Bachelor Thesis

# Frontal Theta Increase in the Add-n Task and its Relation to Working Memory Capacity

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## Abstract

Imaging techniques, such as electroencephalography (EEG), are frequently used to conduct research on working memory and related neuronal structures. Activities of mental processes executed by working memory have been located in the prefrontal cortex, and an increase in frontal theta activity has been frequently reported in relation to an increase in mental effort due to increased loads on working memory tasks. However, such research often leaves aside individual differences in imaging data and the role of possible factors, such as cognitive abilities, in explaining such differences. First, this study aims to contribute to the large body of research showing an increase in frontal theta activity in relation to task difficulty by investigating whether such effect is also observable for participants engaging in a less commonly used working memory task, the Add-n task. Second, the study aims to investigate the role of working memory capacity in explaining individual differences, as earlier findings point to an increase in frontal theta only for individuals with high working memory capacity. While the results of this study indeed show an increase in frontal theta activity with increasing loads on the Add-n task and thus increasing mental effort, this effect does not vary between individuals with low versus individuals with high working memory capacity. Hence, further research is needed to make generalisable claims about the role of working memory capacity in explaining individual differences in frontal theta synchronisation.

# Introduction

During the past decades electroencephalographic (EEG), research in the fields of cognitive psychology, cognitive neuroscience, electrophysiology, and biological psychology has become increasingly popular. Such research is often used to deepen our understanding of complex mental processes such as information encoding, long-term memory, and working memory, to discover more about neuronal structures and to provide evidence for existing theories. However, such complex psychological phenomena are not yet completely understood, and individual differences in imaging data are not yet sufficiently explored. To contribute to existing research, this study will focus on the relation between working memory and mental effort, frontal theta power, and working memory capacity as accounting for individual differences.

## Working Memory and Processes

Working memory is a cognitive system that combines temporary storage and manipulation of information necessary for a variety of several complex cognitive abilities and thought processes (Baddeley, 2003). The prominent model of working memory was proposed by Baddeley and Hitch (1974), and was later extended by Baddeley (2000). The original model described working memory as having three main components: the phonological loop, the visuo-spatial sketchpad, and the central executive. The phonological loop and visuo-spatial sketchpad serve as storage centres for verbal and visuo-spatial content, respectively. The central executive acts as supervisory component controlling the information flow within the system. It is exercising control over encoding and retrieving information, attention and storage allocation and manipulation of information, whereby it coordinates both subsidiary systems. The episodic buffer, added as fourth component to the model in 2000, combines information from the phonological loop, the visuo-spatial sketchpad, and long-term memory into one episodic representation and stores it temporarily (Baddeley, 2000).

Over the years several working memory tasks have been developed, aimed at further examining working memory itself as well as the processes carried out by working memory. The Sternberg task (Sternberg, 1966) and the N-back task (Kirchner, 1958) are working memory tasks frequently applied in research. In the Sternberg task participants are presented with a memory set of length *n*, followed by a series of probe items. For each item the participant has to indicate whether it was part of the memory set. Task difficulty can be adjusted by changing the load factor *n*, hence changing the length of the memory set. In the N-back task, participants are presented with a sequence of items, and are instructed to indicate for each item whether it matches the item from *n* places earlier in the sequence. Again, *n* can be changed to adjust task difficulty. Another working memory task, although not that frequently used, was introduced by Kahneman and Beatty (1966), and is defined as the Add-n task. In this task participants are presented with a four-digit sequence and are instructed to add *n* to each of the digits in the sequence. Again, task difficulty can be adjusted by changing the load factor *n*.

All such tasks require the engagement of working memory in order to be executed correctly. In particular, the central executive plays a crucial role in the performance of those tasks (Baddeley & Hitch, 1974). All three mentioned tasks require (visual or audio) perception and attention as a starting point for correct execution. Perception, visual or audio (depending on the set-up of the task), is needed to be able to perceive the stimuli in the first place. Furthermore, attentional resources need to be allocated to the task at hand. For each task holds: the larger the load factor *n*, the more difficult the task and hence the more attentional resources are required to reach high performance. Furthermore, all described tasks require the participant to maintain a certain amount of items for a certain period of time. In the Sternberg and N-back task the number of to-be-remembered items depends on the load factor *n*, while the sequence that needs to be temporarily remembered in the Add-n task always consists of four digits. Following that, both the Sternberg and N-back task require the central executive to engage in a comparison between the probe item and the memory set or between the current item and the item *n* places earlier, respectively. In the Add-n task, however, the process following maintenance of the information is not a comparison between items, but a manipulation of the to-be-remembered sequence. Although this process is different, it is also executed by the central executive as introduced by Baddeley and Hitch (1974). Lastly, all tasks require the constant updating of the information hold in working memory.

**Frontal Theta, Working Memory and Mental Effort**

Research using imaging techniques such as EEG linked the execution of such mental processes to certain neuronal structures and frequency bands. In particular, the execution of cognitive processes of the central executive, such as explained above, has been shown to be located in the prefrontal cortex (PFC) (Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015). Further, theta band activity (4-6 Hz) has been shown to be a reliable indicator of working memory activity (e.g. Grissmann, Faller, Scharinger, Spüler, & Gerjets, 2017; Gevins, Smith, McEvoy, & Yu, 1997; Popov et al., 2018; Scharinger, Soutschek, Schubert, & Gerjets, 2017). Specifically, an increase in frontal theta activity can be observed in people that perform working memory tasks requiring mental effort (e.g. Akiyama, Tero, Kawasaki, Nishiura, & Yamaguchi, 2017; Gevins et al., 1997; Jensen & Tesche, 2002; Klimesch, 1999; Onton, Delorme, & Makeig, 2005; Scharinger et al., 2017; Zakrzewska & Brzezicka, 2014). Gevins et al. (1997), for example, administered a version of the N-back task with four conditions: verbal & easy; spatial & easy; verbal & difficult; spatial & difficult. In the "easy"-condition each stimulus had to be compared to the first of a block, while in the "difficult"-condition each stimulus was compared to the one three positions back ($n = 3$). In the "verbal"-condition the judgement had to be based on the letter itself, while in the "spatial"-condition it was based on the position of the letter. The results showed a significant peak in frontal theta between conditions "easy" and "difficult", and hence for increased task difficulty. A similar study was conducted by Scharinger et al. (2017). The goal of the study was to compare EEG frequency band power across different loads of the N-back task. In their study, they tested the loads $n = 1$, $n = 2$, $n = 3$, and $n = 4$ in three different conditions (digit value, position, and form). In each condition a comparison between the current stimulus and the $n^{th}$-back stimulus was required along one of the dimensions/conditions. The results showed an increase in theta event-related synchronisation for increased working memory load.

**Individual Differences in Frontal Theta Increase**

Research has provided evidence for individual differences in load-related frontal theta increase (Zakrzewska & Brzezicka, 2014). Inanaga (1998) showed that such variability stems from differences in personality traits such as anxiety, extroversion, and neuroticism. For instance, subjects scoring low on the Manifest Anxiety Scale (MAS) showed higher power increase in the theta band. A similar observation was made by Shi, Gao, and Zhou (2015) who investigated test anxiety in particular. Subjects with low test anxiety showed a larger increase in frontal theta activity compared to subjects with high text anxiety. This effect is likely due to impaired functioning of the central executive resulting from anxiety and stress (Eysenck, Derakshan, Santos, & Calvo, 2007; Gärtner, Rohde-Liebenau, Grimm, & Bajbouj, 2014; Shi et al., 2015).

However, not a lot of research has been undertaken on investigating the role of other factors, such as cognitive ability, that may account for the observed individual differences. Zakrzewska and Brzezicka (2014) have made a start in researching frontal theta variability as a function of working memory capacity. Working memory capacity has been assessed using a variation of the Operation Span task (OSPAN) by Turner and Engle (1989). In the OSPAN task, participants are instructed to remember a series of items while simultaneously solving mathematical equations. In their study, Zakrzewska and Brzezicka (2014) used single letters as to-be-remembered items. Based on their total score on the OSPAN and a median split, participants were classified as having either low or high working memory capacity. Mental effort was induced using the Sternberg task (Sternberg, 1966), as described above. In the version used in the study of Zakrzewska and Brzezicka (2014), the items used for the memory sets and as probe items were digits, and the memory sets had a length between 2 and 5 ($n$ ranges from 2 to 5).

Interestingly, Zakrzewska and Brzezicka (2014) report an increase in frontal theta power only for individuals with high working memory capacity, i.e. for those having a high score on the OSPAN task. This finding supports the hypothesis that frontal theta does not only indicate the amount of information hold in working memory and the effort it takes to hold and manipulate that information, but that it also indicates the efficiency of working memory processes. Individuals with high working memory capacity may show greater efficiency in such processes, and hence show an increase in frontal midline theta (Zakrzewska & Brzezicka, 2014). However, there is not yet sufficient research on this topic to make generalisable claims on individual differences in frontal theta increase related to working memory capacity and its meaning for the interpretation of frontal theta.

**Research Goal**

The goal of this research is to investigate working memory capacity as source of individual differences in frontal theta increase related to mental task performance. First, it will be investigated whether there is an increase in frontal midline theta power related to task difficulty. Based on earlier research, it is hypothesised that there is an increase in frontal theta power with increasing load ($n$) on a working memory task (Hypothesis 1). Second, it will be researched whether this increase varies for people with different working memory capacities, as shown by Zakrzewska and Brzezicka (2014). Assuming the results of Zakrzewska and

Brzezicka (2014) are accurate, it is hypothesised that an increase in frontal theta activity is visible only for people with high working memory capacity (Hypothesis 2).

To test these hypotheses, EEG analysis will be applied to participants performing a working memory task requiring mental effort. To induce mental effort, this study will make use of the Add-n task (Kahneman & Beatty, 1966) instead of the Sternberg task as used by Zakrzewska and Brzezicka (2014). A great amount of research points to an increase in frontal theta with increasing mental effort induced by increasing loads on both the Sternberg and the N-back task (e.g. Gevins et al., 1997; Onton et al., 2005; Scharinger et al., 2017; Zakrzewska & Brzezicka, 2014). Although pupil dilation analysis shows that the Add-n task induces mental effort as well (Kahneman & Beatty, 1966), it is not commonly used in working memory and EEG research in particular. However, since the Add-n task requires (partially) different processes to be executed by the central executive, it is particularly interesting to see whether the effect on frontal theta activity remains the same as for the Sternberg and N-back task. It is expected that mental effort and hence frontal theta activity increases with increasing task difficulty (increasing load factor *n*) on the Add-n task.

In order to assess individuals' working memory capacity a variation of the OSPAN task (Turner & Engle, 1989) will be administered. In this variation, the to-be-remembered items are single digits, which will increase the difficulty of the task and may make it possible to more accurately determine individuals' working memory capacity. Performance on the OSPAN will be determined using total scores, where higher scores indicate higher working memory capacity.

# Methods

## Participants

The experiment was conducted with 20 participants via convenience sampling at the University of Twente, Enschede, The Netherlands. Participants were eligible to participate in the study if they were aged above 18 years and not under the influence of drugs at the time of the experiment. Participation was voluntarily, and all student participants received an incentive of 2.5 credits in the university's BMS Test Subject Pool system SONA. The participants were aged between 18 and 26 years, with a mean age of 20.75 years ($SD = 1.80$). Of the 20 participants, three were male and 17 female, and nationalities ranged from German (n = 13), to Dutch (n = 3), Bulgarian (n= 2), to Latvian (n = 1), and Swiss (n = 1). The study was approved by the Ethics Committee of the University of Twente. All participants signed an informed consent form beforehand, which stated that they participate in the study voluntarily and understand their rights in the context of the research. Participants were informed about the data collection and analysis.

**Stimuli and Procedure**

Each participant was tested individually in the facilities of the BMS lab of the University of Twente. Participation in the study took approximately 2.5 hours per participant. Information and instructions were given in English. Before starting the experiment, participants were informed about the purpose of the study. They were informed that the study is about mental effort and a corresponding increase in frontal theta activity. Participants were asked to sign the informed consent, after which the study started with filling in an EEG questionnaire (Appendix A), which included items about demographics, the participant's medical history, and their handedness. Afterwards, participants were administered the Operation Span Task (OSPAN) by Turner and Engle (1989), which is frequently used to determine working memory capacity. Following the OSPAN, the EEG was set up and the Add-n task was administered.

*Operation Span Task (OSPAN)*

In the OSPAN task participants are instructed to solve mathematical equations by simultaneously remembering unrelated items, which in this study were single-digit numbers. For each mathematical equation (shown for 2500 ms, followed by an equal sign for 500 ms) participants had to indicate verbally whether the single digit (shown for 500 ms) was the correct answer to the equation shown before. Participants had 1500 ms time for this indication until the trial was over and the next trial was presented immediately. Participants were instructed to remember the single digit, even if it was not the correct answer to the equation. The correct answers did not have to be remembered. In this study the OSPAN consisted of two blocks, each consisting of six trials. After each block, the participants were asked to recall the six digits they were supposed to remember.

Psychometric properties of the OSPAN were intensively investigated in a meta-analysis by Conway et al. (2005). Conway et al. (2005) report an internal consistency of at least 0.698, and at maximum 0.814, depending on the scoring system used. An alpha of at least 0.75 was reported by Klein and Fiss (1999). Test-retest reliability in adults was shown to be stable between 0.70 and 0.80 over minutes (Turley-Ames & Whitfield, 2003), over weeks (Friedman & Miyake, 2004; Klein & Fiss, 1999), and over a quarter of a year (Klein & Fiss, 1999). A meta-analysis of independent studies showed significant construct validity, convergent as well as discriminant (Conway et al., 2005).

*Add-n Task*

In the Add-n task, first introduced by Kahneman and Beatty (1966), participants are presented with a four-digit sequence consisting of single digits. Participants are instructed to add *n* digits to each of the four digits. For example, in an Add-1 task, the sequence 5387 has to be transformed to 6498. In an Add-2 task the same sequence would have to be transformed to 7509. The load factor *n* can be adjusted, and during this experiment the loads 0, 1, and 2 were used. Kahneman (2011) claims that the task (specifically when $n = 3$) is one of the most effortful tasks there is, supporting the decision to apply this task to induce mental effort.

A trial consisted of a short instruction, the presentation of a four-digit sequence, a 3000-ms time interval to do the transformation and an open-ended time-interval to respond (Figure 1). The instructions ("ADD ZERO", "ADD ONE", or "ADD TWO") were shown for 2000 ms. Then, the sequence was shown in the centre of the screen for 1000 ms, followed by a 3000-ms time interval during which a green square was presented in the centre of the screen. During this time interval, the participants transformed the sequence in their heads, hence mental effort is expected to be induced in this time period. Afterwards, a question mark appeared on the screen, indicating that participants could now formulate their response, which included first speaking the transformed sequence out loud, and then typing it in the keyboard. The next trial began only after participants had spoken and then entered the transformed sequence using the keyboard.

The Add-n task was administered in six blocks, each consisting of 20 trials. The instructions were the same throughout a block. Each load ($n = 0$; $n = 1$; $n = 2$) was administered in two blocks. The order of loads/blocks was determined beforehand (e.g. 0, 1, 2, 0, 1, 2) and then randomly assigned to the participants.

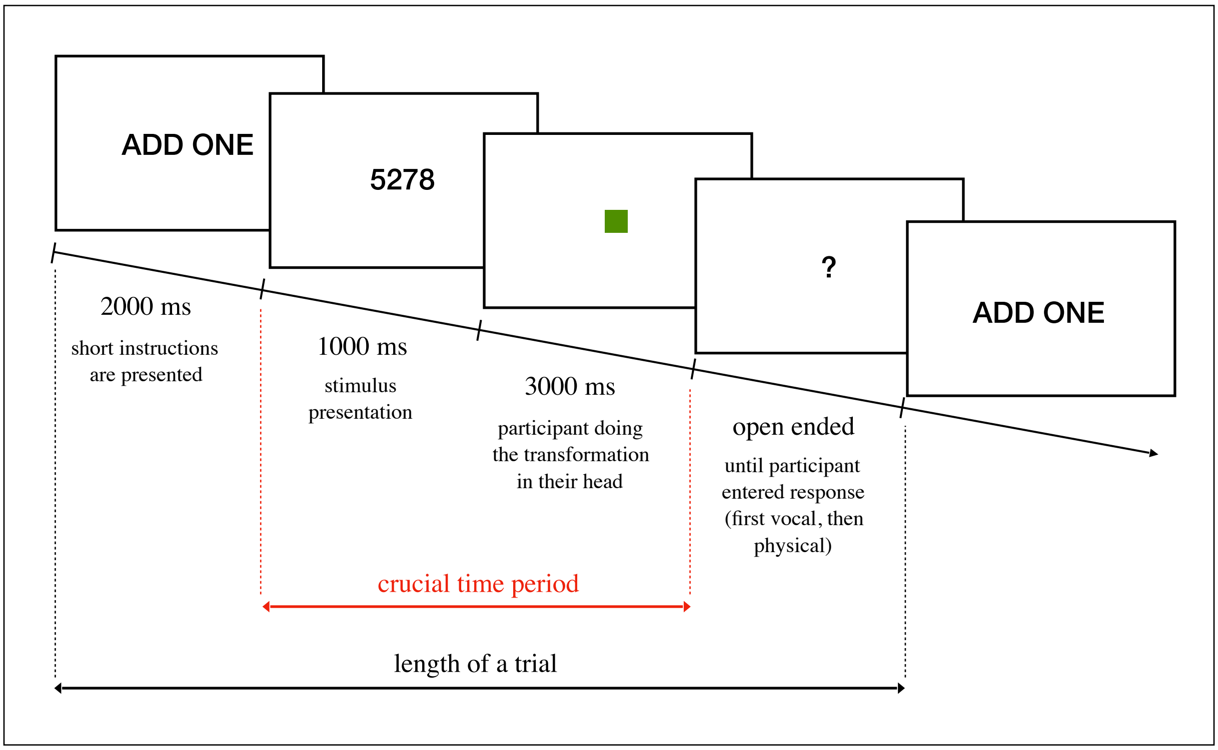


*Figure 1*. Schematic representation of a trial of the Add-n task with load $n = 1$ and example sequence 5278.

## Apparatus and EEG Recordings

The OSPAN was administered on a MacBook Pro (2015) with macOS Mojave Version 10.14 and a 13" display using Microsoft PowerPoint. The Add-n task was administered on a standing PC (Windows 10 Leanmode, 22" LED monitor, refresh rate of 60 Hz) via Presentation Software (Neurobehavioral System, Inc., Berkely, CA). Conditions were the same for all participants: The room was darkened and participants were placed approximately 60 cm in front of the screen. An English keyboard was used to enter responses.

Electroencephalographic recording was done using 32 active electrodes attached to an electrode cap (ActiCap, Brain Products GmbH, Munich, Germany) according to standard 10-20 system positions (Figure 2; Jasper, 1958), with TP8 as reference electrode. The ground electrode was located at AFz. An EOG was used to record eye movements. The sampling rate of the signals was 1000Hz per channel, and signals were amplified using a 72-channel DC amplifier (QuickAmp, Brain Products GmbH, Munich, Germany). Input impedance was kept below under 10 kΩ for all EEG electrodes before starting the recordings. The software BrainVision Recorder (BrainProducts GmbH) was used to register the EEG signal.

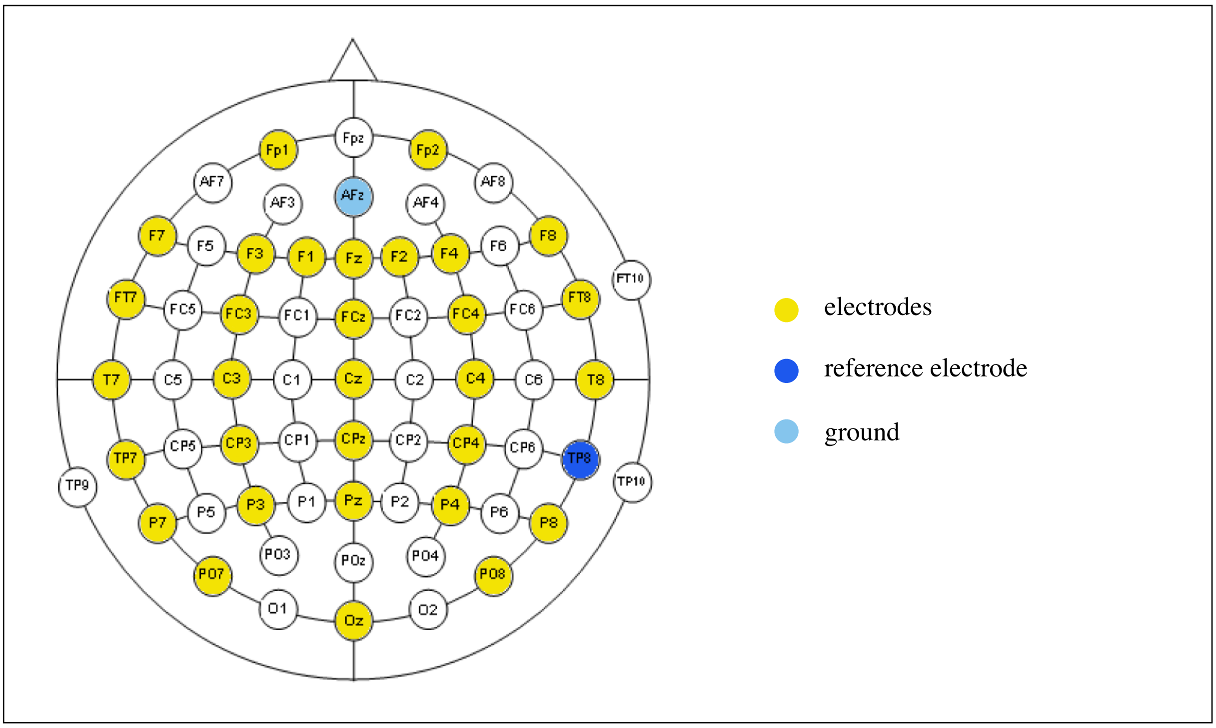


*Figure 2*. Placement of the electrodes based on standard 10-20 system positions. Electrodes attached are: FP1, FP2, F7, F3, F1, Fz, F2, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, PO7, PO8, and Oz. Reference electrode was TP8. The ground electrode was placed on AFz.

## Data Analysis

### *Behavioural Data*

Total scores on the OSPAN were calculated for each participant. To avoid floor effects resulting from using conventional scoring methods (e.g. Unsworth & Engle, 2005), the following method was used: A score of 1 was assigned to correct indication on the mathematical equation. Regarding the to-be-remembered sequence, a score of 2 was assigned if a digit was correctly recalled, including the position in the sequence. A score of 1 was given if the recalled digit was correct, but not on the correct place in the sequence. Adding up the scores on both blocks, the maximum total score possible is 36.

For the Add-n, the proportion of correct digit transformations for each participant on each condition was calculated. Each wrongly transformed digit was considered an error. With 40 trials per condition, each consisting of a four-digit sequence, a total of 160 digits needed to be transformed. Hence, the maximum possible number of errors is 160. Per condition, the proportion correct was calculated by dividing the number of errors by the number of digits that had to be transformed (160 per condition). The conditions were compared using a repeated measures ANOVA based on the proportion of correct transformations. It is expected that the proportion correct decreases with increasing load factor *n*.

*EEG Data Processing*

To begin the analysis, the data were pre-processed using BrainVision Analyser (BrainProducts GmbH, Munich, Germany) through the following steps: First, the data were checked for distorted channels. Channels distorted during the majority of the recorded time were disabled. Segmentation from -500 ms to 4000 ms relative to the markers indicating the stimulus presentation was applied. This time period was chosen for segmentation, as mental effort due to maintenance and manipulation of the stimulus is expected to be induced after the stimulus presentation up until the transformation was performed in the participant’s head (see Figure 1). Then, baseline correction from -500 ms to 0 ms was applied to the data. Subsequently, artefact rejection based on individual channel mode and automatic segment selection was executed with the following criteria: gradient criterion: 50 µV/ms; amplitude criterion: -/+ 350 µV; low activity criterion: 0.5 µV/100 ms. Ocular correction was applied, using data from the vertical and horizontal EOG. Artefact rejection was applied a second time, with an amplitude criterion of -/+ 150 µV, leaving the other two criteria unchanged. Afterwards, a baseline correction (from -500 ms to 0 ms) was applied a second time. Disabled channels were then re-calculated using signals of surrounding channels. Segmentation from again -500 ms to 4000 ms relative to the markers signalling the stimulus presentation of each condition followed, by that separating data of different conditions (loads) from each other. Lastly, to transform the EEG data from the time domain to the frequency domain, a Fast Fourier Transformation (FFT) was performed on the data of each condition separately, followed by a calculation of the average power for each frequency band. The then exported data included the average power for frequency band of 4-6 Hz (theta waves) for each condition.

Before starting any statistical analysis, a log 10 transformation was applied to the data (McEvoy, Smith, & Gevins, 2000). Further, the data of the frontal electrodes (Fz, F1, F2; Zakrzewska & Brzezicka, 2014) were averaged and used for further analysis of frontal theta activity.

*Statistical Analysis*

Statistical analyses were performed using IBM Statistics SPSS 24 (IBM Corporation, Armonk, NY). Before testing the hypotheses, box plots for frontal theta power were created for each condition, and influential outliers were removed based on the following criteria: $x_i >$ Q3+1.5*IQR or $x_i <$ Q1-1.5*IQR. Descriptives were derived for frontal theta power.

To test the hypotheses, two models were applied to the data. First, a repeated measurement ANOVA with the conditions (Add-0, Add-1, Add-2) as factor was applied to the data to test whether there is a significant change in frontal theta activity. If significant, a *post hoc* test for pairwise comparison was applied to the data. Second, the total score on the OSPAN was added to the model as covariate in order to determine whether there is an interaction effect between the conditions of the Add-n task and working memory capacity.

To minimise statistical Type I error, a significance level of alpha = .05 was chosen for all statistical analyses. In order to determine effect size, partial Eta Squared ($\eta_p^2$) was determined for all above described models. Further, observed power (1-$\beta$) was extracted for both models.

# Results

## Behavioural Data

Total scores on the OSPAN range from 13 to 28 ($M$ = 19.20, $SD$ = 4.81), with scores 13 and 17 being present most frequently (15%) (Figure 3).

Regarding the Add-n task, the proportion correct of the transformations range from 0.84 to 1.00 across conditions. For condition $n$ = 0 (Add-0 task), the proportion correct is rather high ($M$ = 0.99, $SD$ = 0.01). The Add-1 task shows a decrease in proportion correct ($M$ = 0.94, $SD$ = 0.04) when compared to the Add-0 task. The Add-2 task again shows a decrease in proportion correct ($M$ = 0.92, $SD$ = 0.04), when compared to Add-0 and Add-1 (Figure 4). The difference in proportion correct between the three conditions is significant, $F(2,36)$ = 19.50, $p < .001$, $\eta_p^2$ = .52, 1-$\beta$ = 1.00. In particular, there is a significant decrease in proportion correct between the Add-0 and the Add-1 and between Add-0 and Add-2, but not between Add-1 and Add-2 (Table 1).

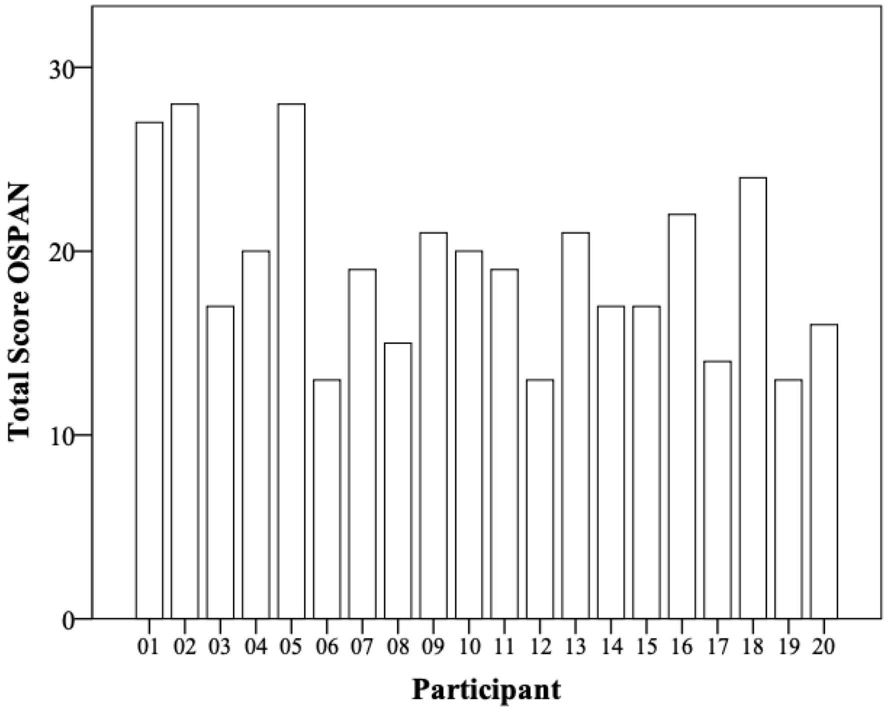


*Figure 3*. Total scores on the OSPAN task per participant. The maximum total score achievable was 36. Total scores ranged from 13 to 28 ($M$ = 19.20, $SD$ = 4.81).

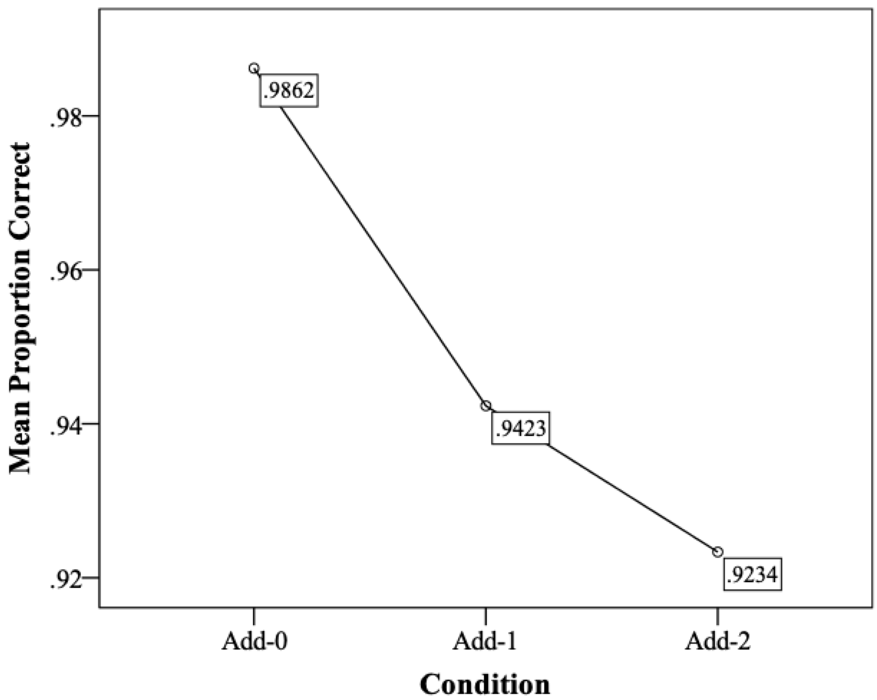


*Figure 4*. Mean proportion of correct transformations on the Add-n task per condition (Add-0, Add-1, Add-2). A decrease in proportion correct is observable with increasing load ($n$) on the Add-n task.

Table 1.

*Pairwise comparison of mean proportion correct between conditions.*

| (I) Condition | (J) Condition | Mean Difference (I-J) | St. Error | Sig. (one-tailed) |
|---|---|---|---|---|
| Add-0 | Add-1 | 0.044 | 0.009 | < .001 |
| | Add-2 | 0.063 | 0.010 | < .001 |
| Add-1 | Add-2 | 0.019 | 0.012 | .065 |

## EEG Data

Topographical maps show an overall increase in theta activity in the frontal-central area compared to other cortical areas when mental effort is induced (Figure 5).

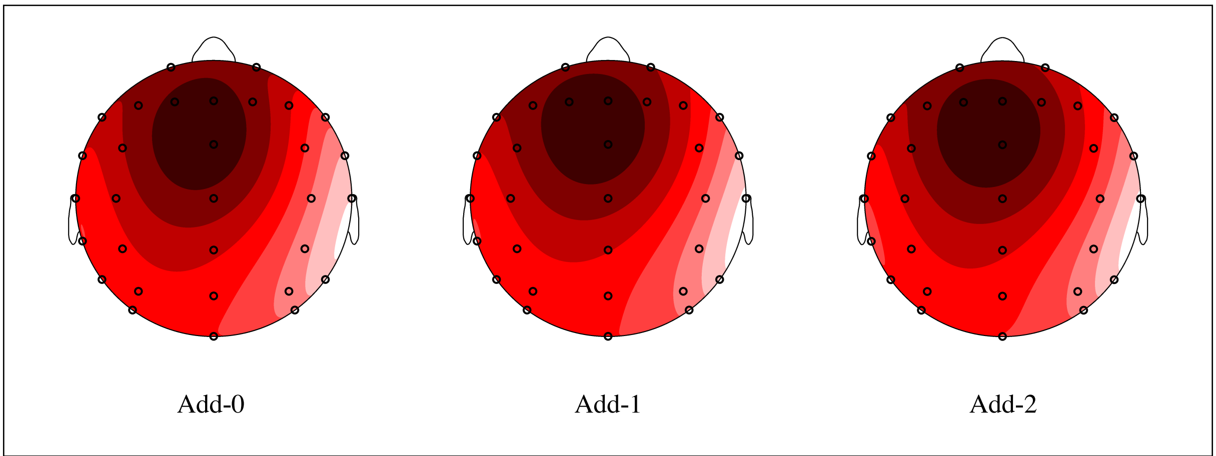


*Figure 5*. Topographical maps of grand average theta activity (4-6 Hz; one outlier removed) from -500 ms to 4000 ms relative to the stimulus presentation per condition (Add-0, Add-1, Add-2). This time interval includes the presentation of the stimulus as well as the time period where participants execute the transformation, and hence are expected to experience mental effort.

## Increase in Frontal Theta and its Relation to Working Memory Capacity

### *Descriptives*

After removing influential outliers from the data (one participant), frontal theta power (4-6 Hz; across channels Fz, F1, F2) shows a mean of -0.84 (*SD* = 0.18) across conditions. The mean theta power differs slightly per condition ($M_{Add\text{-}0}$ = -0.86, $SD_{Add\text{-}0}$ = 0.19; $M_{Add\text{-}1}$ = -0.84, $SD_{Add\text{-}1}$ = 0.17; $M_{Add\text{-}2}$ = -0.83, $SD_{Add\text{-}2}$ = 0.17; Figure 6).

*Hypothesis 1*

To test whether the increase in theta power between conditions is significant, a repeated measurement ANOVA was applied to the data. The analysis shows a significant within-subjects effect, $F(2, 36) = 4.11$, $p = .025$, $\eta_p^2 = .19$, $1\text{-}\beta = .69$, indicating a significant change in frontal theta power across conditions (Figure 6). The pairwise comparison shows that there is a significant increase in frontal theta power between the conditions Add-0 and Add-1, as well as between Add-0 and Add-2 (Table 2). No significant increase was found from conditions Add-1 to Add-2 (Table 2).

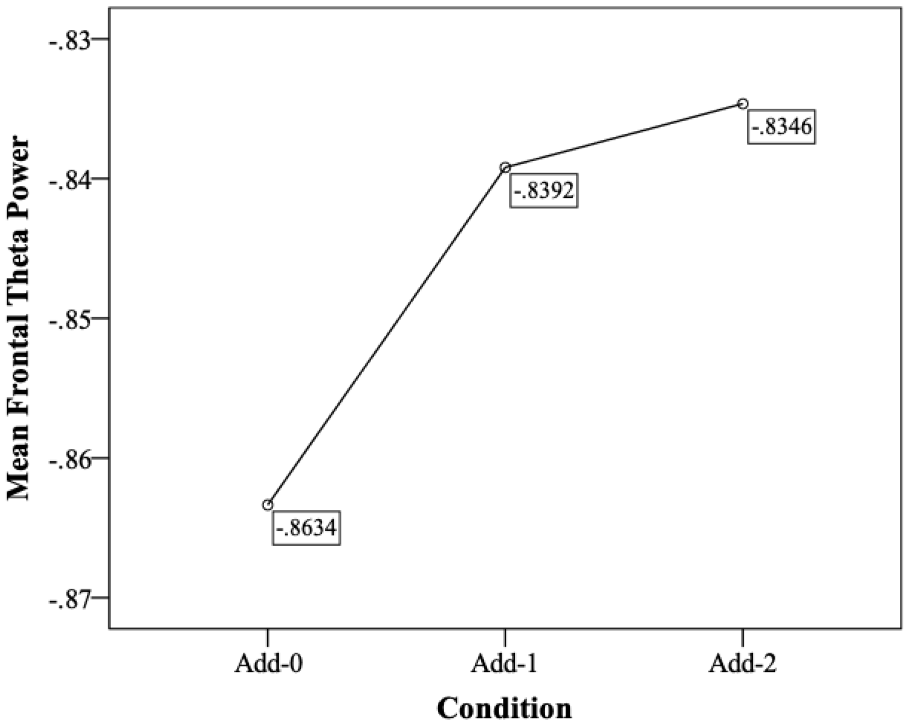


*Figure 6*. Mean frontal theta power per condition (Add-0, Add-1, Add-2). An increase in frontal theta activity is observable with increasing load (*n*) on the Add-n task. Channels used to compute frontal theta powers include Fz, F1, F2.

Table 2.

*Pairwise comparison of frontal theta between conditions.*

| (I) Condition | (J) Condition | Mean Difference (I-J) | St. Error | Sig. (one-tailed) |
|---|---|---|---|---|
| Add-0 | Add-1 | -0.024 | 0.012 | .027 |
| | Add-2 | -0.029 | 0.012 | .016 |
| Add-1 | Add-2 | -0.005 | 0.008 | .279 |

*Hypothesis 2*

To test whether the effect of mental effort on frontal theta is dependent on the individual's working memory capacity, the total scores on the OSPAN task were added as covariate to the model. The model does not support the hypothesis of an interaction effect between the working memory capacity (OSPAN total score) and the condition (Add-0, Add-1, Add-2), $F(2,34) = 0.28$, $p = .758$, $\eta_p^2 = .02$, $1\text{-}\beta = .09$. Further, the main effect of the factor (conditions of the Add-n task) is not significant anymore, $F(2,34) = 0.92$, $p = .410$, $\eta_p^2 = .05$, $1\text{-}\beta = .19$, and there is no significant effect of working memory capacity (OSPAN total score) on overall theta power, $F(1,17) = 0.22$, $p = .644$, $\eta_p^2 = .01$, $1\text{-}\beta = .07$.

## Discussion

This study examines frontal theta power related to mental effort and working memory capacity. It was hypothesised that (1) there is a frontal theta increase with increasing mental effort, and that (2) such theta power increase is dependent on the individual's working memory capacity, with higher working memory capacity leading to a larger magnitude in frontal theta increase. Mental effort was induced using the Add-n task (Kahneman & Beatty, 1966) with three conditions (loads $n = 0$, $n = 1$, and $n = 2$). Working memory capacity was determined using the OSPAN task (Turner & Engle, 1989). The results of this study provide support for one of the two hypotheses.

## Mental Effort

Mental effort was induced using the Add-n task with three different conditions (Add-0, Add-1, Add-2). As expected, the analysis of behavioural data of the Add-n task shows that there is a significant change in proportion correct between the conditions. In fact, a significant decrease in proportion correct was found between conditions Add-0 and Add-1 and between the conditions Add-0 and Add-2, which, in turn, indicates that there is a considerable increase in mental effort between those conditions. Looking at the mental processes involved in the execution of the Add-n task, it is possible to make a distinction of the Add-0 task as opposed to Add-1 and Add-2. In the Add-0 task, participants are instructed to add the number 0 to each of the four digits in the sequence, which means that the sequence remains the same and does not have to be transformed into a new sequence. Therefore, the information maintained in working memory does not have to be manipulated, but only maintained over a short period of time. Hence, the required mental processes for successful execution of the Add-0 task are attention, perception, updating of information, maintenance, and response. For both the Add-1 and Add-2 task, however, the information needs to be manipulated by adding 1 or 2 to each digit in the sequence, by that transforming the digits. The mental process of manipulation is thus necessary and puts additional effort on the central executive as compared to the Add-0 task. Further, the transformed sequence needs to be stored in memory until the response is given, which means that information in working memory needs to updated while transforming the digit, which again puts additional effort on the central executive. This additional mental effort is thought to be reflected in the proportion correct on the Add-n task, particularly between Add-0 and Add-1, as well as between Add-0 and Add-2.

Interestingly, there is no significant decrease in proportion of correct transformations between the Add-1 and Add-2 task. Based on earlier studies showing an increase in frontal theta with increasing mental effort (e.g. Akiyama et al., 2017; Gevins et al., 1997; Jensen & Tesche, 2002; Klimesch, 1999; Scharinger et al., 2017; Zakrzewska & Brzezicka, 2014), it can be assumed that the mental effort put on the central executive to perform the task does not increase significantly between those two conditions. Looking at the mental processes involved, it is clear that the processes do not change from Add-1 to Add-2. Both tasks require attention, perception, updating of information, maintenance, manipulation, updating of information and response. Although the magnitude of the required manipulation differs, the processes itself stay the same and the difference in magnitude does not seem to make a significant difference in mental effort needed to execute the mental processes.

Hence, it can be concluded that mental effort in the Add-n task as used in this study is induced due to an additional mental process required for successful performance of the task, and not due to an increase in the magnitude of manipulation, as originally expected. It is important to note, however, that an increase in the load factor *n* might still be associated with an increase in mental effort if the steps between various conditions are of greater magnitude (e.g. Add-1 and Add-3).

**Mental Effort and Frontal Theta**

Based on earlier research (e.g. Akiyama et al., 2017; Gevins et al., 1997; Klimesch, 1999; Scharinger et al., 2017; Zakrzewska & Brzezicka, 2014), it was expected to find an increase in frontal theta activity with increasing mental effort needed for execution of a working memory task. The results of this study are in line with the discussed literature. In fact, a significant increase in frontal theta was found between conditions Add-0 and Add-1, as well as between Add-0 and Add-2. However, no significant increase was found between conditions Add-1 and Add-2. This is line with the analysis of mental effort, showing no increase between Add-1 and Add-2.

**Frontal Theta and Working Memory Capacity**

Zakrzewska and Brzezicka (2014) revealed that working memory capacity is an important factor in explaining individual differences in frontal theta increase. They conclude that an increase in frontal theta activity is only visible for individuals with high working memory. The results of the present study, however, do not support the findings reported by Zakrzewska and Brzezicka (2014). Contrary to Zakrzewska and Brzezicka (2014), the statistical analysis of this study indicates a non-significant interaction effect between working memory capacity and frontal theta increase. Although Zakrzewska and Brzezicka (2014) provide explanations for their reported effect, it may be questioned whether those are valid.

First, they propose that mental effort needed to execute the working memory task already reaches its maximum in the easiest conditions for individuals with low working memory. Hence, there is no increase in mental effort with increasing task difficulty and thus no increase in frontal theta. However, if maximum mental effort is reached already in the lowest load conditions, this would imply that the capacity of the central executive is exhausted already. Consequently, a decrease in performance over increasing load conditions should be observable. Although a significant decrease in performance (proportion correct) on the Add-n task was found, this effect did not vary across individuals with high or low working memory capacity. Thus, it is questionable whether individuals with low working memory capacity do in fact reach their maximum level of mental effort already in low load conditions.

Second, as the OSPAN task is known to be an indicator of cognitive control efficiency (e.g. Unsworth & Engle, 2005), it was proposed that individuals with larger cognitive control (higher scores on the OSPAN) are able to regulate neural activity, and hence activities of the central executive, more efficiently. Therefore, activities of the central executive can be adjusted to task requirements, which leads to an observable difference in frontal theta activity between different levels of task difficulty for individuals with high working memory capacity (Zakrzewska & Brzezicka, 2014). As such, it is argued that frontal theta does not only reflect mental effort, but also the efficiency of mental processes involved. This notion is supported by Weiss, Müller, and Rappelsberger (2000), who conclude that theta synchronisation takes place when the efficiency needed to perform a certain working memory task increases. Although this is an interesting notion, it is not sufficiently explored yet, as most research focused on increasing task demands and hence increasing mental effort, instead of the efficiency of the execution of mental processes as an influence on frontal theta. As explained, the results of this study do not support the hypothesis that only individuals with high working memory capacity show a synchronisation in frontal theta activity, by that casting doubts on the explanation provided by Zakrzewska and Brzezicka (2014).

However, the present study shows some limitations especially with regard to the OSPAN task and the model testing for an interaction effect between OSPAN scores and conditions. Hence, the results should be treated with care and further exploration of the claims made by Zakrzewska and Brzezicka (2014) should be conducted.

## Limitations and Recommendations

The discussion of the results needs to be regarded carefully, as the study design bears some limitations. It is important to consider the administration and scoring of the OSPAN task. Due to limitations to the scope of the study, the OSPAN task was kept rather short by administering it in only two blocks, as explained above. Consequently, it may be questioned whether reliability and validity of the OSPAN task in this study are sufficiently high. Furthermore, the scoring method used to assess working memory capacity was rather unconventional, potentially contributing to an assessment of working memory capacity that is reduced in its reliability and validity. Unsworth and Engle (2005) propose to set an accuracy criterion of 85% on the mathematical equations to ensure that participants do not trade off between solving the equations and remembering the items. Furthermore, they propose to determine the total score by adding up the number of items of perfectly recalled sequences. However, no participant of this study, except for one, was able to recall a complete sequence. Hence, applying the scoring method proposed by Unsworth & Engle (2005) would lead to a floor effect in total scores. This would result in little variation of scores, making it difficult to distinguish working memory capacity between individuals. Thus, it was decided to apply a different scoring method, as explained above.

Furthermore, the interpretation of the statistical analyses needs to be considered carefully, as *post hoc* power analyses yield questionable results. Regarding the first model, testing for a significant change in frontal theta activity between conditions, the observed power does not reach the desired power level of .80 ($1-\beta = .69$) (Yuan & Maxwell, 2005). In fact, the probability of finding a statistically significant difference when such difference actually exists is 69%, while the probability of making Type II error is 31%, which is considered to be relatively large (Yuan & Maxwell, 2005). Regarding the second model (testing for an interaction effect between working memory capacity and condition), the observed power is very small ($1-\beta = .19$), which indicates a very high probability of committing Type II error ($\beta = .79$). Hence, interpreting the results of this model in particular has to be done carefully, and it has to be considered that there could be, in fact, a significant interaction effect between working memory capacity and condition.

For further research it is recommended (1) to apply a more literature-based administration and scoring method of the OSPAN task, as for example described by Unsworth and Engle (2005), and (2) to increase the sample size to thereby increase statistical power. Further, using the Add-n task with higher loads (e.g. $n = 3$) is recommended to shed light on whether the Add-n task induces mental effort not only through an additional mental process (manipulation of maintained information) involved when comparing Add-0 to Add-1 and Add-2, but also by increasing the magnitude of the manipulation (e.g. between Add-1 and Add-3).

## Conclusion

Although the study bears some limitations it provides interesting results and helps to further understand working memory, mental processes executed by working memory, and related neuronal activity. The study supports a frequently reported finding: an increase in frontal theta activity due to increased working memory task demands and, hence, increased mental effort. The study shows that such effect is not only observable for frequently used working memory tasks such as the Sternberg and N-back tasks, but also for the less widely known Add-n task, by that contributing to the generalisation of such results. Furthermore, the study extends the research of exploring cognitive abilities as factor accounting for individual differences in imaging data. Although the study does not support findings from earlier research claiming an important role of individual's working memory capacity in predicting frontal theta synchronisation, it contributes to the exploration of this topic and provides an interesting basis for further investigation of this topic.

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## Appendix A

### 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?

______________________________

*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 | | | | | |