, only the EEG data from the N-back task was used. The N-back task being the only relevant computerized task for this thesis.

N-back task. The N-back task was administered to assess working memory and cognitive load (Kirchner, 1958; Jaeggi et al., 2010; Schmiedek et al., 2014; Zając-Lamparska et al., 2024). The task was generated using OpenSesame. Participants were presented with sequences of letters and were required to respond when a target letter matched a previously presented letter according to one of the three conditions (0-back, , and 3-back). The task consisted of nine blocks of trials, with three blocks for each of the condition. Each block consists of 16 trials. Within each trial, the stimulus (a letter) was presented for 1 second, followed by a response period for 1.5 second.

Before starting the task, participants completed a practice session so that they could ask questions and the observer could ensure that instructions were clear. The task itself consisted of three conditions, increasing in cognitive load, namely 0-back, 2-back, and 3-back. During the 0-back task, the participants were instructed to press the space bar whenever the letter "X" was presented on the screen. During the 2-back task, participants were instructed to press the space bar whenever a letter (e.g., "R", or "O") matched the one presented 2 trials before. During the 3-back task, participants were instructed to press the space bar whenever a letter matched the one presented 3 trials before. The 2-back task was not used during the data processing, but it was part of the Ageling study.

The participants' responses for each condition were given via desktop keyboard input with the right hand. Task conditions were presented in a pseudorandomized order, and neurophysiological activity was recorded throughout the task.

EEG acquisition. EEG was used to measure the brain activity during the 3-back task. Signals were recorded using a *TMSi REFA EEG* amplifier with a total of 36 EEG scalp electrodes according to the international 10-10 system. Two additional electrodes, A1 and A2, were placed on the left and right mastoids and were used for offline re-referencing to the linked mastoids. To monitor ocular activity, facial electrodes were placed at both temples to

record horizontal electrooculographic activity (EOGH), and above and below the left eye to record vertical electrooculographic activity (EOGV). A ground electrode (GND) was included in the setup. Electrode impedance was monitored using *OpenViBE* and kept below 5 kΩ. Data were sampled at a rate of 512 Hz, and no online filters were applied. The common average was used as the online reference during acquisition.

EEG data preprocessing

EEG preprocessing was performed in *MATLAB* using *EEGLAB*. Raw EEG data were imported from *BrainVision* files. Data were re-referenced to the average of the mastoids (A1/A2), while horizontal and vertical EOG channels (EOGH/EOGV) were excluded from re-referencing. Continuous EEG data were visually inspected using *EEGLAB's* scrolling plot. Noisy channels were manually identified by visual inspection and removed prior to artifact correction. The EOGH and EOGV channels were also removed from subsequent EEG analyses. The continuous EEG data were then band-pass filtered between 0.1 and 40 Hz using a basic finite impulse response (FIR) filter.

Independent component analysis (ICA) was performed in *EEGLAB* to identify and remove ocular and other non-brain artifacts. Component classification was supported using *ICLabel*. After ICA-based cleaning, previously removed bad channels were interpolated using *EEGLAB's* channel interpolation.

Data were segmented into 1.4-s epochs, ranging from 0.2 s before target presentation in the 3-back condition to 1.2 s after target presentation. Epochs were rejected using threshold-based artifact rejection if amplitudes exceeded ±150 µV.

Frontal midline theta (FMT) power spectral density was extracted using a *FieldTrip*-based script with a multi-taper frequency transformation method ('mtfft'). FMT power was quantified in a predefined frontal/frontocentral region of interest consisting of the following

six electrodes: Fz, F3, F4, FCz, FC3, and FC4. FMT was defined as mean theta-band power (4–7 Hz), averaged across the frontal/frontocentral region and across the segmented epochs.

Data Extraction

Behavioural performance on the N-back task was assessed using two variables: Accuracy and Reaction time. Because the current study focused on high working-memory load, both variables were computed as load-cost measures based on the difference in performance on the 0-back and 3-back conditions.

First, mean reaction time for correct responses was calculated for each participant. This was calculated by using the difference in mean reaction time for correct responses between the 0-back and 3-back conditions. These variables were labelled “avgRThit0” and “avgRThit3”. The final Reaction time variable was computed by subtracting reaction time in the 0-back condition from reaction time in the 3-back condition:

pure_avgRThit = avgRThit3 – avgRThit0.

Higher positive values of reaction time load-cost values indicate slower responses in the 3-back condition relative to the 0-back condition. Thus, reflecting slower responses under a higher working-memory load.

Second, Accuracy was operationalized using dprime, which was calculated separately for the 0-back and 3-back conditions. These variables were labelled dprime0 and dprime3. The final Accuracy variable was computed by subtracting the dprime in the 3-back condition, labelled as “dprime3”, from dprime in the 0-back condition, labelled as “dprime0”:

pure_dprime = dprime0 – dprime3.

Higher positive Accuracy values reflect a larger reduction in task sensitivity in the 3-back condition compared with the 0-back condition.

Neurophysiological activity was assessed using frontal midline theta power derived from the EEG data. Frontal midline theta power was extracted during performance of the 3-back

working-memory updating task. Only performance during the 3-back condition was extracted, because the present study focussed on compensatory recruitment and cognitive control demands with a high working-memory load.

Statistical Analyses

Statistical analyses were performed using JASP 0.19.3 (Intel) version. Group differences were examined using three separate one-way between-subjects analyses of variance (ANOVAs). In each ANOVA, group status was the independent variable consisting of three levels: Subjective Cognitive Decline (SCD), Mild Cognitive Impairment (MCI), and healthy older adults (Control). The dependent variables were FMT power during the 3-back condition, Accuracy, and Reaction time. Accuracy was operationalized as the difference in d-prime between the 0-back and 3-back conditions, and Reaction time was based on the difference in mean reaction time for correct responses between the 0-back and 3-back conditions.

Prior to conducting the ANOVAs, the standard assumptions of normality, homogeneity of variance, and independence of observations were evaluated. Normality was assessed by visually inspecting Q-Q plots of the residuals. Homogeneity of variance was assessed using Levene's test. Independence of observations was ensured by the between-subjects study design and independent sampling of participants.

Results

Descriptives

Sample characteristics

The sample size is $N = 41$, and includes 19 males, 21 females, and 1 other, whose ages ranged from 55 to 86 years old ($M = 73$, $SD = 6$). The control group consists of 22 participants (13 females, and 9 males), the SCD group consists of 14 participants (6 females, 7 males, and 1 other), and the MCI group consists of 5 participants (2 females, and 3 males). Table 1 shows the means, standard deviations, and within group percentages of the relevant

demographics of each group. Each group consists of participants with different educational background (to see the education levels per group, see table A1 in the Appendix).

Table 1

Demographic Charactertics by Group

Note. Categorical variables are presented as *n* (% within group). Continuous variables are presented as *M* (*SD*). SCD = Subjective Cognitive Decline; MCI = Mild Cognitive

Demographic study characteristics	Control (n = 22)	SCD (n = 14)	MCI (n = 5)	Full sample (N = 41)
Age, years (*M, SD*)	73.3 (6.1)	69.6 (9.4)	76.8 (4.4)	72.5 (7.5)
Gender (*n, %)*				
Female	13 (59.1)	6 (42.9)	2 (40.0)	21 (51.2)
Male	9 (40.9)	7 (50.0)	3 (60.0)	19 (46.3)
Other	0 (0.0)	1 (7.1)	0 (0.0)	1 (2.4)
Education levels				
1 Basisonderwijs	1 (4.5)	0 (0.0)	0 (0.0)	1 (2.4)
2 LBO	0 (0.0)	2 (14.3)	2 (40.0)	4 (9.8)
3 MAVO/MBO	8 (36.4)	3 (21.4)	1 (20.0)	12 (29.3)
4 HAVO/VWO/HBO	9 (40.9)	9 (64.3)	1 (20.0)	19 (46.3)
5 Universiteit	4 (18.2)	0 (0.0)	1 (20.0)	5 (12.2)
Education, in years (*M, SD*)	19.2 (7.4)	19.80 (7.4)	19.5 (7.8)	19.5 (7.3)
MMSE-score (*M*, *SD*)	28.1 (1.4)	28.0 (1.9)	27.2 (2.9)	27.9 (1.8)
GDS-score (*M*, *SD*)	12.2 (11.5)	9.7 (6.9)	4.4 (5.0)	10.4 (9.7)

Impairment; MMSE = Mini-Mental State Examination; GDS = Geriatric Depression Scale.

Table 2

Clinical and Neuropsychological Characteristics by Group

	Group	M	SD
MMSE-score	Control	28.05	1.39
	SCD	28.00	1.92
	MCI	27.20	2.95
GDS-score	Control	12.23	11.50
	SCD	9.71	6.96
	MCI	4.40	5.03
AES-score	Control	24.86	5.96
	SCD	29.50	6.78
	MCI	24.60	4.93

Note. MMSE = Mini Mental State Examination; GDS = Geriatric Depression Scale; AES = Apathy Evaluation Scale; SCD = Subjective Cognitive Decline; MCI = Mild Cognitive Impairment; MCI

The power spectral density analysis of FMT during N-back shows a sample of $N = 41$, with $M = 0.327$ $\mu V^2/Hz$, and $SD = 0.198$ $\mu V^2/Hz$. The behavioural variables were assessed using Accuracy and Reaction time, corresponding to the pure d-prime and pure average reaction time variables, respectively. The data of the behavioural variables of Accuracy show $N = 41$, with $M = 1{,}503$, and $SD = 0{,}489$, and of Reaction time show $N = 41$, with $M =$ 282.626 ms, and $SD = 266.985$ ms.

The descriptives of the Power Spectral Density in FMT, Accuracy, and Reaction time of each group are presented in table 3.

Table 3

Descriptive Statistics for Outcome Variables by group

	Control, *M* (*SD*) (n = 22)	SCD, *M* (*SD*) (n = 14)	MCI, *M* (*SD*) (n = 5)
Power Spectral Density in FMT	0.294 (0.181)	0.341 (0.198)	0.430 (0.270)
Accuracy	1.526 (0.499)	1.442 (0.491)	1.569 (0.523)
Reaction time	285.801 (198.707)	282.786 (356.71)	268.211 (302.490)

Note. FMT = Frontal Midline Theta; SCD = Subjective Cognitive Decline; MCI = Mild Cognitive Impairment. Accuracy was operationalized as the difference in dprime between the 0-back and the 3-back conditions. Reaction time was operationalized as the difference in mean Reaction time for correct responses between the 0-back and 3-back conditions.

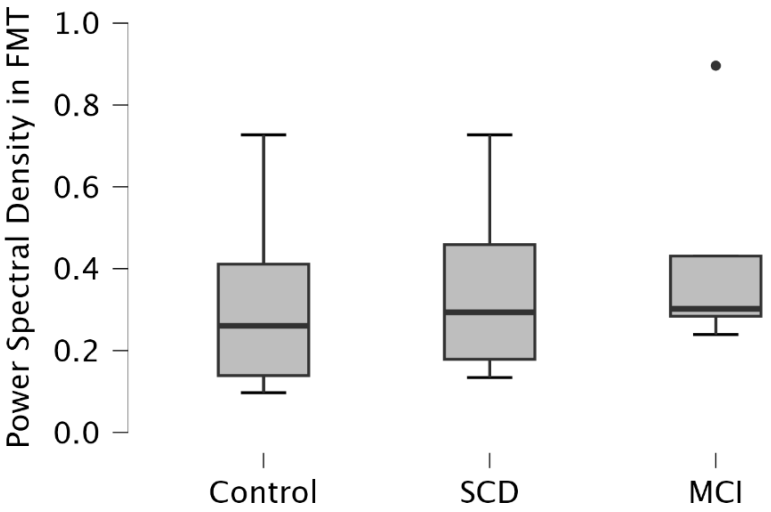
Group Differences in FMT Power Spectral Density

Levene's test of homogeneity did not suggest heterogeneity of variance, $F(2, 38) = 0.312$, $p = 0.734$. Visual inspection of the Q-Q plot did not indicate strong deviations from normality (see Figure A1 in Appendix A for the Q-Q plot). Figure 1 visualizes this group comparison.

The one-way ANOVA showed no significant effects for group differences in FMT power during the N-back task. $F(2, 38) = 1.027$, $p = 0.368$. The effect size shows a small-to-moderate effect, $\eta^2 = 0.051$.

Figure 1

Boxplots for FMT power spectral density during N-back by group



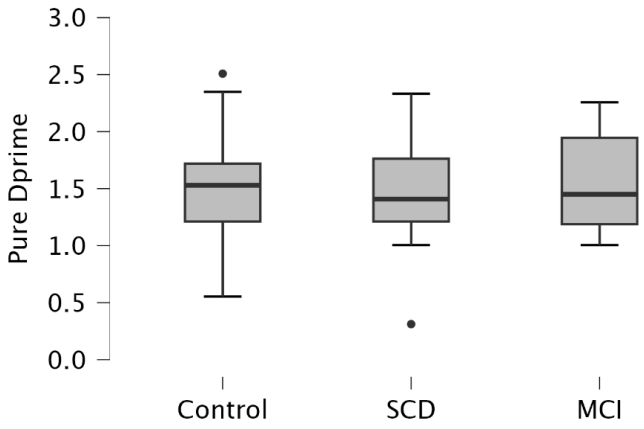
Group Differences in Accuracy During the N-back task

Levene's test of homogeneity did not suggest heterogeneity of variance, $F(2, 38) = 0.104$, $p = 0.901$ Visual inspection of the Q-Q plot did not indicate strong deviations from normality (See Figure A2 in the Appendix A for the Q-Q plot). Figure 2 visualizes this group comparison.

The one-way ANOVA showed no significant effects for groups in Accuracy during the N-back task. $F(2, 38) = 0.086$, $p = 0.841$. The effect size was small, $\eta^2 = 0.009$.

Figure 2

Boxplots for Accuracy during N-back by group



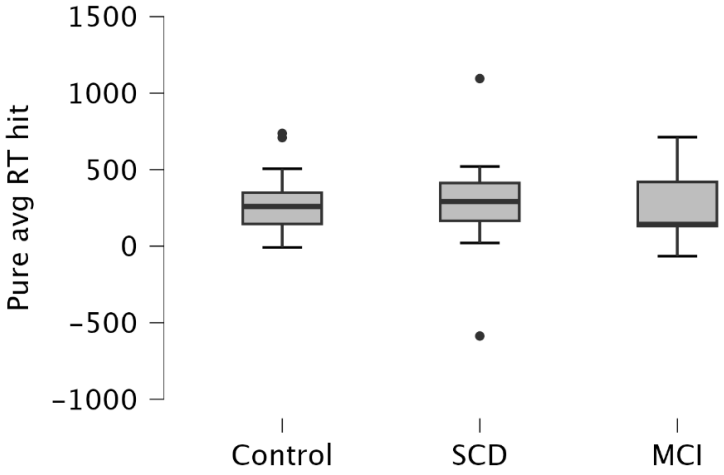
Group Differences in Reaction Time During the N-back task

Levene's test of homogeneity did not suggest heterogeneity of variance, F (2, 38) = 0.790, p = 0.461. Visual inspection of the Q-Q plot did not indicate strong deviations from normality (See Figure A3 in the Appendix A for the Q-Q plot). Figure 3 visualizes this group comparison.

The one-way ANOVA showed no significant effects for Reaction time during the N-back task. F (2, 38) = 0.008, p = 0.992. The effect size shows a negligible effect, η^2 = 0.00044.

Figure 3

Boxplots for Reaction time during N-back by group



Discussion

The present study investigated whether frontal midline theta (FMT) power during high working-memory updating load (3-back condition) differed between individuals with subjective cognitive decline (SCD), individuals with mild cognitive impairment (MCI), and a healthy older adults control group. In addition, behavioural performance was examined during the N-back task, considering Accuracy and Reaction time, to investigate group-related differences in task performance. The aim of this study was to see whether neurophysiological activity and behavioural performance during a high demand working memory updating task

differed across groups with different levels of cognitive functioning, within the AD continuum. This study had a final sample consisting of 41 participants, including 22 healthy older adults, 13 individuals with SCD, and 5 individuals with MCI. The groups were unequal in size, specifically the MCI group being substantially small, this is an important consideration when interpretating the results.

Contrary to the hypotheses, the analyses revealed no significant group differences in FMT power, Accuracy, or Reaction time. Although the observed effect size for FMT power (η^2 =.051), suggests a small-to-moderate proportion of explained variance. Results did not reach statistical significance. The effect sizes were small for Accuracy and negligible for Reaction time, suggesting little evidence for meaningful behavioural group differences in the current sample.

Group differences in FMT Power

The first hypothesis concerned group differences in FMT power during the 3-back condition. Based on previous literature, it was expected that individuals with SCD would show increased FMT power, reflecting greater cognitive effort or compensatory recruitment during a cognitively demanding task (Erk et al., 2011; Rodda et al., 2009; Viviano & Damoiseaux, 2020). In contrast, individuals with MCI were expected to show reduced FMT power, as previous research suggests that MCI may be associated with reduced frontal activation when working-memory load increases (Kirova et al., 2015; Yeung et al., 2016).

However, the present results did not support this hypothesis, since no significant group differences in FMT power were found. For, FMT power was highest in the MCI group, followed by the SCD group and then the healthy older adults control group. This was not in line with the expectations, because the MCI group was expected to show reduced FMT power. Although, it is important to mention that this result was not significant and the MCI group was small, these results should therefore be interpreted with caution. It may reflect

sampling variability, individual differences, or the influence of outliers rather than a reliable group effect.

The absence of significant group differences may fit with previous literature on neural activity in SCD and MCI. Some studies have reported increased activation in individuals with SCD, which has been interpreted as possible compensation or greater cognitive effort (Erk et al., 2011; Rodda et al., 2009). Whereas other studies have shown decreased or altered activation in individuals with SCD, suggesting that neural activity in SCD does not follow one simple pattern (Hayes et al., 2017). Therefore, the current nonsignificant finding may suggest that neural differences in SCD and MCI are subtle and may depend on task demands, disease stage, sample characteristics, and the specific neural measure used. Furthermore, the present study focused specifically on FMT power during the 3-back condition. FMT activity has been linked to cognitive control and working-memory updating and increases in FMT are often interpreted as reflecting recruitment of cognitive control mechanisms (Cavanagh & Frank, 2014; Jensen & Tesche, 2002; Onton et al., 2005). However, FMT power during a high-load and demanding condition may not have been sensitive enough to differentiate between groups.

Group Differences in Behavioural Performance

The second hypothesis concerned group differences in behavioural performance during the N-back task, reflected by Accuracy and Reaction time. It was expected that the SCD group would perform similarly to the healthy older adults control group, whereas the MCI group was expected to show poorer performance. However, the present study did not find significant group differences for either Accuracy or Reaction time. Therefore, the behavioural hypothesis was not supported.

For Accuracy, the groups did not differ significantly in the reduction in task sensitivity between the 0-back and 3-back conditions. Although the MCI group descriptively showed the

highest Accuracy value, suggesting, according to the literature, a larger reduction in task sensitivity in the 3-back condition compared with the 0-back condition and hence performing worse. However, this difference was small and not significant. Therefore, the results do not provide enough evidence that individuals with MCI performed worse in Accuracy than individuals with SCD or healthy older adults.

For Reaction time, no significant group differences were found either. The groups showed similar Reaction time values, suggesting that slowing during the N-back task did not meaningfully differ between groups. This was also contrary to the expectation that the MCI group would show slower responses under higher working-memory load. One possible explanation is that the MCI participants in the present study were still relatively high functioning. Another possibility is that the 3-back task was demanding for all groups, resulting in variability across the whole sample rather than clear group separation.

The absence of behavioural group differences is also relevant for the interpretation of the FMT results. Increased neural activity is most clearly interpreted as compensatory when behavioural performance is maintained or improved. In the present study, however, no significant group differences were found in either FMT power or behavioural performance. Therefore, the findings do not provide strong support for successful compensatory recruitment in SCD or reduced compensatory capacity in MCI.

Models such as CRUNCH suggest that individuals at risk may show increased neural recruitment at lower or moderate task demands, but that compensatory capacity may plateau or break down at higher demands (Reuter-Lorenz & Cappell, 2008). Under this account, group differences might become more detectable when working-memory load is increased even further. For example, a 4-back condition might make it more visible which group reaches the limits of their capacity first. Groups that then are unable to compensate sufficiently anymore will show poorer performance. However, it is still speculative to state

that this might happen. It is also possible that the 3-back condition was already demanding enough to detect group differences, but that significant results were not found due to the small and unequal sample size, specifically the MCI group. Therefore, the present findings cannot determine whether the absence of group differences reflects insufficient task sensitivity, limited statistical power, or genuine similarities in neural activity and behavioural performance across groups.

Limitations and strengths

Several methodological limitations may also have reduced sensitivity to detect group effects. The most critical methodological limitation of this study is the very small MCI subgroup (n = 5). With this group size, the ANOVA had insufficient statistical power to reliably detect even medium-sized effects, meaning the null results for MCI comparisons cannot be interpreted as evidence of no difference. Due to this the findings were susceptible to sampling variability and outliers. This led to the inability to detect true differences, particularly for EEG-derived measures that can show large inter-individual variability.

Second, the operationalization of SCD in this study relied on a limited set of self-report items (Jessen et al., 2020). The two-question classification in this current study does not align with more comprehensive SCD-plus frameworks, which require additional criteria such as onset within the last five years, confirmation by an informant, participants being 60 years or older, concern about decline, and more (Jessen et al., 2020).

This approach may not align fully with more stringent SCD (or SCD-plus) frameworks and may capture non-neurodegenerative contributors such as health anxiety, personality differences, or mood-related concerns. Also, influences of other psychiatric disorders may have played parts. During the neuropsychological assessment the participants were asked if they have had depressive symptoms lately, together with possible other affective factors that may influence both subjective complaints and cognitive performance.

These symptoms may have influenced the results and can be potentially confounding associations between group status and outcomes. Participants with other psychiatric disorders were excluded, however depressive patients were still included. Depression and impaired cognition, both MCI and AD, have shown associations in academic literature (Diniz et al., 2013, & Ismail et al., 2017). Therefore, it cannot be ruled out that depressive symptoms have contributed to the outcome, particularly regarding the SCD group. Future studies should use more comprehensive SCD criteria, such as the SCD plus criteria, and systematically assess depressive symptoms, for example by including depression scores as a covariate or by examining their independent contribution to cognitive and neural outcomes.

Third, EEG measurement can meaningfully influence spectral power estimates. FMT power is sensitive to artifact correction, channel rejection and interpolation, epoch selection, and whether absolute or relative power is used. This is similar when regarding the decisions during ICA-based artifact correction may influence FMT power. Removing too few artifacts could leave eye movement or muscle contamination in the data, whereas removing too many then it could also remove neural activity relevant for theta power. These pre-processing choices are relevant for the current study. If a follow-up study would be done, or if this study would be replicated, different choices could be made concerning the correction of artifacts. This may influence the outcomes of the measures

Additionally, task order and participant fatigue may have contributed to variability in both behavioural performance and EEG measures. In the present study, participants completed several neuroimaging tasks in a fixed order, with the N-back task administered after the resting-state recording and sentence comprehension task. As a result, performance during the N-back task may not only reflect working-memory updating ability, but also the cumulative effects of sustained task engagement, reduced alertness, or cognitive fatigue. The N-back task is placed half-way through the experiment, but then still fatigue could have

influenced performance. This may be particularly relevant in older adults, as fatigue has been associated with cognitive decline and everyday functioning over time, and performance variability is a marker of cognitive functioning in ageing (Bielak et al., 2010; Lin et al., 2013). In addition, cognitive ability may be reflected not only in mean performance, but also in increased intraindividual variability in reaction time over the course of a task, over the course of three hours (Wang et al., 2014). The current study, approximately 2,5 hours of duration, may have shown this effect too.

However, at the neural level, some literature suggest that older adults do not show affected EEG responses. Older adults may show stable behavioural performance accompanied by declining or unchanged neural activity, suggesting limited neural compensation in response to fatigue (Babu Henry Samuel et al., 2019). Therefore, if participants became fatigued by the time they completed the N-back task, this may have influenced behavioural performance and reduced or altered frontal theta upregulation, potentially obscuring group differences. Future studies could counterbalance task order, include subjective fatigue ratings before and after each task to better separate working-memory-related neural activity from fatigue-related variability.

Furthermore, participants in the present study were recruited through nonprobability sampling in a community setting, which may limit the generalizability of the findings to clinical MCI cohorts. Sampling strategy is an important determinant of external validity in clinical research, and community-recruited samples may differ from clinic-based samples in symptom severity, disease stage, comorbidity profile, and likelihood of underlying AD pathology (Elfil & Negida, 2017). This is particularly relevant for MCI, as clinic-based MCI cohorts, a conversion rate to dementia of 13%, have been shown to differ from community-based cohorts, a conversion rate to dementia of 3%, thus showing higher rates of progression to dementia (Farias et al., 2009). So, clinical MCI samples, or biomarker-confirmed AD-

continuum samples, may show stronger and more consistent group separation in both behavioural and neural measures than the present community-based sample.

Conclusion

In conclusion, the current study examined whether individuals with SCD, individuals with MCI, and healthy older adults differed in FMT power and behavioural performance during a working memory updating task. Contrary to the hypotheses, no significant group differences were found in FMT power, Accuracy or Reaction time. Therefore, this study did not provide clear evidence that FMT power during the 3-back task differentiates between these groups. The behavioural findings also did not find support for the expectation that individuals with MCI would show poorer performance compared with SCD and healthy older adults.

Although the results were not significant, they still provide useful information. A small-to-moderate effect size for FMT power suggests that there may have been some group-related differences present, but that this effect was not strong enough to reach statistical significance. Therefore, potential differences in neural recruitment between SCD, MCI, and healthy older adults may be difficult to detect within this study design.

Overall, the present study findings do not support robust group differences in compensatory or behavioural working-memory performance, in this sample. However, these findings show the complexity of investigating neural compensation in early cognitive decline. Future studies should aim for larger and more balanced group sizes, more detailed, or stringent SCD and MCI characterization. In addition, it may be useful to compare FMT power directly across multiple working-memory load levels, rather than analysing only the 3-back condition. This may help clarify whether FMT power reflects compensatory recruitment, reduced neural resources, or general cognitive control demands across different cognitive stages of the AD continuum.

References

Albert, M. S., DeKosky, S. T., Dickson, D., Dubois, B., Feldman, H. H., Fox, N. C., Gamst, A., Holtzman, D. M., Jagust, W. J., Petersen, R. C., Snyder, P. J., Carrillo, M. C., Thies, B., & Phelps, C. H. (2011). The diagnosis of mild cognitive impairment due to Alzheimer's disease: recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. Alzheimer's & dementia : the journal of the Alzheimer's Association, 7(3), 270–279. https://doi.org/10.1016/j.jalz.2011.03.008

Amariglio, R. E., Donohue, M. C., Marshall, G. A., Rentz, D. M., Salmon, D. P., Ferris, S. H., Karantzoulis, S., Aisen, P. S., Sperling, R. A., & Alzheimer's Disease Cooperative Study (2015). Tracking early decline in cognitive function in older individuals at risk for Alzheimer disease dementia: the Alzheimer's Disease Cooperative Study Cognitive Function Instrument. JAMA neurology, 72(4), 446–454. https://doi.org/10.1001/jamaneurol.2014.3375

Babu Henry Samuel, I., Wang, C., Hu, Z., Ding, M., & Kluger, B. M. (2019). Compensatory neural responses to cognitive fatigue in young and older adults. Frontiers in Neural Circuits, 13, Article 12. https://doi.org/10.3389/fncir.2019.00012

Bielak, A. A., Hultsch, D. F., Strauss, E., MacDonald, S. W., & Hunter, M. A. (2010). Intraindividual variability is related to cognitive change in older adults: evidence for within-person coupling. Psychology and aging, 25(3), 575–586. https://doi-org.proxy-ub.rug.nl/10.1037/a0019503

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. Psychology and Aging, 17(1), 85–100. https://doi.org/10.1037/0882-7974.17.1.85

Cappell, K. A., Gmeindl, L., & Reuter-Lorenz, P. A. (2010). Age differences in prefrontal recruitment during verbal working memory maintenance depend on memory load. *Cortex, 46*(4), 462–473. https://doi.org/10.1016/j.cortex.2009.11.009

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences, 18*(8), 414–421. https://doi.org/10.1016/j.tics.2014.04.012

Cavanagh, J. F., & Shackman, A. J. (2015). Frontal midline theta reflects anxiety and cognitive control: Meta-analytic evidence. *Journal of Physiology-Paris, 109*(1–3), 3–15. https://doi.org/10.1016/j.jphysparis.2014.04.003

Ćurčić-Blake, B., Futenma, Y., Willcox, D. C., Tazangi, P. E., Wardana, N. D., Ueda, Y., & Aleman, A. (2025). Difference between Okinawan and Dutch older adults in prefrontal brain activation. *Frontiers in Aging Neuroscience, 17*, Article 1454068. https://doi.org/10.3389/fnagi.2025.1454068

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Qué PASA? The posterior–anterior shift in aging. Cerebral Cortex, 18(5), 1201–1209. https://doi.org/10.1093/cercor/bhm155

Diniz, B. S., Butters, M. A., Albert, S. M., Dew, M. A., & Reynolds, C. F., 3rd (2013). Late-life depression and risk of vascular dementia and Alzheimer's disease: systematic review and meta-analysis of community-based cohort studies. The British journal of psychiatry: the journal of mental science, 202(5), 329–335. https://doi-org.proxy-ub.rug.nl/10.1192/bjp.bp.112.118307

Dubois, B., Feldman, H. H., Jacova, C., DeKosky, S. T., Barberger-Gateau, P., Cummings, J., Delacourte, A., Galasko, D., Gauthier, S., Jicha, G., Meguro, K., O'Brien, J.,

Pasquier, F., Robert, P., Rossor, M., Salloway, S., Stern, Y., Visser, P. J., & Scheltens, P. (2007). Research criteria for the diagnosis of Alzheimer's disease: Revising the NINCDS–ADRDA criteria. *The Lancet Neurology, 6*(8), 734–746. https://doi.org/10.1016/S1474-4422(07)70178-3

Eisma, J., Rawls, E., Long, S., Mach, R., & Lamm, C. (2021). Frontal midline theta differentiates separate cognitive control strategies while still generalizing the need for cognitive control. Scientific reports, 11(1), 14641. https://doi.org/10.1038/s41598-021-94162-z

Elfil, M., & Negida, A. (2017). Sampling methods in Clinical Research; an Educational Review. Emergency (Tehran, Iran), 5(1), e52.

Enriquez-Geppert, S., Huster, R. J., Scharfenort, R., Mokom, Z. N., Vosskuhl, J., Figge, C., Zimmermann, J., & Herrmann, C. S. (2013). The morphology of midcingulate cortex predicts frontal-midline theta neurofeedback success. Frontiers in Human Neuroscience, 7, Article 453. https://doi.org/10.3389/fnhum.2013.00453

Erk, S., Spottke, A., Meisen, A., Wagner, M., Walter, H., & Jessen, F. (2011). Evidence of neuronal compensation during episodic memory in subjective memory impairment. *Archives of General Psychiatry, 68*(8), 845–852. https://doi.org/10.1001/archgenpsychiatry.2011.80

Farias, S. T., Mungas, D., Reed, B. R., Harvey, D., & DeCarli, C. (2009). Progression of mild cognitive impairment to dementia in clinic- vs community-based cohorts. Archives of neurology, 66(9), 1151–1157. https://doi-org.proxy-ub.rug.nl/10.1001/archneurol.2009.106

Farias, S. T., Mungas, D., Harvey, D. J., Simmons, A., Reed, B. R., & DeCarli, C. (2011). The measurement of everyday cognition: Development and validation of a short form of the Everyday Cognition scales. Alzheimer's & Dementia, 7(6), 593–601. https://doi.org/10.1016/j.jalz.2011.02.007

Goh, J. O. S., & Park, D. C. (2009). Neuroplasticity and cognitive aging: The scaffolding theory of aging and cognition. *Restorative Neurology and Neuroscience, 27*(5), 391–403. https://doi.org/10.3233/RNN-2009-0493

Gustavsson, A., Norton, N., Fast, T., Frölich, L., Georges, J., Holzapfel, D., Kirabali, T., Krolak-Salmon, P., Rossini, P. M., Ferretti, M. T., Lanman, L., Santuccione Chadha, A., & van der Flier, W. M. (202). Global estimates on the number of persons across the Alzheimer's disease continuum. *Alzheimer's & Dementia, 19*(2), 658–670. https://doi.org/10.1002/alz.12694

Hayes, J. M., Tang, L., Viviano, R. P., van Rooden, S., Ofen, N., & Damoiseaux, J. S. (2017). Subjective memory complaints are associated with brain activation supporting successful memory encoding. *Neurobiology of Aging, 60*, 71–80. https://doi.org/10.1016/j.neurobiolaging.2017.08.015

Ismail, Z., Elbayoumi, H., Fischer, C. E., Hogan, D. B., Millikin, C. P., Schweizer, T., Mortby, M. E., Smith, E. E., Patten, S. B., & Fiest, K. M. (2017). Prevalence of Depression in Patients With Mild Cognitive Impairment: A Systematic Review and Meta-analysis. JAMA psychiatry, 74(1), 58–67. https://doi-org.proxy-ub.rug.nl/10.1001/jamapsychiatry.2016.3162

Itthipuripat, S., Wessel, J. R., & Aron, A. R. (2013). Frontal theta is a signature of successful working memory manipulation. *Experimental Brain Research, 224*(2), 255–262. https://doi.org/10.1007/s00221-012-3305-3

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*(4), 394–412. https://doi.org/10.1080/09658211003702171

Jensen, O., & Tesche, C. D. (2002). Frontal theta activity in humans increases with memory load in a working memory task. European Journal of Neuroscience, 15(8), 1395–1399. https://doi.org/10.1046/j.1460-9568.2002.01975.x

Jessen, F., Amariglio, R. E., van Boxtel, M., Breteler, M., Ceccaldi, M., Chételat, G., Dubois, B., Dufouil, C., Ellis, K. A., van der Flier, W. M., Glodzik, L., van Harten, A. C., de Leon, M. J., McHugh, P., Mielke, M. M., Molinuevo, J. L., Mosconi, L., Osorio, R. S., Perrotin, A., ... Wagner, M. (2014). A conceptual framework for research on subjective cognitive decline in preclinical Alzheimer's disease. Alzheimer's & Dementia, 10(6), 844–852. https://doi.org/10.1016/j.jalz.2014.01.001

Jessen, F., Amariglio, R. E., Buckley, R. F., van der Flier, W. M., Han, Y., Molinuevo, J. L., Rabin, L., Rentz, D. M., Rodriguez-Gomez, O., Saykin, A. J., Sikkes, S. A. M., Smart, C. M., Wolfsgruber, S., & Wagner, M. (2020). The characterisation of subjective cognitive decline. The Lancet. Neurology, 19(3), 271–278. https://doi.org/10.1016/S1474-4422(19)30368-0

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352–358. https://doi.org/10.1037/h0043688

Kirova, A.-M., Bays, R. B., & Lagalwar, S. (2015). Working memory and executive function decline across normal aging, mild cognitive impairment, and Alzheimer's disease. BioMed Research International, 2015, Article 748212. https://doi.org/10.1155/2015/748212

Lin, F., Chen, D. G., Vance, D. E., Ball, K. K., & Mapstone, M. (2013). Longitudinal relationships between subjective fatigue, cognitive function, and everyday functioning in old

age. International psychogeriatrics, 25(2), 275–285. https://doi-org.proxy-ub.rug.nl/10.1017/S1041610212001718

Mattay, V. S., Fera, F., Tessitore, A., Hariri, A. R., Berman, K. F., Das, S., Meyer-Lindenberg, A., Goldberg, T. E., Callicott, J. H., & Weinberger, D. R. (2006). Neurophysiological correlates of age-related changes in working memory capacity. *Neuroscience Letters, 392*(1–2), 32–37. https://doi.org/10.1016/j.neulet.2005.09.025

McAlister, C., & Schmitter-Edgecombe, M. (2016). Executive function subcomponents and their relations to everyday functioning in healthy older adults. Journal of clinical and experimental neuropsychology, 38(8), 925–940. https://doi.org/10.1080/13803395.2016.1177490

Mitchell, A. J., Beaumont, H., Ferguson, D., Yadegarfar, M., & Stubbs, B. (2014). Risk of dementia and mild cognitive impairment in older people with subjective memory complaints: Meta-analysis. Acta Psychiatrica Scandinavica, 130(6), 439–451. https://doi.org/10.1111/acps.12336

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Niu, H., Álvarez-Álvarez, I., Guillén-Grima, F., & Aguinaga-Ontoso, I. (2017). Prevalence and incidence of Alzheimer's disease in Europe: A meta-analysis. *Neurología, 32*(8), 523–532. https://doi.org/10.1016/j.nrl.2016.02.016

Onton, J., Delorme, A., & Makeig, S. (2005). Frontal midline EEG dynamics during working memory. *NeuroImage, 27*(2), 341–356. https://doi.org/10.1016/j.neuroimage.2005.04.014

Parnetti, L., Chipi, E., Salvadori, N., D'Andrea, K., & Eusebi, P. (2019). Prevalence and risk of progression of preclinical Alzheimer's disease stages: a systematic review and meta-analysis. Alzheimer's research & therapy, 11(1), 7. https://doi.org/10.1186/s13195-018-0459-7

Park, D. C., & Reuter-Lorenz, P. A. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*, 173-196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. G., & Kokmen, E. (1999). Mild cognitive impairment: Clinical characterization and outcome. Archives of Neurology, 56(3), 303–308. https://doi.org/10.1001/archneur.56.3.303

Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. Clinical Neurophysiology, 110(11), 1842–1857. https://doi.org/10.1016/S1388-2457(99)00141-8

2Rabin, L. A., Smart, C. M., Crane, P. K., Amariglio, R. E., Berman, L. M., Boada, M., Buckley, R. F., Chételat, G., Dubois, B., Ellis, K. A., Gifford, K. A., Jefferson, A. L., Jessen, F., Katz, M. J., Lipton, R. B., Luck, T., Maruff, P., Mielke, M. M., Molinuevo, J. L., Naeem, F., … Sikkes, S. A. (2015). Subjective Cognitive Decline in Older Adults: An Overview of Self-Report Measures Used Across 19 International Research Studies. Journal of Alzheimer's disease : JAD, 48 Suppl 1(0 1), S63–S86. https://doi.org/10.3233/JAD-150154

Raghavachari, S., Lisman, J. E., Tully, M., Madsen, J. R., Bromfield, E. B., & Kahana, M. J. (2006). Theta oscillations in human cortex during a working-memory task: Evidence for local generators. *Journal of Neurophysiology, 95*(3), 1630–1638. https://doi.org/10.1152/jn.00409.2005

Rattanabannakit, C., Risacher, S. L., Gao, S., Lane, K. A., Brown, S. A., McDonald, B. C., Unverzagt, F. W., Apostolova, L. G., Saykin, A. J., & Farlow, M. R. (2016). The Cognitive Change Index as a Measure of Self and Informant Perception of Cognitive Decline: Relation to Neuropsychological Tests. Journal of Alzheimer's disease : JAD, 51(4), 1145–1155. https://doi.org/10.3233/JAD-150729

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science, 17*(3), 177–182. https://doi.org/10.1111/j.1467-8721.2008.00570.x

Rodda, J. E., Dannhauser, T. M., Cutinha, D. J., Shergill, S. S., & Walker, Z. (2009). Subjective cognitive impairment: Increased prefrontal cortex activation compared to controls during an encoding task. *International Journal of Geriatric Psychiatry, 24*(8), 865–874. https://doi.org/10.1002/gps.2207

Schmiedek, F., Lövdén, M., & Lindenberger, U. (2014). A task is a task is a task: Putting complex span, N-back, and other working memory indicators in psychometric context. *Frontiers in Psychology, 5*, Article 1475. https://doi.org/10.3389/fpsyg.2014.01475

Schmitter-Edgecombe, M., Parsey, C., & Lamb, R. (2014). Development and psychometric properties of the instrumental activities of daily living: compensation scale. Archives of clinical neuropsychology : the official journal of the National Academy of Neuropsychologists, 29(8), 776–792. https://doi.org/10.1093/arclin/acu053

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: An integrative theory of anterior cingulate cortex function. Neuron, 79(2), 217–240. https://doi.org/10.1016/j.neuron.2013.07.007

Vaughan, L., & Giovanello, K. (2010). Executive function in daily life: Age-related influences of executive processes on instrumental activities of daily living. *Psychology and Aging, 25*(2), 343–355. https://doi.org/10.1037/a0017729

Viviano, R. P., & Damoiseaux, J. S. (2020). Functional neuroimaging in subjective cognitive decline: Current status and a research path forward. *Alzheimer's Research & Therapy, 12*, Article 23. https://doi.org/10.1186/s13195-020-00591-9

Wang, C., Ding, M., & Kluger, B. M. (2014). Change in intraindividual variability over time as a key metric for defining performance-based cognitive fatigability. Brain and Cognition, 85, 251–258. https://doi.org/10.1016/j.bandc.2014.01.004

Westbrook, A., & Braver, T. S. (2015). Cognitive effort: A neuroeconomic approach. Cognitive, Affective, & Behavioral Neuroscience, 15(2), 395–415. https://doi.org/10.3758/s13415-015-0334-y

Willis, S. L., Allen-Burge, R., Dolan, M. M., Bertrand, R. M., Yesavage, J., & Taylor, J. L. (1998). Everyday problem solving among individuals with Alzheimer's disease. The Gerontologist, 38(5), 569–577. https://doi.org/10.1093/geront/38.5.569

Yeung, M. K., Sze, S. L., Woo, J., Kwok, T., Shum, D. H. K., Yu, R., & Chan, A. S. (2016). Reduced frontal activations at high working memory load in mild cognitive impairment: Near-infrared spectroscopy. Dementia and Geriatric Cognitive Disorders, 42(5–6), 278–296. https://doi.org/10.1159/000450993

Zając-Lamparska, L., Zabielska-Mendyk, E., Zapała, D., & Augustynowicz, P. (2024). Compensatory brain activity pattern is not present in older adults during the N-back task performance—Findings based on EEG frequency analysis. *Frontiers in Psychology, 15*, Article 1371035. https://doi.org/10.3389/fpsyg.2024.1371035

Appendix A

Figure A1

Q-Q plots for FMT power spectral density during N-back

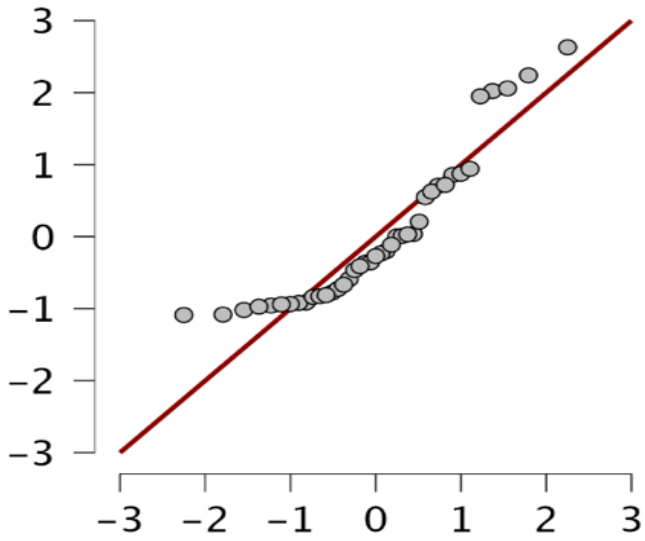


Figure A2

Q-Q plot for Accuracy during N-back

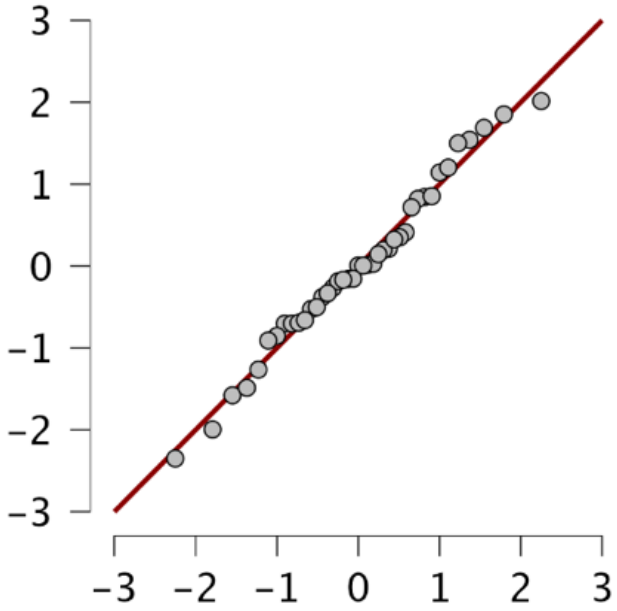


Figure A3

Q-Q plot for Reaction time during N-back

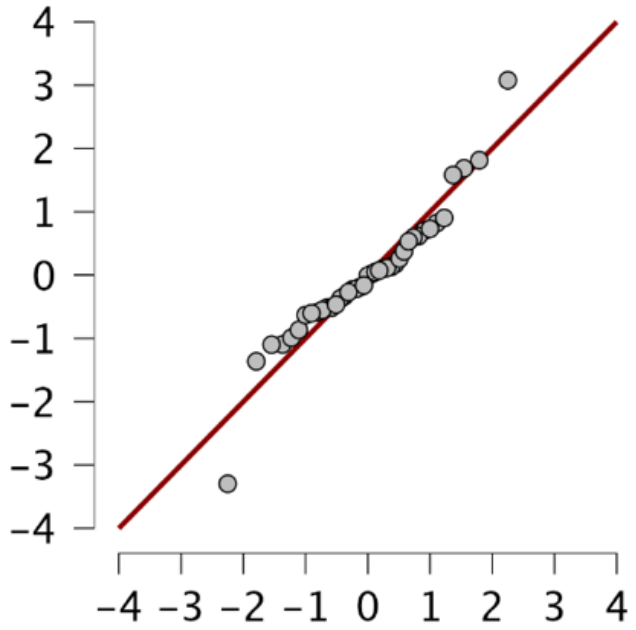


Table A1

Education levels differences between groups

	Education level					Total
	2 Basisonderwijs	4 LBO	5 MAVO/MBO	6 HAVO/VWO/HBO	7 Universiteit	
Control	1	0	8	9	4	22
SCD	0	2	3	9	0	14
MCI	0	2	1	1	1	5
Total	1	4	12	19	5	41

Note. Each cell displays the observed counts. SCD = Subjective Cognitive Decline; MCI = Mild Cognitive Impairment; LBO = Lager Beroeponderwijs; MAVO = Middelbaar Algemeen Voortgezet Onderwijs; MBO = Middelbaar Beroepsonderwijs; HAVO = Hoger Algemeen Voortgezet Onderwijs; VWO = Voorbereidend Wetenschappelijk Onderwijs; HBO = Hoger Beroepsonderwijs