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Relation between working memory capacity and frontal-midline theta increase in the Sternberg Task

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Abstract

The goal of this study was an investigation of the relationship between working memory capacity and individual differences in frontal-midline theta. In dependence on prior research, it was assumed that (1) frontal-midline theta power increases with increasing memory load (*n*) on a working memory task and (2) that this increase would only be visible for individuals with a high working memory capacity as opposed to individuals with a low working memory capacity. In order to test these hypotheses, the current study employed the Sternberg Task as a working memory task and the OSPAN as a working memory capacity measurement in a similar approach as Zakrzewska and Brzezicka (2014). Results did not yield support for both hypotheses. Mental load was successfully manipulated, and mental effort induced by means of the Sternberg Task with focus on retrieval and comparison processes. The mental effort produced by these processes alone seemed not able to induce an increase in frontal-midline theta from a lower to a higher load. These results might suppose a difference in increase of frontal-midline theta for isolated mental processes and mixed mental processes such as seemingly employed in the study of Zakrzewska and Brzezicka (2014). Hence, mental effort might not only be manipulated by memory load (*n*) but further by mixed mental processes.

Introduction

Over the past century, science developed prominent models of cognition and gathered evidence by means of behavioural and imaging data in numerous cases of cognitive processes. Working memory represents one of these well-researched topics in which working memory tasks are increasingly monitored with imaging techniques such as Electroencephalography (EEG). However, these studies often leave aside the individual differences found in imaging data and the implications that these might have for understanding brain activity differences as individual traits. Hence, this study focuses on the relationship between working memory, mental effort and individual differences in frontal-midline theta and working memory capacity.

Working Memory and Mental Effort

Working memory (WM) represents a system of human cognition that enables temporary storage and manipulation of information. In 1974, Baddeley and Hitch proposed a prominent model for working memory in which the system is divided into four components: the visuo-spatial sketchpad, the phonological loop, the central executive, and the episodic buffer. While the visuo-spatial sketchpad and phonological loop seem responsible for the temporary storage, rehearsal, and maintenance of verbally and visually/spatially coded information, the central executive coordinates both by controlling encoding, retrieval, attention, and the mental manipulation of materials (Baddeley & Hitch, 1974). In 2000, Baddeley added the episodic buffer as a temporary storage for multimodal information combined from the visuo-spatial sketchpad, phonological loop, and long-term memory for attaining one unified episodic representation.

The cognitive processes performed by the central executive - encoding, retrieval, attention, and mental manipulation – have been monitored by means of numerous EEG studies. These studies employ behavioral measurements such as the n-back, Add-n, and Sternberg Task. All three represent working memory measurements that induce mental effort by manipulating the memory load (*n*) of participants and require the central executive to direct, divide, and monitor perception and attention accordingly and properly. Task difficulty increases with increasing *n* in all three tasks. In the n-back task (Kirchner, 1958) participants are presented with items sequentially and need to indicate for each item if it matches the item *n* back in the sequence. During the Add-n task (Kahneman & Beatty, 1966), participants are presented with a four-digit number and need to add *n* to each individual digit. In the Sternberg Task (Sternberg, 1969), participants are presented with a memory set consisting of a *n*-digit number (e.g. one, two, or four digits), *n* letters, or *n* words and need to compare probe items with the memory set that were part of the set (i.e. target) or not (i.e. non-target). According to Sternberg (1969), the comparison process that is performed during this task functions as a serial scanning process with increasing *n* leading to increasing reaction times. Differences in reaction times for target and non-target probes are explained in terms of self-terminating and exhaustive models, with self-terminating models proposing a termination of serial scanning when the probe item was found in the memory set and exhaustive models proposing no termination of serial scanning until the whole memory set was compared with the probe item (Van Zandt & Townsend, 1993). Since self-terminating models predict slopes of reaction times for target and non-target trials more accurately, reaction times for target trials are generally expected to be shorter than those for non-target trials during the Sternberg Task (Van Zandt & Townsend, 1993).

All three – n-back, Add-n, and Sternberg Task – involve the maintenance of items in working memory with the Add-n task thereafter requesting a mental manipulation of the four maintained items and the n-back and Sternberg Task requesting a comparison process of the probe item with the item *n* back in the sequence or with the memory set of size *n*, respectively. However, the Sternberg Task has an important advantage over the n-back and Add-n task for EEG studies: Maintenance, retrieval and comparison processes are identified and separated in time as they take place sequentially (Jensen, Gelfand, Kounios, & Lisman, 2002). Hence, the current EEG study will focus on the Sternberg Task as a working memory task to induce mental effort with focus on the retrieval and comparison process performed with onset of the probe presentation.

Frontal-Midline Theta

Numerous EEG studies worked with the Sternberg Task so far and found further consistent results concerning imaging data. Jensen and Tesche (2002) showed that during the maintenance and recall phase of the Sternberg Task, the power of the frontal-midline (4 to 8 Hz) theta frequency band increases systematically with increasing memory load. Consequently, frontal-midline theta power was interpreted in terms of active maintenance and serial search for information (Jensen & Tesche, 2002). These results have been replicated in numerous studies (e.g. Kamiński, Brzezicka, & Wróbel, 2011; Maurer et al., 2015; Onton, Delorme, & Makeig, 2005; Zakrzewska & Brzezicka, 2014) and specified the increase in frontal-midline theta during working memory tasks to be located at the anterior cingulate cortex (ACC) of the prefrontal cortex (e.g. Onton, Delorme, & Makeig, 2005).

Individual Differences in Theta Increase

Zakrzewska and Brzezicka (2014) showed that the systematic increase in frontal-midline theta (4 to 6 Hz) with increasing memory load can only be demonstrated for individuals with a high working memory capacity. These scholars investigated the matter by employing the Sternberg Task with a memory set consisting of two to five digits, digits as the probe items, and a new memory set prior to each single trial. Average reaction times did increase with a slope of b = 39.6 ms from Load 2 to Load 5. Furthermore, Zakrzewska and Brzezicka (2014) divided the participants in two groups according to their working memory capacity. The groups were determined by administering the Operation Span (OSPAN) task, a task in which participants are requested to solve mathematical computations while simultaneously remembering items presented after each computation (Turner & Engle, 1989). As the to-be-remembered (TBR) items, Zakrzewska and Brzezicka (2014) chose for single letters. As reported by these scholars, frontal-midline theta power seems to indicate individual working memory efficiency by marking the amount of information stored as well as the effort for maintenance and efficiency of underlying neuronal processes. Therefore, frontal-midline theta might represent an individual trait of working memory efficiency leading to an increase in frontal-midline theta only for those with high working memory capacity.

Current Study

The goal of this study is an investigation of the relationship between working memory capacity and individual differences in frontal-midline theta. In dependence on prior research, two hypotheses were formulated. First, it was assumed that frontal-midline theta power increases with increasing memory load (n) on a working memory task. Second, it was hypothesised that the increase in frontal-midline theta power with increasing memory load on a working memory task would only be visible for individuals with a high working memory capacity as opposed to individuals with a low working memory capacity.

In order to test these hypotheses, the current study will employ the Sternberg Task as a working memory task and the OSPAN as a working memory capacity measurement in a similar fashion as Zakrzewska and Brzezicka (2014). Increases in frontal-midline theta power will be assessed by administering the Sternberg Task to participants while monitoring their brain activity by means of EEG measurements. Different from Zakrzewska and Brzezicka (2014), the current study utilises three memory loads with one, two, or four items in one memory set to ensure an increase in difficulty while decreasing mental fatigue caused by redundant measurements of similar difficulty. Furthermore, one memory set needs to be maintained in working memory for more than one trial to decrease the possibility of simple recognition strategies and to ensure measurement of sequential retrieval and comparison processes. To enable this approach, a repetitive counterbalancing of the three memory loads (e.g. Load 2, Load 1, Load 4, Load 2, Load 1, Load 4) will be employed with the order of loads determined beforehand. This will decrease training effects for one memory load and mental fatigue due to prolonged periods of maintaining the same memory set. The relationship between increases in frontal-midline theta power and working memory capacity will be assessed by administering the OSPAN to participants. Different from Zakrzewska and Brzezicka (2014), single digits instead of single letters will be used as TBR items during the OSPAN. Thereby, the same format (i.e. digits) for both the Sternberg Task and OSPAN will be ensured and differences in working memory performance due to format minimised. Furthermore, mnemonic strategies such as chunking of single letters should be impeded by the competing digits of the mathematical computations. Different than Zakrzewska and Brzezicka (2014), the current study employs less blocks for the OSPAN to decrease mental fatigue and any influences for the subsequent Sternberg Task.

Methods

Participants

Twenty students (3 male, 17 female) were sampled at the University of Twente for a voluntary participation in the study. In exchange for participation, students received an incentive in form of 2.5 credits in the BMS Test Subject Pool system SONA. The age of the participants ranged from 18 to 26 (*M= 20.75, SD = 1.80*) years. Students were of German (n = 13), Dutch (n = 3), Bulgarian (n = 2), Latvian (n = 1), and Swiss (n = 1) nationality. Eligibility was restricted to participants aged 18 and older without cognitive impairments and free of any influences that might constrain cognitive abilities at the time of the experiment. All participants gave informed consent. The study was ethically approved by the BMS (Behavioural, Management, and Social Sciences) Ethics Committee of the University of Twente.

Stimuli and Procedure

Participants were assessed individually at the “RecogNice” laboratory of the University of Twente. Each assessment took 2.5 hours with instructions given in English. Prior to any measurement, each participant was informed about the purpose of the study as well as asked to provide informed consent by signing a form and give further information by filling in an EEG questionnaire (Appendix A). Thereafter, two computerised tasks were assessed: The Operation Span (OSPAN) Task and the Sternberg Task.

Operation Span (OSPAN) Task

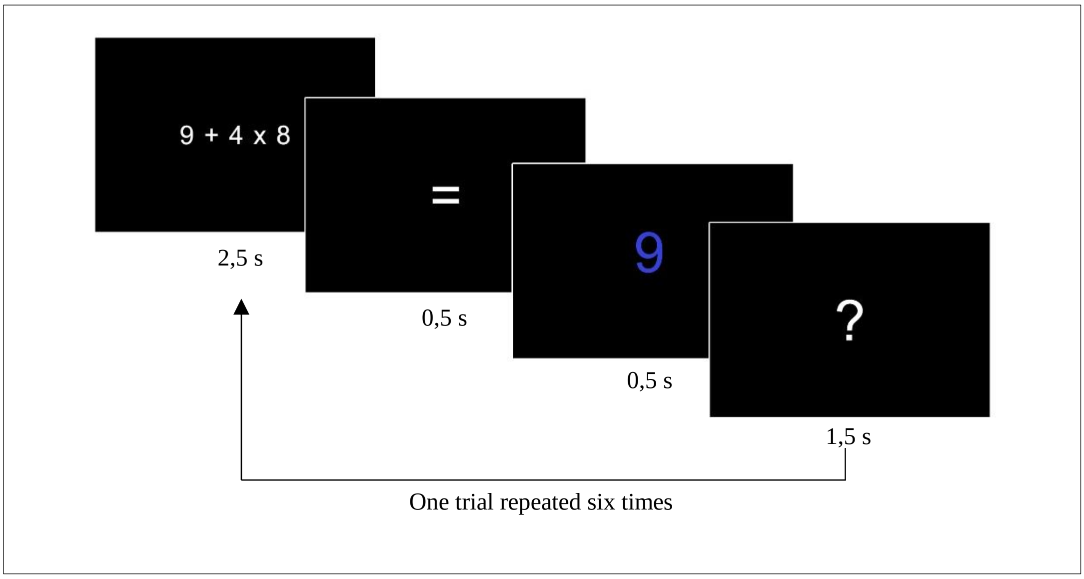

Figure 1. Depiction of one trial of the OSPAN task. Participants are shown a mathematical computation for 2.5 s, followed by an equal sign (“=”) for 0.5 s, a blue digit for 0.5 s and a question mark (“?”) for 1.5 s. One block consists of six trials.

Working memory capacity was measured with the OSPAN task as a .pptx file displayed by executing Microsoft PowerPoint 2019 on a MacBook Pro with a macOS Mojave system (Version 10.14) and 13-inch display. Responses were given verbally and notated by the researcher. Digits were used as the TBR items (“Operations Digit”) (Turner & Engle, 1989). Participants were shown one practice block of one trial and two blocks of six trials consisting of operations alternating with blue digits presented after the operations. Each operation was presented for 2.5 seconds and took the form of mathematical equations following the structure $X +/- Y \div or \ \times Z$. Subsequently, an equal sign (“=”) was shown for 0.5 seconds followed by a blue digit as the TBR item presented for 0.5 seconds. Participants were instructed to verbally indicate for every blue digit whether it was the solution to the antecedent operation or not while being presented with a question mark (“?”) for 1.5 seconds. Furthermore, participants were asked to remember the blue digits independent from their correctness or incorrectness. After six trials (i.e. 30 seconds) the block was completed, and participants were asked to verbally recall the blue digits as the TBR items in the correct sequence. Generally, the OSPAN is a popular and widely used measurement for working memory capacity (Unsworth, Heitz, Schrock, & Engle, 2005) with an adequate internal consistency as shown by an α coefficient between .76 to .83 for different scoring techniques (Đokić, Koso-Drljević, & Đapo, 2018). Hence, the OSPAN used in this research should represent a valid and reliable measurement of working memory capacity.

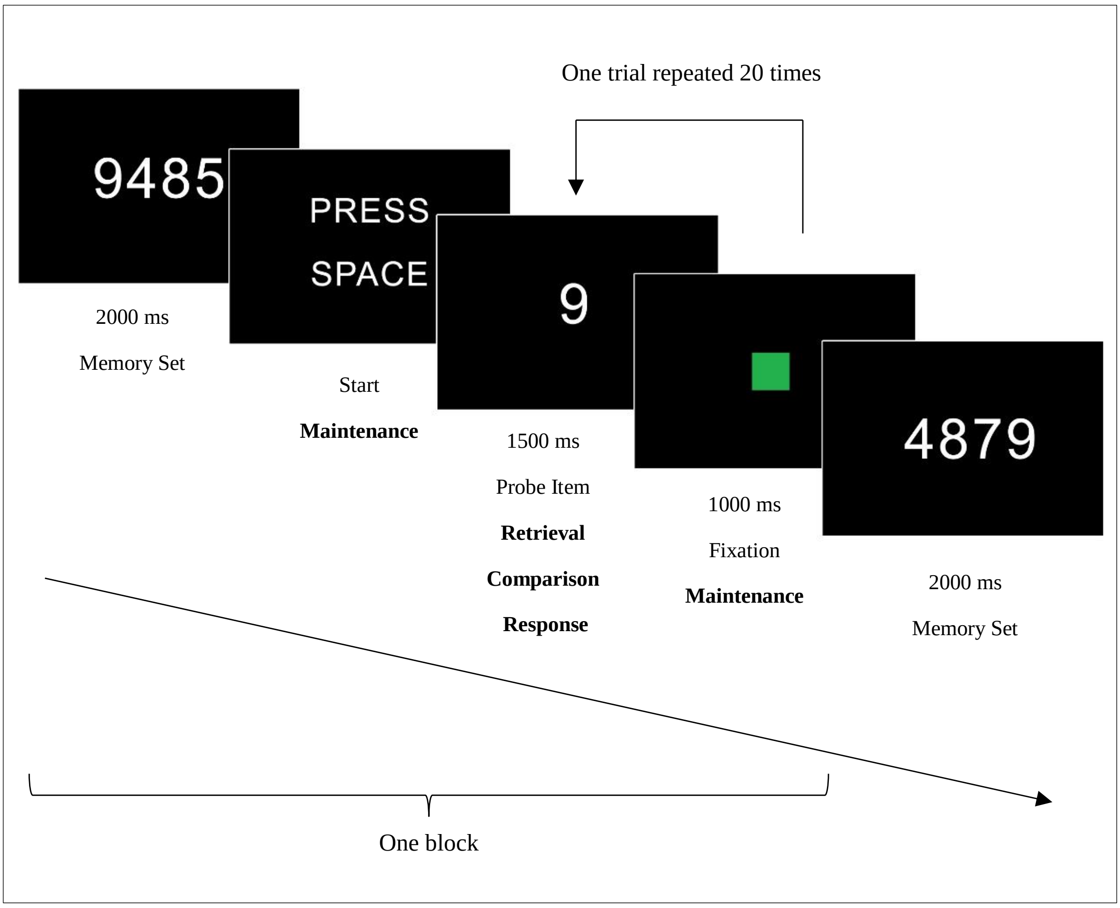

Figure 2. Depiction of Sternberg Task trial and block structure by means of a Load 4 block example. During one block, participants are presented with a memory set of size *n* (Load 1, Load 2, Load 4) for 2000 ms. Participants start the first trial by pressing the spacebar. Subsequently, they are presented with a probe item for 1500 ms. During this period, they need to retrieve the memory set, compare the probe item with the memory set and respond by pressing the right or left control key. Afterwards, a green fixation dot is presented for 1000 ms. Probe item and fixation dot presentation are repeated 20 times. Thereafter, the block is completed, and the next memory set presented for 2000 ms.

Mental effort was induced by means of the Sternberg Task. The task was administered by executing the Presentation software by Neurobehavioral Systems Inc. on a computer with a Windows 10 Enterprise system (executed in Windows Leanmode) and 22-inch monitor used to control the presentation of stimuli and for sending markers to the EEG amplifier to code the onset of relevant events. Responses were given with a QWERTY keyboard by pressing the spacebar, enter, right or left control keys.

In this task, participants are presented with a memory set of n digits and required to memorise this set. Subsequently, probe items were shown to the participants who had to decide whether the probe was part of the memory set (i.e. target) or not (i.e. non-target). At the beginning of a block, participants were shown the memory set for 2000 ms. Subsequently, they started the block by pressing an adequate key and were presented with probe items at the centre of the screen for 1500 ms each, followed by a green fixation dot at the centre of the screen for 1000 ms each (Figure 2). For every probe item, the participants were instructed to indicate whether the item was part of the memory set by pressing the left or right control key. One block consisted of 20 trials and each load (Load 1, Load 2, Load 4) included one practice and two experimental blocks. Hence, participants were requested to fulfil three blocks for each load and each load two times with the order of loads being determined beforehand (e.g. Load 2, Load 1, Load 4, Load 2, Load 1, Load 4).

The Sternberg Task represents a popular and agreed on measurement of serial storage, retrieval, and comparison speed in working memory, as the reaction time increases with memory set size. Since this measurement is especially popular in EEG studies on (frontal-midline) theta (e.g. Kamiński, Brzezicka, & Wróbel, 2011; Maurer et al., 2015; Onton, Delorme, & Makeig, 2005; Zakrzewska & Brzezicka, 2014), it was judged as a valid and reliable assessment tool for the current study with the time interval of importance found during the 1500 ms of probe item presentation in which participants are engaged in retrieval of the memory set for serial comparison with the probe item (Figure 2).

Apparatus and EEG Recording

Participants were seated in a darkened room at a distance of approximately 60 cm from the monitor. Electrical brain activity was measured during the Sternberg Task through an elastic electroencephalography (EEG) cap called Braincap by Brainproducts GmbH with 32 active Ag/AgCI electrodes. These electrodes were placed at the positions: Fp1, F7, F3, F1, Fz, FT7, FC3, FCz, T7, C3, Cz, TP7, CP3, CPz, P7, P3, Pz, PO7, Oz, PO8, P8, P4, TP8, CP4, T8, C4, FT8, FC4, F8, F4, F2, Fp2 with TP8 as the reference electrode and an additional electrode placed at AFz as the ground electrode (Figure 3). In order to record horizontal and vertical saccades, electro-oculographic (EOG) electrodes were placed at the temples of the participants close to the corner of the eyes (hEOG) and above and below the left eye in line with the pupil (vEOG) respectively. A ground electrode for the electro-oculography was placed in the middle of the forehead. For lowering the resistance below 10kΩ, electrolytical gel was filled in between skin and electrode by making use of a syringe. In order to amplify the EEG and EOG signals, a 64-channels Actichamp amplifier by Brain Products GmbH was used. A second computer with a Windows 10 Enterprise system and 22-inch monitor was equipped with the programme BrainVision Recorder by BrainProducts GmbH to register EEG and EOG signals as well as codes representing task related events (e.g. stimulus presentation, responses).

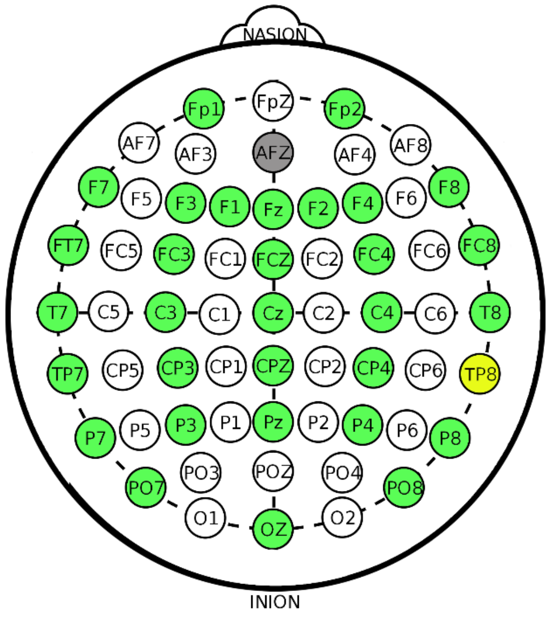

Figure 3. Electrode placement during EEG measurements with AFZ as the ground electrode and TP8 as the reference electrode.

Data Analysis

Processing of Behavioral Data

Total scores on the OSPAN were generated by assigning a 1 for correctly identifying whether the blue digit was the solution to the mathematical equation, an additional 1 for correctly recalling a digit, and an additional 1 for correctly recalling a digit at the correct position in the sequence. Thereby, participants were able to attain a maximum total score of 36 on both blocks. This scoring approach differed from Zakrzewska & Brzezicka (2014) who scored only perfectly recalled sequences and included participants that were able to recall minimum 80 % of sequences in total. As digits as the TBR items might increase task difficulty due to hindering mnemonic strategies, this partial scoring method should ensure variability of OSPAN scores and prevent flooring effects.

Behavioural data of the Sternberg Task was analysed by employing Matlab scripts on the marker data. Thereby, the percentage of correct responses and the reaction time between stimulus presentation and response were identified for all three loads divided by target and non-target trials.

Processing of EEG Data

The raw data was analysed using BrainVision Analyzer and SPSS. After checking for distorted channels and deleting them if needed, the data was segmented selecting a −500 to 1000 ms time window relative to cue onset. The baseline of the segmented data was set from -500 to 0 ms. Furthermore, data was checked for artefacts (Min/max: ± 350 μV, gradient with 50 μV/ms, low activity for 100 ms > 0.5 μV) and corrected for eye movements. Subsequently, the data was checked for residual artefacts (Min/max: ± 150 μV, gradient with 50 μV/ms, low activity for 100 ms > 0.5 μV) and a second baseline set from -500 to 0 ms. The data was then segmented within a -500 to 1000ms time window relative to the onset of markers for each load in order to separate the data of the three loads into different sets of data. A Fast Fourier Transformation (FFT) was applied to each of these sets in order to disaggregate the data into the various frequency bands. This transformation allowed for an analysis of the average power of the frequency band of interest later on. The average power of each frequency band was calculated and the average power of the theta (4 to 6 Hz) band exported as a .cvs file. Before further statistical analysis was conducted, the data from the .cvs file was transformed by performing a log-10 transformation and the average theta power of the electrodes Fz, F1, and F2 averaged as a replication of the electrodes of interest utilised by Zakrzewska and Brzezicka (2014).

Statistical Analysis

Outliers were removed prior to the statistical analysis in concordance with the exclusion criteria $x_i > Q3 + 1.5 * IQR$ or $x_i < 1.5 * IQR$. Descriptive statistics of the OSPAN scores as well as percentage of correct responses and reaction times during the Sternberg Task were derived. A repeated measurement ANOVA with the three loads (Load 1, Load 2, Load 4) as factor as well as a repeated measurement ANOVA with the two trial types (target and non-target) as factor was applied to the reaction time data. Furthermore, a repeated measurement ANOVA with the three loads (Load 1, Load 2, Load 4) as well as a repeated measurement ANOVA with the two trial types (target and non-target) as factor was applied to the percentage of correct responses data. In order to investigate whether average frontal-midline theta increases with increasing memory load, a repeated measurement ANOVA with the three loads (Load 1, Load 2, Load 4) as factor was be applied to the data. Thereafter, the OSPAN scores were added as a covariate in order to check for interaction effects between frontal-midline theta increase with increasing memory load and working memory capacity. For all repeated measurement ANOVA models, Partial Eta squared, and the observed power were calculated.

Results

One outlier (Participant 19) was removed for further analysis based on the exclusion criterium $x_i > Q3 + 1.5 * IQR$.

Behavioural Data

Operation Span Task. Scores on the Operation Span Task ranged from 13 to 28 (*M* = 19.2, *SD* = 4.7257) (Figure 4).

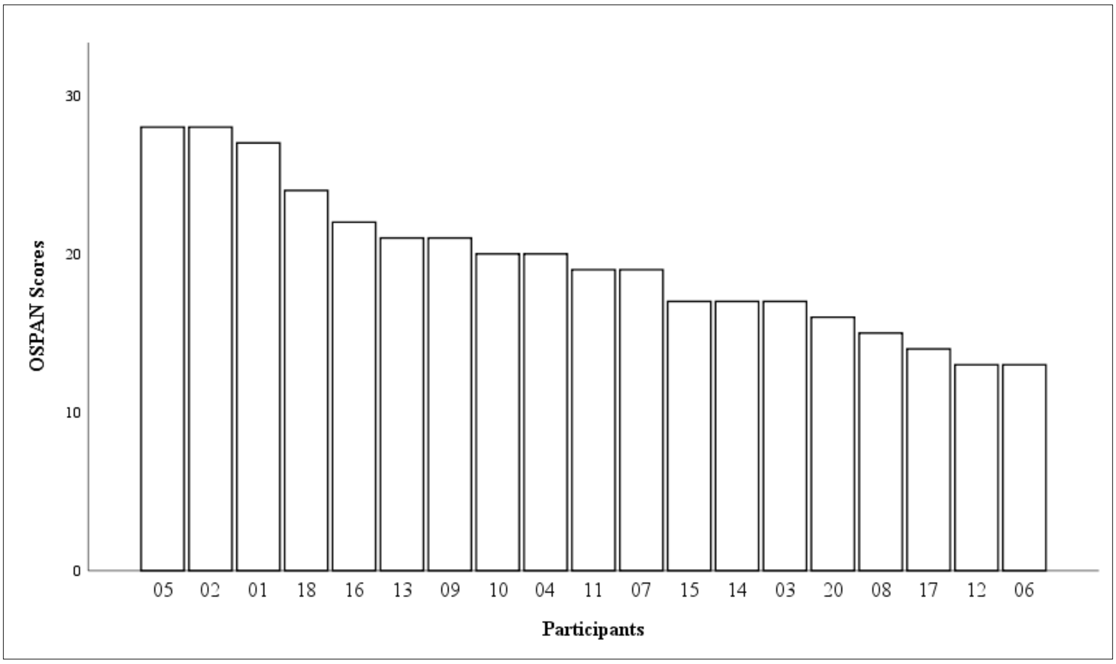

Figure 4. Distribution of OSPAN scores with 36 as the highest attainable total score. Scores ranged from 13 to 28 *(*M *= 19.2,* SD *= 4.7257).*

Sternberg Task. The reaction time ranged from 487.9 ms to 704.3 ms (*M* = 593.3 ms, *SD* = 63.6 ms) across the three loads of the Sternberg Task (Table 1).

Table 1.

Descriptive Statistics for Reaction Times on the Sternberg Task Divided by Load and Type of Trial.

Load	Minimum	Maximum	Mean	Standard Deviation
Load 1	410.6 ms	663.2 ms	529.4	74.59
Load 2	461.1 ms	755.4 ms	584.6	82.16
Load 4	582.7 ms	758.8 ms	665.8	50.03
Type of Trial	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Target	466.95 ms	754.66 ms	580.88	73.20
Non-Target	508.75 ms	745.00 ms	605.61	63.64

The difference in reaction time between the three loads (Load 1, Load 2, Load 4) was significant ($F(2,36) = 81.107$, $p < .001$, $\eta_p^2 = .787$, $1\text{-}\beta = 1.00$) (Figure 5) between all of the loads in a pairwise comparison ($p < .001$). Average reaction time increased from Load 1 to Load 4 with a slope of $b = 68.2$.

The difference in reaction time between target and non-target trials was not significant ($F(1,18) = 3.829$, $p = .066$, $\eta_p^2 = .175$, $1\text{-}\beta = .457$). Post hoc analysis showed that the difference in reaction time between target and non-target trials was not significant for Load 1 ($F(1,18) = 2.285$, $p = .148$, $\eta_p^2 = .113$, $1\text{-}\beta = .299$) and Load 2 ($F(1,18) = .371$, $p = .550$, $\eta_p^2 = .020$, $1\text{-}\beta = .089$) while it was significant for Load 4 ($F(1,18) = 6.379$, $p = .021$, $\eta_p^2 = .262$, $1\text{-}\beta = .666$).

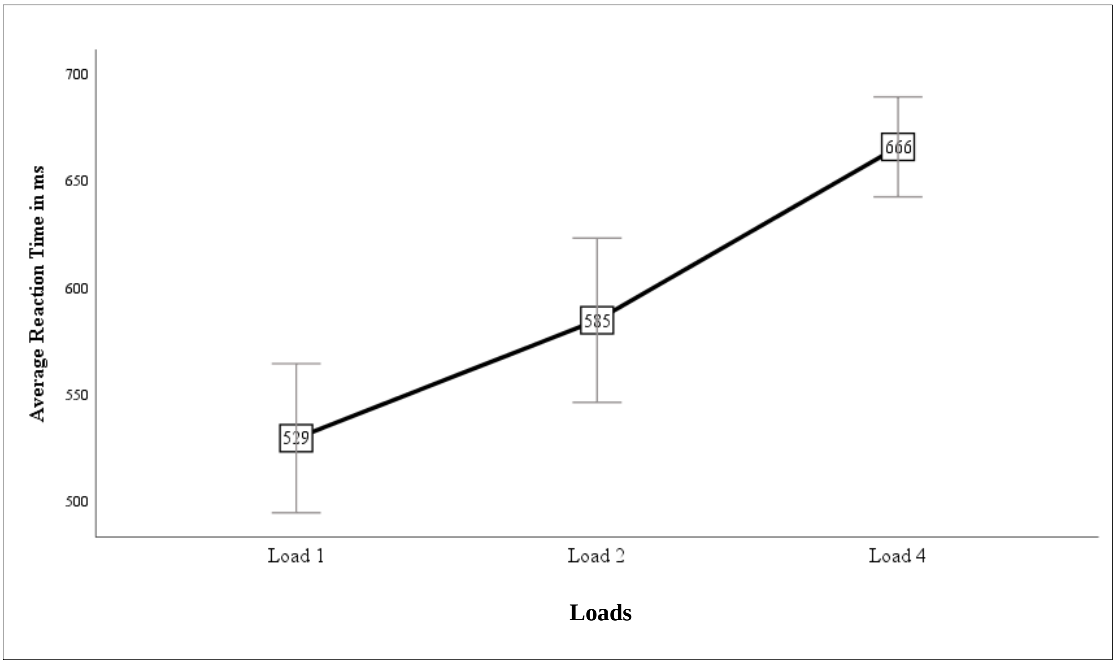

Figure 5. Significant increase in mean reaction time with increasing memory set size from the first to the third load.

The percentage of correct responses ranged from 65.63 % to 100 % (*M* = 96.43, *SD* = 3.39) across the three loads of the Sternberg Task (Table 2).

Table 2.

Descriptive Statistics for Percentage of Correct Responses on the Sternberg Task Divided by Load and Type of Trial.

Load	Minimum	Maximum	Mean	Standard Deviation
Load 1	78.13 %	100 %	97.24	5.42
Load 2	75.52 %	100 %	95.94	5.44
Load 4	86.25 %	100 %	96.13	3.39
Type of Trial	Minimum	Maximum	Mean	Standard Deviation
Target	82.71 %	100 %	95.25	4.65
Non-Target	87.64 %	100 %	97.62	3.01

The difference in percentage of correct responses between the three loads (Load 1, Load 2, Load 4) was not significant ($F(2,36) = .923$, $p = .406$, $\eta_p^2 = .049$, $1\text{-}\beta = .196$). Furthermore, the difference in percentage of correct responses between target and non-target trials was significant ($F(1,18) = 12.423$, $p = .002$, $\eta_p^2 = .408$, $1\text{-}\beta = .915$) (Figure 6) with an increase in percentage of correct responses from target to non-target trials.

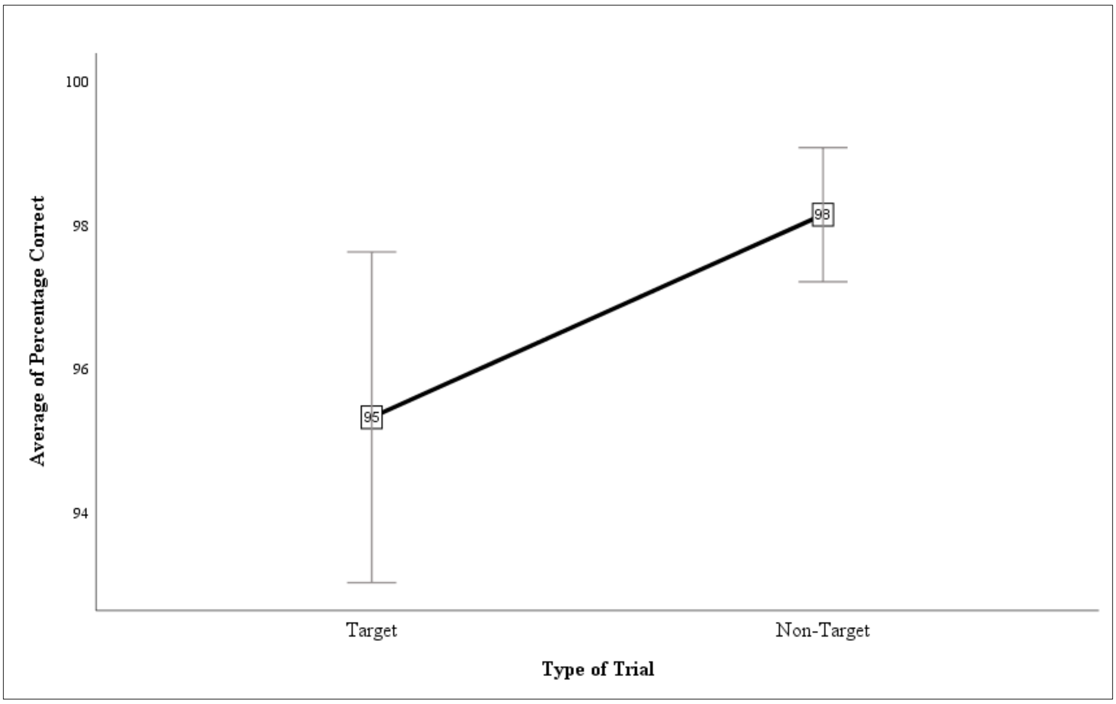

Figure 6. Significant increase in mean of percentage of correct responses from target trials (i.e. including the probe in the memory set) to non-target trials (i.e. not including the probe in the memory set).

Electroencephalographic Data

Electroencephalographic data was log-10 transformed prior to statistical analyses. Average frontal-midline theta (4 to 6 Hz) power recorded in the Fz, F1, and F2 electrodes centred around *M* = 1.26 μV (*SD* = 1.15 μV). This average differed between the first (*M Load 1* = -.046 μV, *SD Load 1* = .043 μV), second (*M Load 2* = -.043 μV, *SD Load 2* = .041 μV), and third (*M Load 4* = -.041 μV, *SD Load 4* = .0.41 μV) load of the Sternberg Task with an increase in frontal-midline theta power from the first to the third load (Figure 7).

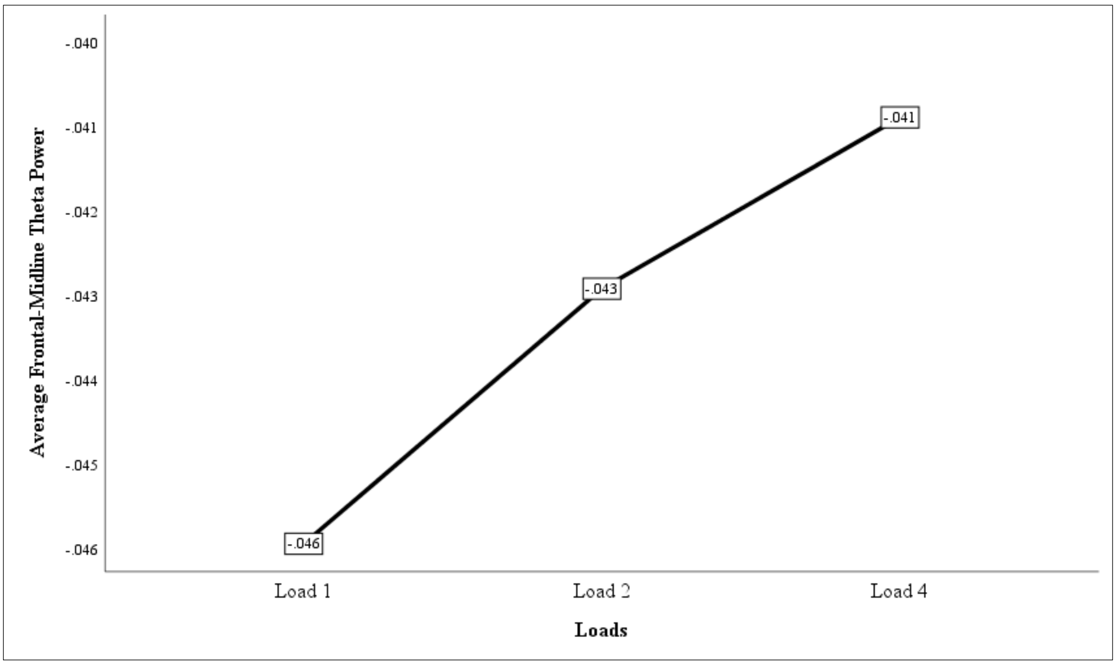

Figure 5. Average frontal-midline theta (4 to 6 Hz) power for the three Sternberg Task loads (Load 1, Load 2, Load 4).

Topographical Data. Topographical data of brain activity shows frontal-midline theta (4 to 6 Hz) for all three loads of the "Sternberg Task" (Figure 8).

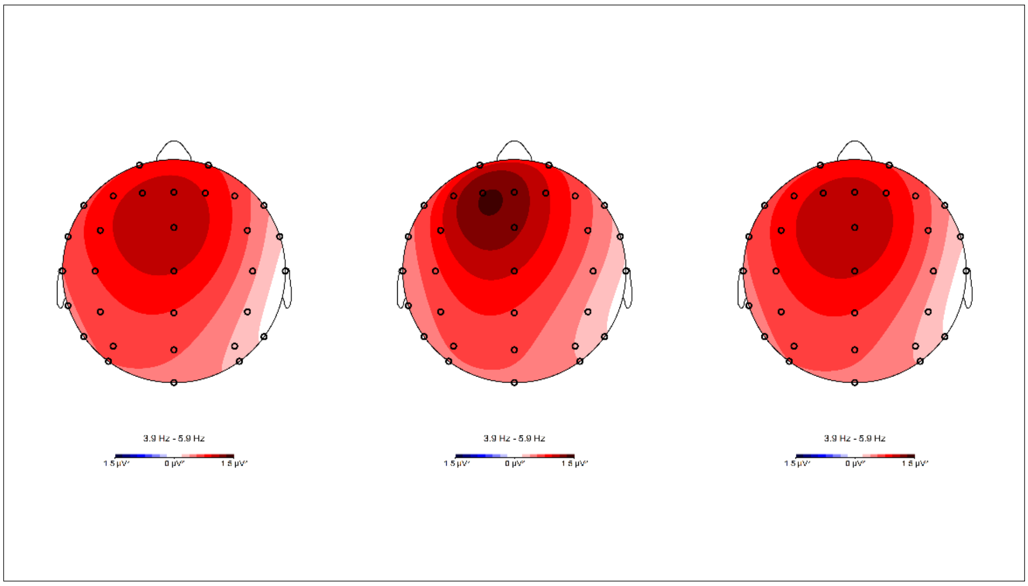

Figure 8. Topographical data shows theta (4 to 6 Hz) power ranging from 0 μV^2 (i.e. white) to 1.5 μV^2 (i.e. dark red) for the three loads Load 1 (left), Load 2 (middle), and Load 4 (right). Increases in theta power seem to be concentrated at frontal-midline areas (i.e. F1, Fz, F2, FCz, Cz).

Increase in Theta Power with Memory Load. In order to check for an increase in average frontal-midline theta (4 to 6 Hz) power with increasing memory load in the Sternberg Task loads, a repeated measurements ANOVA with the three Sternberg Task loads (Load 1, Load 2, Load 4) as factor was performed. Results were not significant ($F(2,34) = .102$, $p = .904$, $\eta_p^2 = .006$, $1\text{-}\beta = .064$). Hence, an increase in average theta (4 to 6 Hz) power with increasing memory load in the Sternberg Task could not be supported by data.

Differences in Theta Power with Working Memory Capacity. In order to check for an influence of working memory capacity as measured through OSPAN scores on average frontal-midline theta (4 to 6 Hz) power, a repeated measurements ANOVA with the three loads (Load 1, Load 2, Load 4) as factor and OSPAN scores as a covariate was performed. Results were not significant ($F(2,32) = .020$, $p = .977$, $\eta_p^2 = .001$, $1\text{-}\beta = .053$) and could not support an interaction effect of working memory capacity on average frontal-midline theta (4 to 6 Hz) power.

Discussion

The goal of this research was an investigation of the relationship between working memory capacity and individual differences in frontal-midline theta. In dependence on prior research, two hypotheses were formulated. First, it was assumed that frontal-midline theta power increases with increasing memory load (*n*) on a working memory task. Second, it was hypothesised this increase would only be visible for individuals with a high working memory capacity as opposed to individuals with a low working memory capacity. The Sternberg Task was utilised as a working memory task for testing the first and the OSPAN as a working memory capacity measurement for testing the second hypothesis. Results did not yield any support for both hypotheses as neither an increase in average theta (4 to 6 Hz) power with increasing memory load nor an interaction effect of working memory capacity on average frontal-midline theta (4 to 6 Hz) power in the Sternberg Task could be supported by data.

Working Memory and Mental Effort

The Sternberg Task was employed as a working memory task that induces mental effort with the three loads (Load 1, Load 2, Load 4) of increasing memory set size from $n = 1$ to $n = 4$. In line with prior research (Sternberg, 1969), it was expected that reaction times would increase significantly with increasing memory load as the serial scanning process in retrieval of the memory set and comparison with the probe item would be extended with increasing *n*. In concordance with self-terminating models (Van Zandt & Townsend, 1993), a significant increase in reaction times from target to non-target trials was expected as the serial scanning would on average terminate faster for trials in which the probe was included in the memory set. No significant difference in percentage of correct responses was expected.

Analysis of behavioral results did show a significant increase of reaction time from Load 1 to Load 4 with a slope of $b = 68.2$ ms for average reaction time from the first to the third load, while there was no significant difference in reaction time between target and non-target trials. Post hoc analysis revealed a significant increase from target to non-target trials only for Load 4. This fits with the self-terminating model as the reaction times for Load 1 are expected to be equal for both types of trials and the reaction times for Load 2 only expected to be lower for target trials when the probe is located at the first position of the memory set. Hence, differences in reaction time between target and non-target trials might be more pronounced for larger loads. As expected, no significant difference in percentage of correct responses between the loads was found. However, a significant increase of percentage of correct responses from target to non-target trials was found.

Overall, the current study seems to support the Sternberg Task as a working memory task that induces mental effort by manipulating the memory load *n* with increasing memory set size. Thereby, more attentional resources are required for serially and self-terminating scanning the memory set for the probe item as shown by increasing reaction times from Load 1 to Load 4 and from target to non-target trials for larger loads.

Frontal-Midline Theta

In line with prior research (e.g. Kamiński, Brzezicka, & Wróbel, 2011; Maurer et al., 2015; Onton, Delorme, & Makeig, 2005; Zakrzewska & Brzezicka, 2014) it was assumed that frontal-midline theta power increases with increasing memory load (*n*) on a working memory task. Unexpectedly, no significant increase in average theta (4 to 6 Hz) power with increasing memory load on the Sternberg Task could be supported by the current study.

The current study used the Sternberg Task in a similar fashion as Zakrzewska and Brzezicka (2014) with deviations concerning fewer loads, decreased memory set sizes, as well as the duration of memory set maintenance for numerous rather than single trials. Increasing reaction times from Load 1 to Load 4 and from target to non-target trials for larger loads supported the successful manipulation of memory load and mental effort in the current study. Furthermore, the slope of the increase of average reaction time was higher in the current study (b = 68.2 ms) than for Zakrzewska and Brzezicka (2014) (b = 39.6 ms), indicating a successful induction of increasing mental effort during serial retrieval and comparison from Load 1 to Load 4 that exceeds the study of Zakrzewska and Brzezicka (2014). Still, the increase in frontal-midline theta power with increasing memory load (*n*) could not be replicated. This might be explained by the methodological deviation concerning duration of memory set maintenance for numerous rather than single trials. By updating the memory set for each single trial, Zakrzewska and Brzezicka (2014) might have induced mental effort due to a mental process of constant memory load updating and maintenance of the new memory set, whereas the actual retrieval and comparison process might have been less effortful in their study as shown by the slower increase of average reaction time from Load 2 to Load 5. Hence, the current study might represent a more sensitive but less effortful measurement of retrieval and comparison processes during the Sternberg Task that led to no significant increase in frontal-midline theta power.

Individual Differences in Theta Increase

Further in line with Zakrzewska and Brzezicka (2014), it was hypothesised that the increase of frontal-midline theta power with increasing memory load (*n*) on a working memory task would only be visible for individuals with a high working memory capacity as opposed to individuals with a low working memory capacity. Unexpectedly, no interaction effect of working memory capacity on average frontal-midline theta (4 to 6 Hz) power in the Sternberg Task could be supported in the current study.

This result can be explained with an extension of the line of argument given above. As a result of the methodological approach of Zakrzewska and Brzezicka (2014), the Sternberg Task might have induced mental effort due to the mental process of constant memory load updating and maintenance of the new memory set rather than due to retrieval and comparison processes. Memory updating represents a predictor for verbal working memory capacity in children aged 7 to 11 years (Magimairaj & Montgomery, 2013) and for fluid intelligence in adults (Ecker, Lewandowsky, Oberauer, & Chee, 2010) which is commonly reported as correlating with working memory capacity (e.g. Au et al, 2015; Colom et al, 2014; Kane et al, 2004; Salthouse & Pink, 2008; Unsworth, Fukuda, Awh, & Vogel, 2014). Hence, an interaction effect between working memory capacity as measured by OSPAN and frontal-midline theta power as induced by memory updating in Zakrzewska’s and Brzezicka’s (2014) version of the Sternberg Task seems in line with prior research as memory updating performance predicts working memory capacity and fluid intelligence.

Limitations and Recommendations

Limitations mainly concern the administration of the OSPAN and Sternberg Task which deviated from the approach chosen by Zakrzewska and Brzezicka (2014) and other scholars. First, the OSPAN was administered only with single digits instead of single letters and digits as the TBR items. This deviation might have caused an increased task difficulty due to competing stimuli in form of digits as part of the mathematical computations, which could not be controlled for as single letters were not used as a second format for comparison purposes. Second, this deviation required a partial scoring method as the scoring method of Unsworth and Engle (2005) proposes an accuracy criterion of 85% accuracy and total scores computed by adding up the perfectly recalled sequences which would have led to the exclusion of 19 participants. Third, the reliability and validity of scores might have further been decreased by administering fewer blocks of the task. Fourth, the Sternberg Task seemed unable to induce enough mental effort for producing an increase in frontal-midline theta power as it focused on retrieval and comparison only.

Additionally, the interpretation of some results of statistical analyses seems questionable against the background of observed power. The chance of detecting a true significant difference does not reach 80 % for various parts of the analysis and specifically for those that test the two hypotheses: for the differences in average frontal-midline theta (4 to 6 Hz) power with increasing memory load ($1-\beta = .064$), as well as for the analysis of the interaction effect between frontal-midline theta (4 to 6 Hz) power and working memory capacity ($1-\beta = .053$). Hence there is a high probability of committing Type II error for parts of the statistical analysis, with a chance of 94 % for an actually significant difference in average frontal-midline theta (4 to 6 Hz) power with increasing memory load, and 95 % for an actually significant interaction effect between frontal-midline theta (4 to 6 Hz) power and working memory capacity. Therefore, the possibility of an actually significant difference in average frontal-midline theta (4 to 6 Hz) power with increasing memory load and an interaction effect between frontal-midline theta (4 to 6 Hz) power and working memory capacity needs to be considered.

In order to meet these limitations, future research should, therefore, compare the results of OSPAN with single digits to those of OSPAN with single letters or words to investigate the influence of format on task difficulty and scores. Furthermore, future studies should employ reliable and valid scoring methods for the OSPAN and administer enough blocks to allow for the computation of a reliable and valid average working memory capacity score. With regard to the Sternberg Task, future studies should administer varied loads with more extreme memory set sizes to induce enough mental effort in retrieval and comparison processes, as well as compare the approaches of random trial presentation and counterbalancing of loads with consecutive trials to further elucidate the differences between involved mental processes. Increasing the sample size could further improve the observed power of statistical analyses.

Conclusion

The current study did provide new insights into the relationship between working memory, mental effort, working memory capacity and individual differences in frontal-midline theta. While mental effort was induced by means of the Sternberg Task with focus on retrieval and comparison processes, the mental effort produced by these processes alone was not able to induce an increase in frontal-midline theta from a lower to a higher load. Furthermore, no interaction between working memory capacity and frontal-midline theta was observable. These results might suppose a difference in increase of frontal-midline theta for isolated mental processes and mixed mental processes, probably caused by increased mental effort in tasks with mixed mental processes. Thereby, the current study complements existing research on individual differences in imaging data and might serve as a basis for future research on this topic.

References

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. (2015). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin & Review*, *22*(2), 366-377. doi:10.1037/e524912015-029

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417-423. doi:10.1016/s1364 6613(00)01538-2

Baddeley, A. D., & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation*, 47-89. doi:10.1016/s0079-7421(08)60452-1

Colom, R., Privado, J., García, L. F., Estrada, E., Cuevas, L., & Shih, P. (2015). Fluid intelligence and working memory capacity: Is the time for working on intelligence problems relevant for explaining their large relationship? *Personality and Individual Differences*, *79*, 75-80. doi:10.1016/j.paid.2015.01.051

Đokić, R., Koso-Drljević, M., & Đapo, N. (2018). Working memory span tasks: Group administration and omitting accuracy criterion do not change metric characteristics. *PLOS ONE*, *13*(10), e0205169. doi:10.1371/journal.pone.0205169

Ecker, U. K., Lewandowsky, S., Oberauer, K., & Chee, A. E. (2010). The components of working memory updating: An experimental decomposition and individual differences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(1), 170-189. doi:10.1037/a0017891

Jensen, O., Gelfand, J., Kounios, J., & Lisman, J. E. (2002). Oscillations in the Alpha Band (9-12 Hz) increase with memory load during retention in a short-term memory task. *Cerebral Cortex, 12*(8), 877-882. doi:10.1093/cercor/12.8.877

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. doi:10.1046/j.1460-9568.2002.01975.x

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science, 154*(3756), 1583-1585.

Kamiński, J., Brzezicka, A., & Wróbel, A. (2011). Short-term memory capacity (7±2) predicted by theta to gamma cycle length ratio. *Neurobiology of Learning and Memory, 95*(1), 19-23. doi:10.1016/j.nlm.2010.10.001

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189-217. doi:10.1037/0096-3445.133.2.189

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of experimental psychology, 55*(4), 352.

Maurer, U., Brem, S., Liechti, M., Maurizio, S., Michels, L., & Brandeis, D. (2014). Frontal midline theta reflects individual task performance in a working memory task. *Brain Topography*, *28*(1), 127-134. doi:10.1007/s10548-014-0361-y

Magimairaj, B. M., & Montgomery, J. W. (2013). Examining the relative contribution of memory updating, attention focus switching, and sustained attention to children’s verbal working memory span. *Child Development Research*, *2013*, 1-12. doi:10.1155/2013/763808

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

Salthouse, T. A., & Pink, J. E. (2008). Why is working memory related to fluid intelligence? *Psychonomic Bulletin & Review, 15*(2), 364-371. doi:10.3758/pbr.15.2.364

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. *American scientist, 57*(4), 421-57. Retrieved from: https://www.researchgate.net/publication/17809464_Memory-scanning_Mental_processes_revealed_by_reaction-time_experiments

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*(2), 127-154. doi:10.1016/0749-596x(89)90040-5

Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology*, *71*, 1-26. doi:10.1016/j.cogpsych.2014.01.003

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*(3), 498-505. doi:10.3758/bf03192720

Van Zandt, T., & Townsend, J. T. (1993). Self-terminating versus exhaustive processes in rapid visual and memory search: An evaluative review. *Perception & Psychophysics*, *53*(5), 563-580. doi:10.3758/bf03205204

Zakrzewska, M. Z., & Brzezicka, A. (2014). Working memory capacity as a moderator of load-related frontal midline theta variability in Sternberg task. *Frontiers in Human Neuroscience*, *8*. doi:10.3389/fnhum.2014.00399

Appendix

Appendix A: EEG Questionnaire

Participant __

EEG questionnaire

Please circle the best fitting answer.

Vision

Do you have normal or corrected to normal vision?

Yes No

If you have corrected to normal vision, do you wear glasses now?

Yes No

Circumstances

Have you ever had head or brain surgery?

Yes No

Do you suffer from epilepsy?

Yes No

Do you suffer from colorblindness?

Yes No

Do you suffer from any other neurological disorder?

Yes No

Do you suffer from any psychiatric disorder?

Yes No

Do you have a pacemaker?

Yes No

Do you have piercings that you have not yet removed in or around your face?

Yes No

Did you drink alcoholic beverages in the last 24 hours?

Yes No

Demographics

What is your age?

____

What is your gender?

____

What is your nationality?

____

Participant __

Handedness

	Always left	Mostly left	No preference	Mostly right	Always right
Writing a letter					
Throw a ball to hit a target					
To play a racket in tennis, squash etc.					
What hand is up to handle a broom removing dust from the floor					
What hand is up to manipulate a shovel					
Lighting matches					
Scissors when cutting paper					
To hold a wire to move it through the eye of a needle					
To distribute playing cards					
To hit a nail on the head					
To hold your toothbrush					
To remove the cover from a jar					