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# Does a cognitive load metric predict behavioural and physiological responses in a working memory task?

## - Evaluating the Time-Based Resource-Sharing model

**Faculty of Electronics, Communications and Automation**

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Supervisor: Professor Mikko Sams
Instructor: Anu Holm, Ph. Lic.

Aalto University
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The goal of this study was to attempt to replicate the results obtained by Barrouillet et al. (2004) in a study introducing the Time-Based Resource-Sharing (TBRS) model, which postulates that working memory spans are positively and linearly correlated to the retrievals / time -ratio, i.e. cognitive load, a given processing task involves. We also attempted to determine whether the effects of cognitive load are measurable with neurophysiology by examining the event-related potentials (ERPs), in particular the P300 and late positive components.

We were unable to replicate the results of the original study to any extent, and did not find an effect for cognitive load on working memory spans similar to that predicted by the TBRS model. Clear effects for cognitive and memory load were found in the ERPs, but these results did not indicate a trade-off between processing and storage.

Questions for future research are presented regarding memory and processing performance, the role of speech in working memory tasks, and the effect of cognitive load.

**Keywords:** working memory, working memory span, executive function, cognitive load, event-related potentials, P300, late positive components, dual tasks

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Tutkimuksen tavoitteena oli toistaa TBRS-työmuistimallin (Time-Based Resource-Sharing) esittelevässä tutkimuksessa (Barrouillet et al. 2004) havaitut tulokset. Malli esittää työmuistisillan olevan suoraan verrannollinen muistisuoritusta häiritsevän tiedonkäsittelytehtävän vaatimaan muistihakuja / aika -suhteeseen. Tutkimuksessa yritettiin myös selvittää, voiko tämän suhteen määrittelemän kognitiivisen kuorman vaikutuksia mitata fysiologisin menetelmin tutkimalla tehtävän aikana syntyneitä herätevasteita, erityisesti P300-aaltoa ja myöhäisiä positiivisia komponentteja.

Tutkimuksessa ei onnistuttu toistamaan alkuperäisen tutkimuksen tuloksia. Havainnot eivät tukeneet TBRS-mallin ennustamaa kognitiivisen kuorman lineaarista vaikutusta työmuistisillan pituuteen. Herätevasteista havaittiin selkeät vaikutukset sekä kognitiiviselle, että muistikuormalle. Nämä havainnot eivät kuitenkaan tue ajatusta ristivaikutuksesta tiedonkäsittelyn ja muistisuorituksen välillä.

Tulokset herättävät useita mielenkiintoisia tutkimuskysymyksiä tiedonkäsittelystä ja muistisuoriutumisesta, puheen vaikutuksesta työmuistitehtävissä suoriutumiseen sekä kognitiivisen kuorman vaikutuksesta.

**Avainsanat:** työmuisti, työmuistisilta, toiminnanohjaus, kognitiivinen kuorma, herätevaste, P300, hitaat positiiviset komponentit, kaksoistehtävä

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Espoo, April 3rd, 2010

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# Abbreviations

| | |
|---|---|
| CL | Cognitive load |
| EEG | Electroencephalography or electroencephalogram |
| EMG | Electromyography or electromyogram |
| EOG | Electro-oculography or electro-oculogram |
| EP | Evoked potential |
| ERP | Event-related potential |
| hEOG | Horizontal EOG |
| ICA | Independent component analysis |
| ILI | Inter-letter interval |
| IOI | Inter-operation interval |
| LPC | Late positive component |
| LTM | Long-term memory |
| LTS | Long-term store |
| PSP | Post-synaptic potential |
| PSW | Positive slow wave |
| SD | Standard deviation |
| STM | Short-term memory |
| STS | Short-term store |
| TBRS | Time-Based Resource-Sharing |
| vEOG | Vertical EOG |

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# 1 Introduction

Working memory is defined as a system for processing and storing information relevant to any and all tasks and goals one might be performing or pursuing at any given moment. It is often regarded as the cornerstone of intelligence. Because of its well-acknowledged significance it has generated a substantial amount of research. Working memory capacity has been shown to predict performance in various demanding cognitive activities, such as reading comprehension, programming, and reasoning. As a strong indicator of such complex cognitive tasks, and even fluid intelligence, discovering the source and limitations of working memory capacity would greatly broaden our understanding of human thought, behaviour, and cognitive performance. A classic measure of working memory capacity is the working memory span.

Working memory span is measured using tasks that combine two subtasks: one task involving processing of information, and the other requiring storage and maintenance of items. The capacity of working memory is measured in span length, i.e. the number of items that can be successfully maintained in memory while performing the processing task.

The goal of this study is to attempt to replicate the results obtained by Barrouillet et al. (2004) in a study introducing the Time-Based Resource-Sharing model. The model defines cognitive load as a quantifiable metric corresponding to the retrievals / time -ratio a given task involves, and postulates that working memory spans are positively and linearly correlated to this ratio. Barrouillet et al. also introduce a new working memory span task called continuous operation span task, which involves memorizing letters while performing simple computer-paced arithmetic operations. In the continuous operation span task, the imposed cognitive load, as defined by the model, can be easily controlled. In a series of experiments, they provide strong evidence supporting their hypothesis.

We also attempt to determine whether the effects of cognitive load are measurable with neurophysiology by examining the event-related potentials (ERP). In particular, we study the P300 component seen in the ERP as a positive peak at 300 ms post-stimulus, and late positive components in a time window of 500 - 900 ms post-stimulus. The P300 is often used in assessing workload and resource allocation in dual task situations. The late positive components have been associated with executive control processes that are needed in switching attention between the two tasks.

## 1.1 Thesis structure

Chapter 2 gives a brief introduction to the history of working memory research, and an overview on a few of the most influential models of the structure and functioning of working memory.

Chapter 3 elaborates the framework of the Time-Based Resource-Sharing model, and the findings that led to its development. The concept of cognitive load is defined, and its effect on working memory spans is viewed from the perspectives of the different models.

Chapter 4 describes what the electroencephalogram (EEG) is, where it originates from, and how it is measured, and Chapter 5 introduces the EEG-based event-related potential (ERP) measurement technique, its use in research and how it is relevant to this study.

In Chapter 6, the study design is presented, and the methods used in the measurements are explained. Chapter 7 gives an account of both the behavioural and physiological results obtained.

Finally, in Chapter 8 the results and their correlation with our predictions are examined, possible explanations for the differences are speculated, and questions for future research are presented.

# 2 Working Memory

Working memory is generally considered as a system devoted to the coordination of processing and storage of information, and regarded as the basis of consciousness and complex human thought. Ericsson and Delaney (1999) define it to include all the mechanisms that maintain selective access to the information and procedures necessary for a participant to perform and complete one or more specific concurrent tasks. Because it is widely recognized as playing a key role in the performance and behaviour of humans, it has also generated a substantial amount of research and a number of attempts at modelling its functions and limitations.

This chapter gives a brief history of developments in the field of working memory research and an overview of some of the most influential models. The history of working memory research has been thoroughly introduced by Baddeley in his 2007 book 'Working memory, thought, and action'.

## 2.1 The history of working memory research

### 2.1.1 Early research

In the late 19th century William James suggested human memory to be divided into two subsystems: a temporary primary memory, which James described as 'the trailing edge of consciousness', and a long-lasting secondary memory. His view did not gather much support at the time, however, and by the middle of the twentieth century the dominant view was that human memory is a single system in which learning is the result of forming new associations, and forgetting is the result of these associations interfering with each other. The two-component view was revived by Donald Hebb, when he proposed that the memory system was divided into a short-term memory (STM) and a long-term memory (LTM), the former functioning through electrical activity in the brain and the latter through more durable neurochemical mechanisms. This view was supported by Peterson and Peterson, who designed an experiment in which rehearsal was prevented, and where they observed a rapid loss of information of even small amounts. As the rehearsal prevention task did not involve any material similar to the recall task items, they ruled out theories based on interference of similar items and proposed the idea of a rapidly fading memory trace.

In the 1960s there was controversy regarding the modelling of the human memory. Several researchers put forward evidence to support a distinction between STM and LTM, while some researchers showed that STM tasks had a long-term component, and thus a separate STM storage was not necessary. However, in the late 1960s and early 1970s strong evidence suggesting that there was, in fact, at least two different memory systems came from studies of patients with neuropsychological dysfunction. Some studies documented patients with very poor LTM performance performing well on classic STM tasks (Baddeley and Warrington 1970), whereas other studies described patients with normal LTM having a digit span[1] of one or two items (Shallice and Warrington 1970). These findings clearly indicate that STM and LTM are two different functional components.

---

[1] The digit span is a typical measure of short-term memory: the maximum length of a list of digits a participant is able to recall immediately after presentation

### 2.1.2 The modal model

In the early 1970s, the distinction between two or more kinds of memory gained heavy support, reflected by a number of memory models, the most influential of which was the modal model of Atkinson and Shiffrin. The modal model assumes three kinds of memory, the first and briefest being a parallel array of sensory memory systems. The two main components of this system are a visual memory termed iconic memory and an auditory memory termed echoic memory. These sensory registers are the interface between environmental input and a working memory of limited capacity called the short-term store (STS). Information could be held and manipulated in the STS and it was also in charge of encoding and retrieving information to and from a long-term store (LTS). Because of this interaction between the STS and the larger capacity LTS, long-term learning would rely on both storage systems.

The interaction between the STS and the LTS in the modal model suggested that simply holding information in the STS was enough for it to be transferred to the LTS, thus being learned. Several attempts to test this were unsuccessful, and suggested instead that much more important than the duration the information was held in the STS, was the nature of operations performed on it: Items processed simply on terms of their physical appearance were quite poorly recalled, items that were verbalized were recalled clearly better, and items encoded in terms of their meaning, as interpreted by the Levels of Processing hypothesis of Craik and Lockhart (1972), were recalled the best. This suggests that the success of long-term learning depends on the depth of encoding of the items in memory rather than the time they are held in the STS, as the modal model assumes. Also neuropsychological evidence from patients with STM impairment having normal LTM performance, as described above, contradicts the assumption of the STS playing such a crucial role in long-term learning.

## 2.2 The multicomponent model

### 2.2.1 Evolution of the multicomponent model

In 1974, Baddeley and Hitch presented their highly influential multicomponent model, in which they suggest replacing the STS of the modal model with a three-component system termed working memory. This working memory comprises of an attentional control system called the central executive, along with two subsidiary limited capacity storage systems for visual and auditory information: the visuospatial sketchpad and the phonological loop, respectively.

In the initial model, the central executive was defined as a limited pool of general processing capacity, i.e. storage and control of attention, and research was focused on the two subsystems. During the next two decades of research, Baddeley noted that an executive of general processing capacity is too powerful a concept and potentially able to explain any result, and thus is not an empirically productive model in generating experiments that enlighten how the system actually functions. Thus, in the 1990s Baddeley and Logie updated the model by defining the central executive to be incapable of storage and have a purely attentional role in working memory (Baddeley and Logie 1999).

However, without the general processing executive control, the multicomponent model seemed too limited to account for some of the more complex working memory functions, such as the ability to remember large chunks of prose or performance in the complex working memory span tasks of Daneman and Carpenter (1980). To deal with these shortcomings, Baddeley added a fourth component, the episodic buffer (Baddeley 2000). The episodic buffer is thought of as an interface between the other three working memory components and LTM, and is accessible through conscious awareness. It differs from episodic LTM by being temporary in nature, but provides access to LTM for learning and retrieval.

### 2.2.2 The current framework of the multicomponent model

Below, the current views on the components are discussed in more detail, with emphasis on the central executive and the phonological loop, as these are the components relevant to this thesis.

#### 2.2.2.1 Central executive

The central executive is thought of as a limited pool of attentional resources, and research is focused on its potential subprocesses. Currently, three different subprocesses have been defined: the capacity to focus attention, the process of dividing attention, and the process of switching attention (Baddeley 2002).

Robbins et al. (1996) investigated the effect that disrupting each of the three subsystems (the central executive, the phonological loop, and the visuospatial sketchpad) had on playing chess, an activity regarded to place great demand on the central executive. While articulatory suppression had no effect on performance in remembering a chess position or choosing the best move, a concurrent visuospatial task did deteriorate performance, implying that the visuospatial sketchpad has a role in chess playing, as would seem reasonable. However, impairment was strongest, when the participants were given the task of generating random digits, which has been found to place heavy load on the central executive (Baddeley et al. 1998). These results support the notion that the capacity of focusing attention is an important feature of the central executive (Baddeley 2002).

Evidence for the second attentional subprocess attributed to the central executive, the process of dividing attention, is found largely based on studies of patients with Alzheimer's disease, who are likely to suffer from central executive impairment. For instance, Logie et al. (2000) studied the performance of Alzheimer patients and control groups of young and old participants in two separate tasks depending mainly on the phonological loop (digit span) or the visuospatial sketchpad (pursuit tracking[2]), and in a dual-task combining the two. Their results indicate that while performance in the individual tasks is not affected differently by increased difficulty in Alzheimer patients or the control groups, performance in the dual-task condition was dramatically impaired in participants with Alzheimer's, but not affected by age. This suggests that dividing attention is a separable subprocess of the central executive.

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[2] In pursuit tracking, the participant is required to keep a stylus in contact with a moving spot of light. Difficulty is adjusted by changing the speed of movement of the light.

The process of switching attention is perhaps the most controversial one of the subprocesses attributed to the central executive, and in recent years several studies have found evidence that it might be less dependent on the executive and based more strongly on the phonological loop (Baddeley et al. 2001, Emerson and Miyake 2002).

#### 2.2.2.2 Phonological loop

The phonological loop is considered a well-established component of the multicomponent model as it has provided a simple and coherent account of a wide and complex set of data. It was defined as a system of two subcomponents: a phonological store and an articulatory rehearsal system. The information held in the store was considered to decay over a period of about two seconds unless refreshed by rehearsal through subvocal or vocal articulation. Consistent with this theory is the word length effect, whereby immediate serial recall of short words is better than that of long words. This effect is usually attributed to slower rehearsal of longer words (Baddeley et al. 1975), although some of the effect can also be a result of forgetting during recall, as this is slower with longer words (Cowan et al. 1992). Recent research indicates that both of these processes are important factors in the effect (Baddeley et al. 2002).

Strong evidence supporting the notion of subvocal rehearsal and its importance has come also from studies with patients with different speech and language deficits. Patients who have lost the physical ability to produce speech are still able to rehearse (Baddeley and Wilson 1985), whereas patients who have lost the capacity to produce speech centrally are not (Caplan and Waters 1995). These results indicate that rehearsal should be viewed as a function of central control of speech rather than an ability to overtly articulate (Baddeley 2002).

One important shortcoming of the model is the failure to give any account of how the serial order of items to be remembered is maintained. Although some simple chaining models have been proposed, they do not seem to fit the observed data (Henson et al. 1996). Yet another unresolved question is whether short-term forgetting is based on decay of memory traces or interference between them. (Baddeley 2002)

In recent years, research has implicated a more sophisticated role for the phonological loop in working memory performance than a simple control and storage component for auditory information. In a series of experiments, Baddeley et al. (2001) showed evidence that in a task switching task[3], the central executive contributes to both arithmetic performance and processing switching, but in a setup where the processing switching program needs to be endogenously maintained, articulatory suppression greatly decreased performance. This suggests that the phonological loop is used to facilitate the operation of the processing switching program.

Here, the term 'task switching' is not to be confused with switching between storage and processing in the context of working memory span tasks, also referred to as 'task switching' in for instance Barrouillet et al. (2004), and Towse et al. (2000). In order to avoid confusion, through the remainder of this thesis the term 'task switching' refers to switching between processing and storage, and the term 'processing task switching' is used when referring to alternating between instructions, e.g. adding and subtracting.

#### 2.2.2.3 Visuospatial sketchpad

Logie (1995) has suggested that the visuospatial sketchpad comprises of two subcomponents, a passive store dubbed the visual cache and an active component called the inner scribe, analogously to the two components of the phonological loops, i.e. the phonological store and the articulatory rehearsal system. However, Logie proposes that the scribe handles only the spatial, not the visual, aspects of the system, and that all visual information enters the sketchpad through LTM instead of sensory input. All in all, examining the visuospatial sketchpad and separating it into subcomponents has proved to be a more arduous task than dissecting the phonological loop.

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[3] In Baddeley et al. (2001), 'task switching' refers to a paradigm, where the participant is given a column of digits, and the task to alternate between adding and subtracting a digit from each of them. In one condition, the plus and minus signs are provided along with the digits (exogenous switching), and in the other the participant is required to maintain the switching program without cues (endogenous switching).

#### 2.2.2.4 Episodic buffer

In current opinion, the episodic buffer is regarded as a storage system using a multimodal code. It binds information from the phonological loop, the visuospatial sketchpad, LTM, and perceptual input into a coherent episode. It is thought to provide a link between LTM and the central executive. It is thought to handle chunks of information bound together by strong associative links. Different chunks of information can be further associated through relatively weak links. Through this binding process, the episodic buffer codes information from diverse sources into unified conceptual objects or coherent episodes. This conceptualization process is assumed to be the basis of conscious awareness.

## 2.3 Other models and views

A classic measure of working memory performance is the working memory reading span introduced by Daneman and Carpenter (1980). In their study, participants were to read a number of sentences and memorize the last word in each. They calculated the maximum number of sentences that the participants could process and words they could recall, and gave this number the term working memory span. They also showed a significant correlation between this span and reading comprehension in college students. Inspired by the results of Daneman and Carpenter, other span measures were also developed, for instance counting and operation spans (Case et al. 1982; Turner and Engle 1989). Further research has shown that these different spans predict performance in a wide variety of complex cognitive tasks, such as reading comprehension (Daneman and Carpenter 1983) and reasoning (Barrouillet 1996; Kyllönen and Christal 1990).

Due to the spans' close link with a wide range of complex tasks, and power of predicting performance in them, many models attempt to examine and explain the functioning, capacity, and limitations of working memory through examining performance in various span tasks. Many models also share the idea of domain-specific short-term storages for different types of information, while others see short-term storage as an activated subset of LTM items. Perhaps the most disputed aspect of working memory is the role of attention and the central executive: do the processing and retrieval processes rely on a common resource, namely attention, and how is this resource managed between the two? A few models that address these questions are presented below.

### 2.3.1 Cowan's model of information processing

The concept of executive control in Cowan's (1988) model of information processing has much in common with the central executive in the multi-component model. However, in Cowan's model there are no specialized short-term storage components, but items are stored as activated sets of information codes in LTM. Cowan's model describes the flow of information through the components more thoroughly than the multi-component model.

The activated sets in LTM act as a short-term storage, and their activation can be refreshed through voluntarily directing attention to them. This process of voluntary attention is controlled by the central executive. Spontaneous thoughts arise from the activation level of certain items in LTM reaching a critical threshold without assistance from the central executive. A perception, i.e. conscious awareness of an object or concept, is formed by matching a set of featural and semantic categories to a set stored in the LTM network. All experiences contribute to an episodic or "auto-biographical" long-term trace and may modify the sets stored in LTM.

According to Cowan, working memory contains the items represented by the sets that are activated in LTM. These items are outside the focus of attention, but sufficiently activated to be readily accessible. Items that are in the focus of attention receive activation, but as soon as attention is switched away they suffer from a time-related decay. As attention is needed for both refreshing the decaying traces and processing information, working memory span tasks require attentional capacity to be divided between the two, in order to keep the memory traces identifiable. When the processing task is too demanding and activation is not refreshed often enough, the decay results in forgetting.

### 2.3.2 The cognitive space model

Case et al. (1982) studied the performance of children in a counting span task[4] and found a developmental increase in their counting spans. They also found that the counting spans correlated with the maximum counting speeds of the children. To account for their results, Case et al. suggested a cognitive space model, according to which each individual has a fixed amount of "total processing space", or cognitive resources, that can be shared between different tasks that are to be performed, for instance processing and rehearsal. Cognitive space was considered to remain constant across age, and the observed developmental increase was attributed to automatization and practice in the counting activity. As the counting becomes faster with age, a larger part of the cognitive space can be dedicated to the storage process and hence older children have higher spans.

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[4] In the counting span task, participants are asked to count out loud the number of dots on cards (processing task), and after each card recall the totals of dots on previous cards. Their counting span is the maximum number of totals they are able to remember.

### 2.3.3 The memory decay model

Towse and Hitch (1995) suggested a simplistic resource-switching memory decay model of working memory based on their research on the counting spans of children. According to them, the attentional resource critical in performing a working memory span task is not shared between the maintenance and processing components during processing and rehearsal as suggested in the resource-sharing cognitive space model of Case et al. (1982). Instead, attention is switched from one to another when a task has been performed, i.e. the current processing task solved, a new item memorized, or the list to be maintained rehearsed. When this resource is occupied by the processing component, the memory traces suffer from time-related decay. According to this model, the difficulty of the processing task does not affect the deterioration of the memory trace directly, but through extending the duration for which memory functions have been "switched off" and the processing requirements occupy the attentional resource of the participant. This view was supported by the observation that concurrent STM load did not affect the speed of the processing operations, which suggests that there is no trade-off between processing and storage, but they are separate processes independent of each other.

To differentiate the effect of processing intensity from processing duration, Towse and Hitch (1995) designed an experiment in which they increased the duration of the counting task by increasing the number of targets and the difficulty of the counting task by making the targets less identifiable. They matched the durations of the two tasks of increased difficulty, and compared performance in them to performance in the original small-total (i.e. few targets per card) counting task. According to the authors, the cognitive space hypothesis of Case et al. (1982) predicts that spans are:

1. highest in the small-total (i.e. few targets per card) condition,
2. lower in the high-total (i.e. many targets per card) condition of equal processing intensity but increased duration, and
3. lowest in the increased-difficulty condition, where processing intensity is increased but duration is equal to the high-total condition.

In contrast, the memory decay hypothesis of Towse and Hitch (1995) predicts that because of the irrelevance of processing intensity spans are:

1. highest in the small-total condition, but
2. equal in the high-total and increased-difficulty conditions,

for in these the processing durations are equal. Indeed, in line with their own hypothesis, they observed an equal span in the high-total and increased-difficulty conditions of equal duration, providing strong evidence in favour of the memory decay model.

In a later study, Towse et al. (1998) note that evidence for the memory decay model was almost solely based on the performance of children, and differences in processing speed do not account for the differences in working memory spans between adult individuals conclusively. Towse et al. (2000) studied the effects of processing durations in adults, and conclude that also with adults, the decay of memory traces depends on the time spent on the processing task rather than on processing intensity, although there may be a developmental progression from resource-switching to resource-sharing strategies. That is, they attribute the shift to changes in task completion strategies rather than processing efficiency, as the processing component in the counting span paradigm may include gaps between stimuli, providing an opportunity for rehearsal.

# 3 Time-Based Resource-Sharing model for working memory spans

## 3.1 Do working memory limitations rise from resource sharing or memory decay?

Barrouillet and Camos (2001) argue that when increasing the number of targets to be counted, Towse and Hitch may not only have increased the duration of the processing component but possibly the cognitive load it imposed as well, i.e. processing intensity. It is possible that counting a larger number of items is cognitively more demanding in terms of the pointing activities required in keeping track of which targets have already been and which remain to be counted. Also, the number sequence is learned gradually starting with the lowest, so at least for young children producing and keeping track of larger numbers might come at a greater cognitive cost. If this is the case, the results of

Towse and Hitch (1995) might also be explicable in terms of the resource-sharing cognitive space hypothesis of Case et al. (1982).

In order to test whether cognitive load does affect recall performances, Barrouillet and Camos (2001) compared the memory performance of 6-, 8-, and 11-year-old children in a counting span task with performance under simple articulatory suppression, where the participants were to repeat the syllable 'ba' for periods identical to the duration of the counting tasks (called *baba* span task). Baddeley has shown that articulatory suppression does not involve cognitive load, and argues that it affects working memory performance only by preventing subvocal rehearsal (Barrouillet and Camos 2001; Baddeley 1986). Hence, as counting involves both a cognitive demand and an articulatory suppression, this setup allows for investigating the pure effect of cognitive demand, and comparing the two models conclusively.

The results of their experiments show that there is no difference between the *baba* span and the counting span, in fact the children performed even slightly better in the counting span task. This indicates that the additional cognitive demand of coordinating pointing of targets in the counting span task has no effect on memory performance, and the level of impairment is dependent only on the duration of the processing task, as predicted by the memory decay hypothesis. Also, as the cognitive space hypothesis dictates that the total processing space available remains constant across age, there should be a more significant developmental increase in counting span than in *baba* span, due to counting being a less demanding process for older children. However, the results contradicted this prediction as well.

In a third experiment, Barrouillet and Camos compared the results from an operation span task[5] (Turner and Engle 1989) and a *baba* span task, where the retention periods were held identical. The arithmetic processing component of the operation span task requires the use of complex algorithms for breaking the additions into smaller parts and keeping track of intermediate results, thus imposing a heavy cognitive load. According to the memory decay hypothesis, only retention period should affect span results and thus there should be no difference between the two spans investigated in this experiment. The results argue against this hypothesis, and cognitive load seems to have an impact on the span of the participant. However, seeing that the operation span task is thought to induce a high cognitive load, whereas the *baba* span condition induces none, the decreasing effect of about 20% the load had on spans can be considered quite small, and actually reached significance only in 9-year-old children, and not in 11-year-olds. Also, the fact that cognitive load affects span does not rule out the notion of a temporal decay weakening the memory traces. These results do not contradict the memory decay hypothesis, but show evidence that it may be an oversimplification, and the authors state the need for a more sophisticated model, that incorporates both the time and resource limitations evidently involved in working memory performance.

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[5] In the operation span task, participants are asked to perform arithmetic operations of three-operand additions (e.g. 3 + 9 + 7) while remembering letters for recall.

## 3.2 The framework of the Time-Based Resource-Sharing model

Inspired by the conclusions of Barrouillet and Camos (2001), in their 2004 paper Barrouillet et al. integrate both time and resource constraints into a new model that predicts the performance of a participant in working memory span tasks as a function of the cognitive load of the processing component. In this model, attention is rapidly switched between processing and storage *during* the performance of the task. The Time-Based Resource-Sharing (TBRS) model is based on four main proposals:

1. Both the processing and maintenance components in most working memory span tasks rely on the same limited attentional resource, and to successfully perform such a task, this resource must be shared between the two.
2. When attention is switched away from the memory traces of the items to be recalled (i.e. continuous rehearsal is interrupted), the traces suffer a time-related decay. These traces can be refreshed by retrieving them from memory, but this requires focusing attention to the retrieval process.
3. Although there may be several ways in which different processing tasks switch attention away from maintenance, tasks that occupy the retrieval mechanism in a similar way needed to refresh the decaying memory traces should have a more pronounced effect on maintenance.
4. When the retrieval mechanism is occupied by the processing task, attention sharing is time-based, as only one memory retrieval can be performed at any one time. Hence, sharing attention requires a rapid and frequent switching between processing and maintenance in order to successfully complete both components of the task.

The models that regard STM and working memory as subsets of LTM, as opposed to independent storage components, provide more fitting frameworks for these proposals, e.g. Cowan's model of information processing (1988) described in chapter 2.3.1. According to Cowan's model, STM is that part of LTM, which has recently received activation, and is still activated above threshold. Working memory consists of the items in the focus of attention, and those outside of focus, but in a state of sufficient activation for them to be readily accessible. Because this activation is achieved by attentional focusing, maintenance relies on the attentional resource also needed in performing the processing component of most working memory tasks. Thus completing such a task requires resource-sharing between processing and storage.

Also in line with the information processing model of Cowan is the notion of temporal decay of memory traces. Cowan suggests that the memory traces of items to be remembered receive activation when in the focus of attention. This activation starts decaying as soon as attention is switched away from their maintenance. To refresh the decaying memory traces during the performance of a working memory span task, they need to be retrieved by attentional focusing before the decay renders them irretrievable. Since this attentional resource is shared between processing and storage, the decay is dependent on the duration for which processing captures attention and impedes the refreshing of memory traces.

The processing components of most working memory span tasks involve complex activities, for instance counting, reading sentences, or solving operations. All of these activities, in addition to requiring controlled attention in planning strategies and storing intermediary results, also involve retrievals from LTM. Rohrer et al. (1998) have demonstrated that two memory retrievals cannot be performed simultaneously, and suggest the metaphor of a *spotlight of retrieval*, that can be directed toward only one category at a time. Thus, individuals can only retrieve one item from working memory at any one time, and this constitutes the central bottleneck involved in working memory span tasks.

However, Rohrer and Pashler (2003) have demonstrated that a choice reaction task involving no retrievals and requiring only attention also has a detrimental effect on performance in a concurrent free-recall task. These results suggest, in line with the TBRS model, that even simple processing components, that do not include retrievals but only attentional demand, hamper maintenance as they too capture the resource needed in refreshing the decaying memory traces. However, this effect should be especially detrimental when the central bottleneck of memory retrieval is captured by the processing task (Barrouillet et al. 2004).

The authors conclude that as both components of most working memory span tasks require series of retrievals and hence compete for the spotlight of retrieval, attention is shared between the two tasks through rapid switching from one to the other. In contrast to the proposal of Towse et al. (1998), who argued that attention is switched only when a new item to memorize, or a problem to solve is presented, the TBRS model assumes that individuals may engage in a covert retrieval process by keeping short pauses, during which they momentarily switch attention to the reactivation of memory traces, while performing the processing component of the various span tasks.

## 3.3 Defining the cognitive load metric

Most working memory span tasks involve complex processing tasks, because from a resource-sharing viewpoint, in order to sufficiently interfere with the primary maintenance task, the secondary task is supposed to capture a substantial proportion of cognitive space. It has been assumed that this is achieved through complex activities that involve planning, controlling processing, and storing intermediate results. In effect, these tasks have been found to severely interfere with recall activities. However, the notion that complex processing interferes with recall does not imply that this interference is due to processing complexity. (Barrouillet et al. 2004)

Within the TBRS framework, complex concurrent activity is not required in interfering with recall performance. The model provides a simple cognitive load metric that involves time constraints and number of retrievals as the main factors. The cognitive load a task imposes is a function of the time during which it captures attention and prevents refreshing the decaying memory traces. When this time increases, the opportunities for shifting attention to rehearsal of the items to be remembered become fewer and shorter, and as a result memory performance decreases. Rohrer and Pashler (2003) have pointed out that the centrally demanding stages of an activity are almost certain to occupy only a part of the total time taken to perform the activity. In retrieval activities this would correspond to the time the central bottleneck is fully occupied. Monsell (1991) has shown that some retrievals are costlier than others, for instance words are retrieved faster as their frequency in language increases. It is likely, that the more difficult the retrieval, the longer it occupies the spotlight of retrieval. (Barrouillet et al. 2004)

Based on these assumptions, the authors define the cognitive load of a task involving an uninterrupted series of retrievals as a function of the number and difficulty of retrievals to be performed in a given period of time:

$$CL = \sum \frac{a_i n_i}{T}$$

where $n_i$ is the retrievals of type *i*, $a_i$ the difficulty of these retrievals *i*, i.e. the time each of these retrievals totally capture attention, and *T* the total duration during which these retrievals are to be performed. In a controlled experiment, where all retrievals are identical in nature and involve a similar difficulty, i.e. parameter *a*, the function can be simplified to:

$$CL = \frac{aN}{T}$$

where a is the constant difficulty of each retrieval, *N* the total number of retrievals, and *T* the period of time for performing these retrievals. Thus, the cognitive load a task induces is directly proportional to the retrievals / time -ratio. This allows for cognitive load to be delicately controlled through experimental design. (Barrouillet et al. 2004)

## 3.4 The continuous operation span task

Barrouillet et al. (2004) designed a new working memory span task, the *continuous operation span* task, in which cognitive load can be accurately adjusted. The task consists of presenting a list of letters to be memorized while performing simple computer-paced calculations. Each calculation consists of a small seed number (from 1 to 9) and a series of operations of adding and subtracting 1 or 2 (e.g. 4 / + 1 / + 2 / - 1). The seed and the operands are presented on screen successively for only short periods of time. The participants are asked to solve these operations aloud, for instance by articulating: "four" / "plus one, five" / "plus two, seven" / "minus one, six" in the calculation example above.

Barrouillet and Fayol (1998) have shown that in adults, simple arithmetic operations using small numerals (i.e. short shifts along the number chain) are solved by retrieving the result directly from memory instead of using algorithmic strategies. Hence, solving the operations used in the continuous operation span task can be thought to require only memory retrievals, and this makes controlling the cognitive load of the task accurate and straight-forward. The cognitive load of a task involving similar memory retrievals is directly proportional to the retrievals / time ratio. At a comfortable pace, the gaps between subsequent operations (see Figure 1a) could allow participants to take pauses from the processing task and refresh the decaying memory traces of the letters to be remembered when the central bottleneck for retrieval is available, resulting in high spans. This pace, and consequently the cognitive load the task imposes, can be adjusted in two ways: either by increasing the number of operations to be performed within the same amount of time (see Figure 1b), or by decreasing the time allowed to perform the same amount of operations (see Figure 1c). According to the model, this should result in poorer recall and shorter spans. (Barrouillet et al. 2004)

## 3.5 Predictions of the different models

In Figure 1, three single trials of the continuous operation span task under different cognitive load cases are presented.

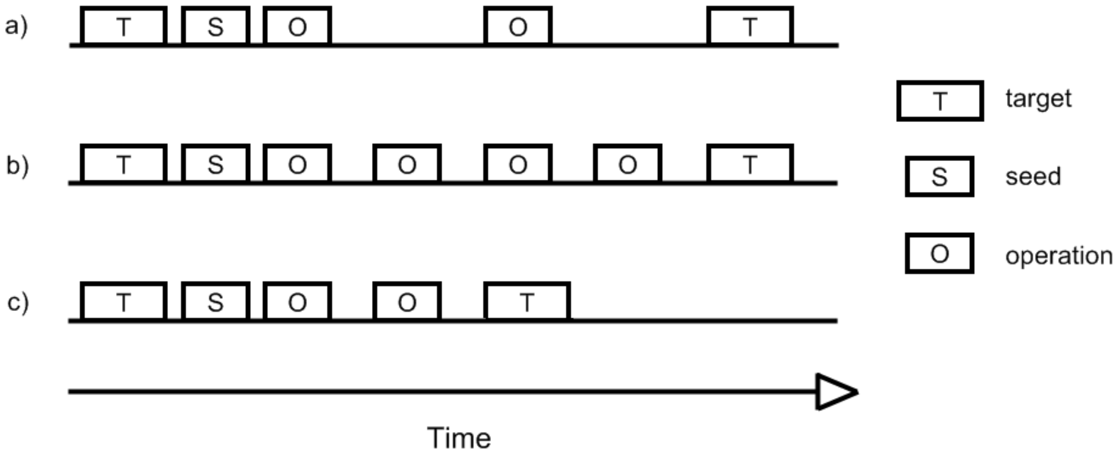

**Figure 1** Schematic representation of a single trial of the continuous operation span task imposing a light cognitive load (a), and two ways of increasing the cognitive load it imposes: increasing the number of operations (b), or decreasing the time allowed for performing the operations (c).

In terms of the retrievals / time -ratio of the TBRS model, cases (b) and (c) impose an equal cognitive load double to that in (a). However, the inter-letter interval of condition (b) is approximately twice as long as in condition (c), but equal to condition (a). If considered from the viewpoint of the amount of cognitive work each condition involves, conditions (a) and (c) both include two operations, and thus an equal amount of cognitive work, whereas condition (b) has four operations, i.e. twice the amount in (a) and (c). Based on these differences, each of the three models presented above (the cognitive space model of Case et al. (1982), the memory decay model of Towse and Hitch (1995), and the TBRS model of Barrouillet et al. (2004)) gives a different prediction of how performance should vary under these three conditions. These predictions are as follows:

**Cognitive space model:**
As the amount of pure cognitive work to be done is equal in (a) and (c), performance under these conditions should be approximately equal, and better than that in (b), where the amount of cognitive work is doubled.

**Memory decay model:**
Performance should be equal in (a) and (b), where the inter-letter intervals, and thus the duration memory traces are subject to decay, are the same. Condition (c) involves an inter-letter interval of about half the length, and should thus result in shorter retention periods and better performance

**TBRS model:**
The cognitive load, i.e. retrievals / time -ratio in (b) and (c) are equal, and thus performance should be similar. Furthermore, condition (a) imposes a load approximately half of that in (b) and (c), and hence should result in significantly better performance.

# 4 Principles of EEG and its measurement

Electroencephalography is a neurophysiological measurement technique in which the voltage differences between two different locations on the scalp are graphically represented as plotted over time. This graphic representation is referred to as an electroencephalogram (EEG). The EEG has many clinical application areas, such as the assessment of sleep, diagnosing epilepsy, identifying brain damage, and monitoring anaesthesia. It is also widely used in neurophysiological research (Lang et al. 1994). In the last few decades, EEG applications for assessing cognitive workload and allocation of resources have been developed and have gained interest as a tool for memory research (Duncan et al. 2009; Dunn et al. 1998; Sirevaag et al. 1989).

In 1875, an English physician, Richard Caton was the first to observe 'continuous spontaneous electrical activity' from the brain surface of rabbits and monkeys. In 1912, Vladimir Vladimirovich Pravdich-Neminsky recorded and published the first mammalian EEG. However, the invention of EEG is most often credited to German physiologist Hans Berger, who was the first to record human EEG in 1929. He also gave the method its name: 'electroencephalogram'. Later major advances in the field have been due to improvements in measurement electronics and the introduction of computers in analyzing EEG data. (Swartz and Goldensohn 1998)

## 4.1 Measurement practices

EEG is normally measured with electrodes attached to the scalp. The most common electrode type is the Ag/AgCl -electrode. When measuring from the scalp, the electrode sites are cleaned and dead skin is removed by scratching the skin surface, and a conductive attaching paste is applied in order to minimize electrode impedance. The electrodes are usually positioned according to the international 10-20 system (see Figure 2), which was accepted as a standard for surface EEG recordings in 1949 (Klem et al. 1999).

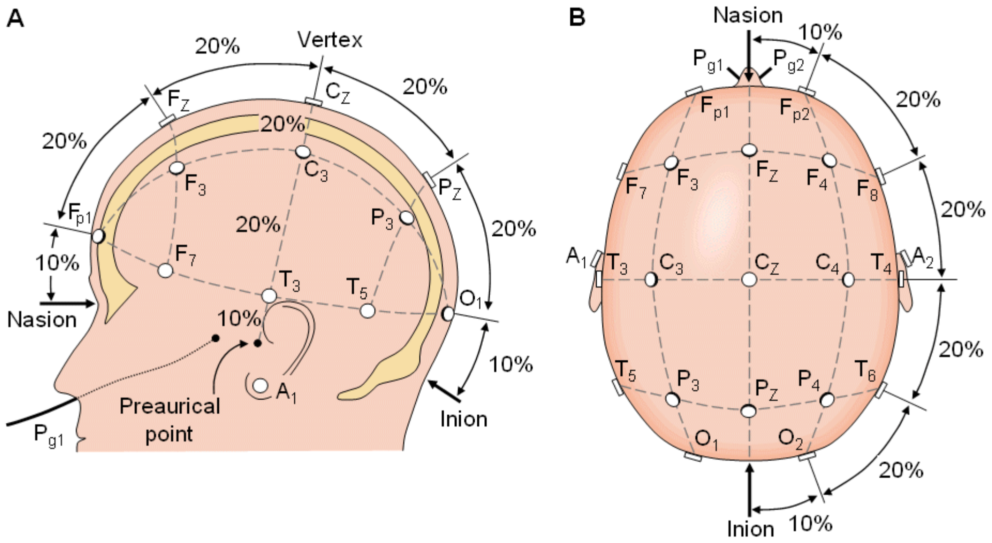

**Figure 2** Electrode positions according to the international 10-20 system seen from left of (A) and above (B) the head. (Copied from Malmivuo and Plomsey (1995))

The temporal resolution of EEG is very high, and rapid changes in activity can be measured. However, spatial resolution is relatively low, as the location of the signal source has to be estimated from a two-dimensional projection of the three-dimensional electrical field created by the neurons in the brain areas under the electrode and attenuated by the scalp, skull, and cerebrospinal fluid. Hence it is theoretically impossible to accurately determine the exact location of the EEG generator based on scalp-recorded EEG alone. In the context of EEG, this is referred to as the inverse problem. (Olejniczak 2006)

## 4.2 Signal source

In order to be detected with electrodes, the duration and strength of an electrical signal must be sufficient. The fast action potentials propagating along the neurons are generally too quick for detection. Only synaptic activity, both excitatory and inhibitory, is strong and long-lasting enough. The electrical signals measured from the scalp are generated by the postsynaptic potentials (PSP) of cortical neurons. (Olejniczak 2006)

A single PSP is not nearly strong enough to be detected from the scalp. Measurable EEG requires the summation of many simultaneous PSPs, and in order for the PSPs to enforce each other rather than cancel each other out, the neurons must be orientated in parallel to each other on the cortex. The pyramidal cells of the cortex fulfil these requirements and their synapses are the most significant source of EEG potentials. As the human cortex is heavily folded, a large part of it is too far away from the electrodes on the scalp for the activity to be registered. Also, with EEG, deeper brain functions can only be examined indirectly through the synchronizing effect they have on cortical neurons. (Lang et al. 1994)

The synchronization of cortical activity can be detected as periodical waves in the EEG. This synchronization can rise from either controlling activity from deeper brain areas (e.g. thalamic activity) or cortical feedback loops. (Lang et al. 1994) In clinical practice, the observable EEG frequencies are divided into frequency bands based on observations on their relation to different processes. For instance, it is well known that alpha activity desynchronizes (decreases) and theta activity synchronizes (increases) during mental activity (Klimesch et al. 1997). The frequencies are usually divided into bands as listed in Table 1. However, the use of fixed frequency bands has been criticized, as there is evidence that they are not constant across individuals (Klimesch 1999).

**Table 1** EEG frequency bands and nomenclature (Lang et al. 1994)

| Frequency band [Hz] | Name | Symbol |
|---|---|---|
| < 4 | delta | δ |
| 4 - 8 | theta | θ |
| 8 - 13 | alpha | α |
| > 13 | beta | β |

## 4.3 EEG artefacts

When measuring EEG from the scalp, the electrodes pick up all electrical signals including undesired ones that may introduce significant changes in cerebral signals. These undesired signals are called artefacts.

Artefacts are classified by source into non-physiological and physiological artefacts. Non-physiological artefacts may originate for instance from power lines or changes in electrode impedance (Fatourechi et al. 2007). The most common sources for physiological artefacts are ocular artefacts, i.e. eye blinks and movements, and electromyographic, i.e. muscular, activity of the scalp and neck muscles (Niedermeyer and Lopes da Silva 2005).

### 4.3.1 Ocular artefacts

Ocular artefacts, namely eye blinks and movement, are a major source of EEG artefacts most prominent at anterior electrode sites, but they may extend to other sites as well. Ocular artefacts are easy to detect from the electro-oculogram (EOG), usually recorded with four EEG electrodes: one positioned above and one below the other eye for detecting vertical movements (vEOG) and blinks, and one electrode placed on each temple for detecting horizontal eye movements (hEOG) (see Figure 3). (Niedermeyer and Lopes da Silva 2005)

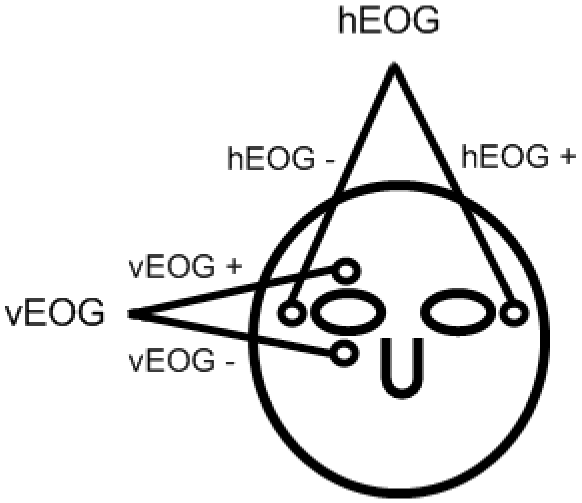

**Figure 3** Montage of the EOG electrodes for bipolar measurement of horizontal (hEOG) and vertical EOG (vEOG).

The eye globe is an electrically charged dipole, as the cornea is positive with respect to the retina (Lang et al. 1994). This dipole changes orientation as the eye globe rotates either horizontally or vertically. The eyes are usually moved in fast jerks called *saccades*. Saccades show up as low-frequency, high-amplitude stepwise deflections from the EEG baseline (Fatourechi et al. 2007).

Eye blink artefacts are a result of the movement of the eye lids, the altered geometry of the conducting volume around the eye globe, and the change in the orientation of the dipole, as the eye globes turn upwards when the eye lids are closed. These changes are seen as an upward deflection in EEG. (Lang et al. 1994)

A number of methods have been developed for detecting and correcting ocular artefacts, especially blink artefacts. In this thesis, an implementation of an ICA-based (independent component analysis) template matching method of correcting blinks elaborated in Li et al. (2006) was used. Due to the small number of saccade-corrupted trials, instead of correcting for saccade artefacts, the affected trials were removed from the raw data prior to analysis.

### 4.3.2 Electromyographic activity

Electromyographic (EMG) activity is electrical activity that originates from changes in the membrane potentials of muscles. In the scope of EEG measurements, EMG activity is generally considered undesired activity that disturbs EEG analysis.

EMG activity has a wide frequency range, mainly at frequencies above 30 Hz, although some activity reaches as low as 10 Hz and thus overlaps with cerebral EEG frequencies (see Table 1). Unlike with ocular artefacts (see previous chapter), it is impossible to record a source signal for EMG activity from the electrode sites. Because of this and the overlapping frequency spectra, detecting and cancelling all EMG originated signal is virtually impossible. (Niedermeyer and Lopes da Silva 2005)

Scalp-recorded EMG is most prominent frontally and temporally as it mainly originates from the facial and jaw muscles (Lang et al. 1994). Difficult tasks may increase EMG activity due to frowning and movement of facial muscles (Fatourechi et al. 2007). Speaking during a measurement induces severe artefacts called *glossokinetic* artefacts, caused by activity of the jaw muscles and the tongue (Lang et al. 1994).

# 5 Event-related potentials

## 5.1 Time-locking and averaging the EEG

The exogenous changes elicited by external stimuli in the electrical activity of the brain are called evoked potentials (EP). These changes consist of the propagation and processing of the information concerning the physical attributes of the stimulus, e.g. intensity, duration, and frequency. The endogenous changes rising from different cognitive processes, e.g. attention, interpretation, memory, association, and learning, are called event-related potentials (ERP). (Lang et al. 1994)

The EP or ERP elicited by a single stimulus is nearly impossible to detect from the EEG, as it is masked by other activity in the brain caused by incoming sensory information unrelated to the stimulus and different cognitive "background" processes. In order to construct the EP and ERP created by a certain stimulus, the stimulus is presented multiple times, and the post-stimulus EEG activity measured from these trials is time-locked to the presentation of the stimulus, and averaged. This averaging process should cancel out the spontaneous and unrelated activity and single out the activity related to the processing of the stimulus. (Lang et al. 1994)

The averaging process creates a waveform, which consists of positive and negative peaks. This waveform has traditionally been divided into separate components corresponding to these peaks. In most cases the components are labelled based on both the polarity and approximate latency of the peak (e.g. N100 is a negative peak occurring approximately 100 ms after stimulus onset). The amplitude and latency of the earliest components, those occurring within the first 100 ms, have been shown to be influenced by the physical attributes of stimuli (e.g. intensity, modality, presentation rate). These exogenous components form the EP. Later components such as N200, P300, and N400 are nonobligatory responses to stimuli. They vary in amplitude, latency, and scalp distribution, and are influenced by the strategies, expectancies and other mental activities triggered by the stimulus event. These endogenous components form the ERP. (Lang et al. 1994; Kramer et al. 1985)

## 5.2 The P300

In line with the nomenclature standard, the P300 can be seen as a positive deflection in the ERP approximately 300 milliseconds post-stimulus, usually observed in studies using oddball paradigms. In an oddball paradigm the participant is presented with low-probability deviant stimuli mixed in a series of high-probability standard stimuli, and required to either respond to or count the number of the deviant stimuli.

From oddball studies, it is known that the P300 is related to the probability of a given event: the rarer the event, the more likely it is to elicit a P300 response. Also, the amplitude of the P300 is inversely related to the probability of the event. However, it has also been shown that it is the subjective, not the prior probability of the stimulus that determines the amplitude (Donchin 1980). These results could be seen as evidence for the view that the P300 is a component related to updating working memory in response to task-relevant events. Donchin and Coles (1988) have suggested that the P300 is a surface manifestation of certain internal information processing operations invoked by the updating process, not the updating process itself. In other words, it is a by-product of a complex neural process that transforms information. In an opposing view, some researchers suggest a role in linking perception and response processing (Verleger et al. 2005).

Within the context of working memory updating, the amplitude of the P300 elicited by the presentation of items might predict the probability that the items would be remembered (Donchin and Coles 1988). In fact, in a study on recall performance, Karis et al. (1984) found that recalled items elicited a higher amplitude P300 upon presentation. However, this effect was mainly found for subjects using rote memorization[6], not subjects who used mnemonic techniques or elaboration to aid their recall. The latency of the P300 has been found to be proportional to the duration of stimulus categorization, and relatively independent of the time required for response selection and execution (Donchin 1980).

### 5.2.1 The P300 in dual task situations

In studying dual task situations, where two separate processing tasks are performed concurrently, the P300 has been found to be a useful psychophysiological index in providing information concerning the allocation of resources. It is known that P300s elicited by discrete secondary task events decrease in amplitude with increases in the perceptual and cognitive difficulty of the primary task (Kramer et al. 1985). This reciprocal behaviour of the amplitude of the P300 in dual task situations provides a measure for assessing the mental workload of a subject (Sirevaag et al. 1989).

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[6] Rote memorization is a memorization strategy of simply iterating the list to be memorized over and over again, instead of e.g. attempting to form associations between items.

## 5.3 The late positive components

Recently, most ERP memory research has focused on the role of late positive components (LPCs) in memory and retrieval (e.g. Dunn et al. 1998; Kusak et al. 2000). These components occur at 500 - 900 ms post-stimulus, and research has shown that their amplitude is positively correlated with recognition and recall. There has been some controversy regarding LPCs as some researchers view them as late P300s, while others believe they are not related to P300s at all. Some studies comparing ERP waveforms of items that were recalled to waveforms of items that were not recalled have found a positive difference waveform in the 400 - 900 ms range, suggesting the LPCs might contribute to successful memory encoding. (Dunn et al. 1998)

The ERP results from an experiment by Garcia-Larrea and Cézanne-Bert (1998) implicate a functional link between the P300 and a LPC they labelled 'positive slow wave' (PSW), occurring at 500 - 800 ms post-stimulus. In addition to similar behaviour under different conditions, the authors found that the two waveforms have similar scalp topographies. Also, according to them, the PSW appeared to be related to memory retrieval, and not memory updating. However, they note that this may be a task specific phenomenon, and conclude that the PSW is likely to be a waveform rising from executive function, and thus could prove to be a valuable tool in studying attentional and working memory control during multi-task performance.

In a memory updating task, Kusak et al. (2000) found positive activity ranging up to 1000 ms after stimulus onset. They speculate that this activity might arise from individual update strategies that scatter the electrical activity after averaging, different update processes at various time ranges, or a uniform control mechanism with larger temporal extent. In any case, they attribute the waveform to executive processes controlling the updating of memory traces. However, they also detected late activity in situations, where memory updating was not required. This would imply that there are other late processes involved besides memory updating. The authors suggest that this activity could reflect the directing of controlled attention, i.e. the maintenance process of keeping the items active in memory.

The current view holds that the executive processes concerning working memory maintenance and updating are reflected in the late potentials of ERP waveforms. These potentials are usually observed in the frontal regions of the brain, corresponding to physical findings from neuroimaging studies on working memory. (Kusak et al. 2000)

## 5.4 Predictions of the physiological measurements

Even though not entirely analogue to the processing and maintenance trade-off in our experimental design (see chapter 6.1), the reciprocal behaviour of the P300 in dual task situations would predict that when the maintenance task requires more attentional resources, i.e. the memory load is increased, the P300 elicited by the result categorization process of the processing task should decrease in amplitude. The effect the subjective probability of a stimulus has on P300 amplitude should not be a factor in our paradigm, as the ratio of correct and false result suggestions is approximately even. Furthermore, the inter-letter intervals (and hence the intervals between result verification stages) in our study (6.5, 8.5, and 10.5 s) should eliminate the effect of possible differences in subjective probabilities, as according to Gonsalvez and Polich (2002), when inter-stimulus intervals are 6 s or longer, probability effects on the P300 are eliminated.

Late positive activity is likely to increase with concurrent memory load (i.e. for letters presented at later positions within a list), as encoding and storing them to the list should involve greater demands on the executive functions of working memory including both maintenance and updating.

# 6 Materials and methods

## 6.1 Study design

The study design was adopted from the second experiment in Barrouillet et al. (2004), and slightly modified in order to concentrate on studying the effects of the increasing cognitive load of the task, and also make measuring EEG feasible. First, the modified design is described in detail, and then the modifications are explained and justified.

The participants were to perform a continuous operation span task, in which a target consonant to be remembered was presented to the participant, followed by a serially presented arithmetic task consisting of a seed, two to four sign-operand pairs (operations) of adding or subtracting the digit one, and a result suggestion. Screenshots from a single trial, along with the presentation time of each screen, are presented in Figure 4.

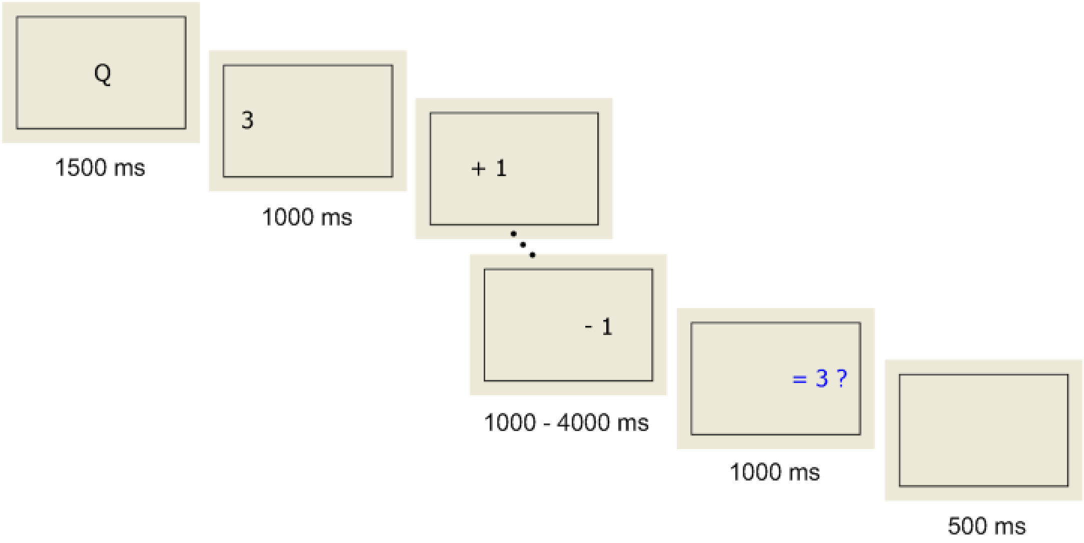

**Figure 4** Screenshots and presentation times for a single trial of the continuous operation span task (with size of characters increased for discriminability)

The target consonant was presented in the centre of the screen for 1500 ms. It was immediately followed by the seed, which was displayed on the left side of the screen for a period of 1000 ms. The seed was followed by the string of two to four operations. Each operation was presented a step right of the previous item on screen in order to avoid confusion between two consequent identical operations, and for a period ranging from 1000 to 4000 ms, depending on which of the nine cognitive load classes the trial belonged to. After the appropriate number of operations had been presented, a result suggestion was presented at the right side of the screen for a period of 1000 ms. The result suggestion consisted of an equals sign ("="), the suggested digit, and a question mark ("?") to emphasize the need for the participant to verify the result by pressing a button labelled 'true' or 'false' with either the right or the left index finger, respectively. In order to motivate the participant to give the verification in time, the result suggestion disappeared from the screen after the 1000 ms display period and was followed by a blank screen for 500 ms, during which the participants were still allowed to give their answer. After this, either a new target or an order to recall the previously presented list of letters ("Palauta kirjaimet") was presented.

In the original experiment of Barrouillet et al. (2004), the participants calculated the arithmetic task out loud by first articulating the seed digit, then the first operation and the intermediate result after this operation, the next operation and its result, and so on. Thus, the correctness of the calculation could be verified at each step of the processing task. In our setup, speaking during the task would induce severe artefacts in the EEG, and hence was not suitable for our paradigm. In order to be sure that the participants paid attention to the arithmetic task, we had to find a way for them to present their answers without articulating them. We decided to introduce a result verification stage (Figure 5), which lengthened each condition by 1500 ms, resulting in inter-letter intervals of 6.5, 8.5, and 10.5 seconds instead of the 5, 7, and 9 second intervals used in the original experiment.

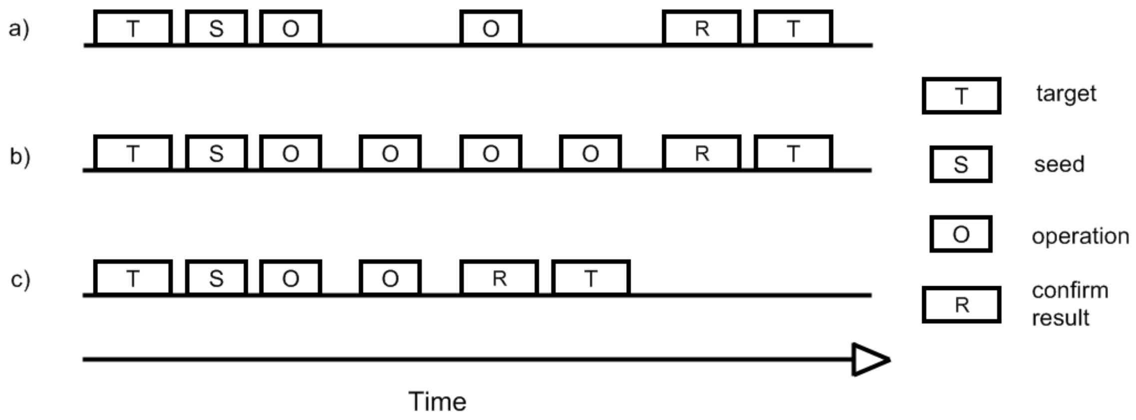

**Figure 5** Schematic representation of the modified trial design

Having the participants solve only simple operations of adding or subtracting 1 or 2 from a digit with a computer-dictated pace is an ingenious way of controlling the cognitive load of the processing component, as browsing the number chain is a universal skill in literate individuals and each shift can be considered as a simple memory retrieval (Lépine et al. 2005). However, as cognitive load is defined as being directly proportional to the retrievals / time - ratio in the TBRS framework, we decided to use only single-step operations (i.e. adding or subtracting 1), because this emphasizes the simplicity and linearity of comparing processing at different paces when the retrievals are identical in nature.

Because our aim was to study the effects of the increasing cognitive load instead of determining the spans of the participants, we studied performance with three different inter-letter intervals (*T*) of 6.5, 8.5, and 10.5 seconds, and two, three, or four operations (*N*), resulting in nine different cognitive load classes as listed in Table 2.

**Table 2** Operation durations and cognitive load classes. *N* is the number of operations, *T* is the inter-letter interval in milliseconds.

| N | T [ms] | operation duration [ms] | N / T | CL class |
|---|---|---|---|---|
| 2 | 10500 | 4000 | 0.250 | 1 |
| 3 | 10500 | 2667 | 0.375 | 3 |
| 4 | 10500 | 2000 | 0.500 | 6 |
| 2 | 8500 | 3000 | 0.333 | 2 |
| 3 | 8500 | 2000 | 0.500 | 5 |
| 4 | 8500 | 1500 | 0.667 | 7 |
| 2 | 6500 | 2000 | 0.500 | 4 |
| 3 | 6500 | 1333 | 0.750 | 8 |
| 4 | 6500 | 1000 | 1.000 | 9 |

## 6.2 Pilot study

As the mean span length of the participants in the original experiment, i.e. experiment 2 of Barrouillet et al. (2004), was 2.60 (SD = 0.63) when the duration of each operation was 2000 ms, we hypothesized that studying span lengths two and four with operation durations ranging from 1000 to 4000 ms was sufficient to cover both conditions the participants could perform in, and conditions they would have trouble coping with.

### 6.2.1 Results of the pilot study

After completing measurements on three participants, it became evident that the task was not challenging enough for these participants in order for us to thoroughly examine the effects the increasing cognitive load had on performance. Even with the greatest cognitive load ($T$ = 6500 ms, $N$ = 4), two participants recalled all three four-letter lists, and the third participant failed only in one list. We decided to introduce lists of length 6 into the design. This is the mean adult letter span usually observed in short-term memory studies without a secondary processing task (Dempster 1981). We hypothesized, that with the processing task in our study, the participants should fail in recalling these long lists, at least under the most demanding cognitive load classes.

The data from the three participants in the pilot study were not included in the final analysis.

## 6.3 Final study design and participants

### 6.3.1 Participants

The data was gathered as part of the Tekes-funded (the Finnish Funding Agency for Technology and Innovation) Brain@Work project at the Brain and Work Research Center of the Finnish Institute of Occupational Health (FIOH). Ten healthy individuals (three women, seven men) aged 25 - 32 years (mean 27.7, SD 2.9 years) volunteered as participants in the study.

### 6.3.2 Material and procedure

The study design used is described in chapter 6.1. List lengths of two, four, and six letters were used. The experiment included three repetitions of each three list lengths under each of the nine cognitive load conditions, resulting in a total of 81 trials. These trials were divided into three sets of 27 trials, so that each set included one trial of each list length under each cognitive load condition. The trials within a set were randomized, and the participant had no way of knowing the list length and cognitive load condition of the trial to be presented. Before the experimental trials, the participants were familiarized with the task with a practice trial that included four lists of lengths 2, 6, 4, and 2, and cognitive load classes 1, 3, 7, and 8, respectively. After each trial, the participant was allowed to keep a few-minute pause if desired. A complete diagram of the experimental setup is presented in Appendix A.

The lists of consonants were constructed so that common acronyms and alphabetically consecutive letters were not used. Also, the same letter never occurred more than once within a list. Each number from one to nine was used as the seed for approximately the same number of times, and associated with a random string of sign-operand pairs of '+ 1' or '- 1', with the restriction that at any point, the intermediate or final result of the operation was not lower than one or higher than nine.

The spans of the participants were scored in an analogue manner to that used by Barrouillet et al. (2004) in the original experiment. They presented the participants with increasingly long series of the continuous operation span with three trials of each series length. Each correctly recalled trial of a certain length counted as one third, and the total number of thirds was added up to provide a span score. As we studied only series of lengths two, four, and six, we counted each recalled trial as two thirds. The maximum achievable span score was six, if all lists under a certain cognitive load class were recalled. It should be noted, that due to this scoring procedure, should a participant be able to recall all of the lists under a certain condition, a span score of six was awarded, even though the participant would possibly have been able to recall even longer series. Hence, if not accurate, the span scores obtained in our study are lower limit estimations of the true spans.

In order to obtain reliable event-related potentials (ERPs), i.e. for each ERP to be the result of the averaging of a sufficient number of trials, the nine cognitive load classes were grouped into three separate groups of light, medium, and heavy cognitive load as listed in Table 3. For consistency, these groups were also used in analyzing the behavioural results. In determining whether increased cognitive load has an effect on spans, the light and heavy cognitive load groups are compared. In comparing our results with those obtained by Barrouillet et al. (2004) in the original experiment, the medium cognitive load group is used, as in this group the pace of the processing task is the same as in their experiment. Also, the effects of the number of operations to be performed, and the inter-letter interval were studied.

**Table 3** The nine cognitive load classes divided into three groups of three classes each:
1) light, medium, and heavy cognitive load
2) short, medium, and long inter-letter intervals
3) small, medium, and large amount of cognitive work, represented in green, blue, and red, respectively.

| **( 1 ) Cognitive load** | | **( 2 ) Inter-letter interval** | | **( 3 ) Cognitive work** | |
|---|---|---|---|---|---|
| operation duration | CL class | T | CL class | N | CL class |
| 4000 | 1 | 6500 | 4 | 2 | 1 |
| 3000 | 2 | 6500 | 8 | 2 | 2 |
| 2667 | 3 | 6500 | 9 | 2 | 4 |
| 2000 | 4 | 8500 | 2 | 3 | 3 |
| 2000 | 5 | 8500 | 5 | 3 | 5 |
| 2000 | 6 | 8500 | 7 | 3 | 8 |
| 1500 | 7 | 10500 | 1 | 4 | 6 |
| 1333 | 8 | 10500 | 3 | 4 | 7 |
| 1000 | 9 | 10500 | 6 | 4 | 9 |

## 6.4 Presentation software

The experiments described here were run on CognWare software developed at the Finnish Institute of Occupational Health (FIOH). The software includes two main components: the CognFuse platform for implementing and administering psychophysiological tasks, and the CognLight analysis tool for synchronizing the task-related event logs to the physiological data measured (see Figure 6).

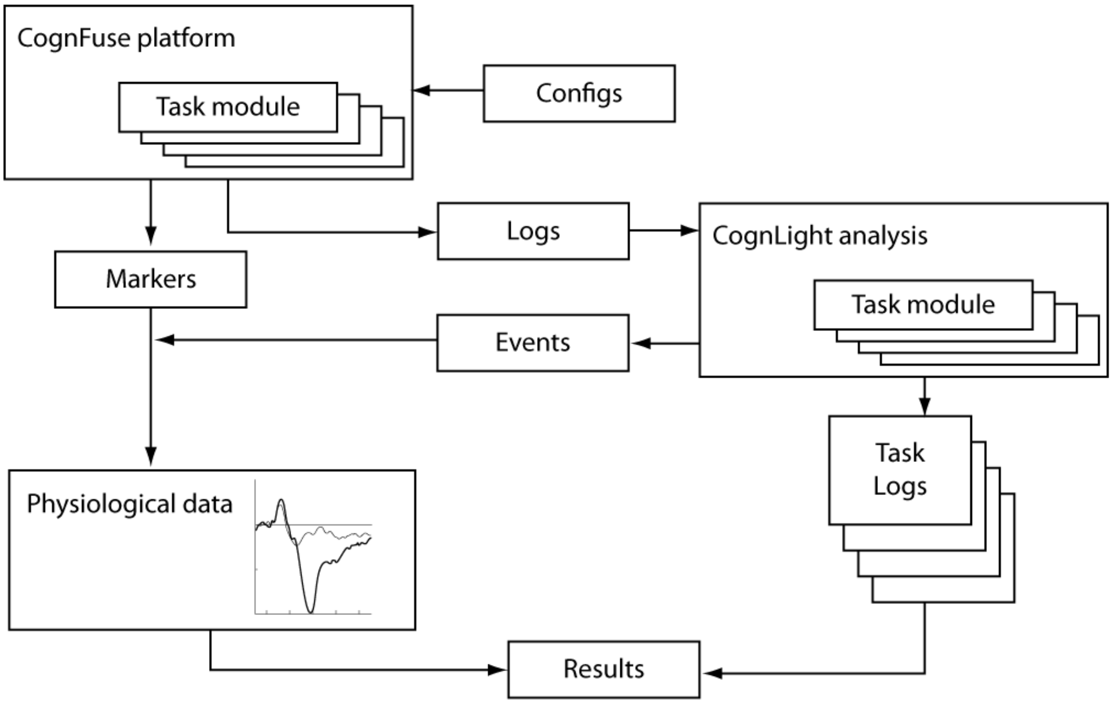

**Figure 6** Schematic diagram of the CognWare software

The CognFuse platform facilitates the implementation and presentation of various psychophysiological tasks by offering a set of required functions, i.e. millisecond-accurate timing, presenting stimuli, triggering physiological measurement devices, and logging events.

The CognWare software was developed as part of the Tekes-funded Brain@Work project. The CognFuse platform is programmed with the CodeGear Delphi programming environment, and the CognLight analysis tool with Python. The author has contributed to the development of the software as part of a team of programmers, and also implemented the task module for the continuous operation task used in this thesis.

## 6.5 Measurement setup

EEG signals were recorded with a SynAmps device (Compumedics Ltd, Texas). For synchronizing the EEG data with the task-related events (e.g. presentation of a target letter, or result suggestion to be verified), the CognFuse platform sent markers indicating the beginning and end of each task run, and a clock signal to the SynAmps device.

EEG was recorded from three midline sites and two occipital sites (midline sites: Fz, Cz, and Pz, and occipital sites: O1 and O2 in accordance with the international 10-20 system, see Figure 2). Bipolar electrode setups were used to measure both hEOG and vEOG signals, with electrodes at the right and left temples and above and below the right eye (see Figure 3 on page 29). All electrode sites were referenced to the right mastoid with the left mastoid acting as the ground. Impedances for all electrodes were kept under 5 kΩ. A sampling rate of 500 Hz was used, with digital high-pass filtering at 0.05 Hz and low-pass filtering at 30 Hz. Both filters had a voltage gain of -6 dB at cutoff frequency, and slopes greater than or equal to -12 dB / octave.

The measured EEG data was matched with the respective events with the CognLight analysis tool. Saccade and EMG contaminated data was manually rejected with the EEGLAB Toolbox (Swartz Center for Computational Neuroscience, University of California, San Diego, USA) for Matlab (The MathWorks Inc, Massachusetts, USA). The ERP waveforms were averaged using custom averaging functions (Jussi Korpela, Brain and Work Research Center, FIOH).

## 6.6 Statistical methods

For the statistical analyses in this thesis, non-parametric tests had to be chosen, as neither the span score nor the reaction time data are normally distributed. For comparing more than two means across several conditions, a Friedman test was used.

The Friedman test is a non-parametric statistical test used to detect differences of treatment across several conditions. It tests whether matched samples were drawn from the same population, and is based on ranks. The null hypothesis is that the distributions of the ranks are the same for each group. A significant result from the Friedman test does not give indication of where the difference is. To determine the source of the difference, separate post-hoc tests are required. For these non-parametric paired comparisons, Wilcoxon signed ranks test was used. (Field 2005)

The Wilcoxon signed ranks test is a non-parametric test used for repeated measurements of a single variable. Like the Friedman test, the Wilcoxon test is based on ranks, and assumes a paired test setting, where the data elements of the two samples have a logical connection, e.g. belong to the same subject. The Wilcoxon test does not make assumptions about the distribution of the data; hence it can be used for our data, which is not normally distributed. The null hypothesis is that the medians of the two samples are equal. (Field 2005)

In order to maintain the planned significance level in a post-hoc multiple comparisons test, the p-value needs to be adjusted. The simplest method for determining the new p-value for a post-hoc multiple comparisons test to reach significance is the Bonferroni correction. The corrected significance level is the p-value of the original test divided by the number of tests conducted. (Field 2005)

In this thesis, the null hypothesis of the Friedman test is tested with a p-value of 0.05. If an indication of a significant difference is found, the p-value for the paired Wilcoxon tests after the Bonferroni correction is 0.017. The statistical tests were run on SPSS software (SPSS Inc, Illinois, USA).

# 7 Results

Two participants were excluded from the analyses, as in the processing task they showed rates for correctly verified results lower than 75%. Hence we could not be sure that they had paid sufficient attention to the processing task, and may have opted to ignore some of the arithmetic operations and concentrate only on maintenance. The other eight participants had a high mean rate for correctly verified results of 92% (SD = 4%) in the processing task.

## 7.1 Behavioural results

### 7.1.1 Results for the maintenance task

A Friedman test on the mean span scores under low (4.56, SD = 1.45), medium (4.92, SD = 1.44), and high (4.31, SD = 1.81) cognitive loads showed an effect for cognitive load ($X^2(2) = 10.174$, $p = 0.006$).

After the Bonferroni correction was applied, paired Wilcoxon tests between the groups were performed, and they showed no significant effect for cognitive load in any of the comparisons (see Table 4).

**Table 4** Statistical p-values from Wilcoxon tests on the dependence of the mean span scores on cognitive load groups

| CL group | medium | high |
|---|---|---|
| low | 0.058 | 0.198 |
| medium | - | 0.185 |

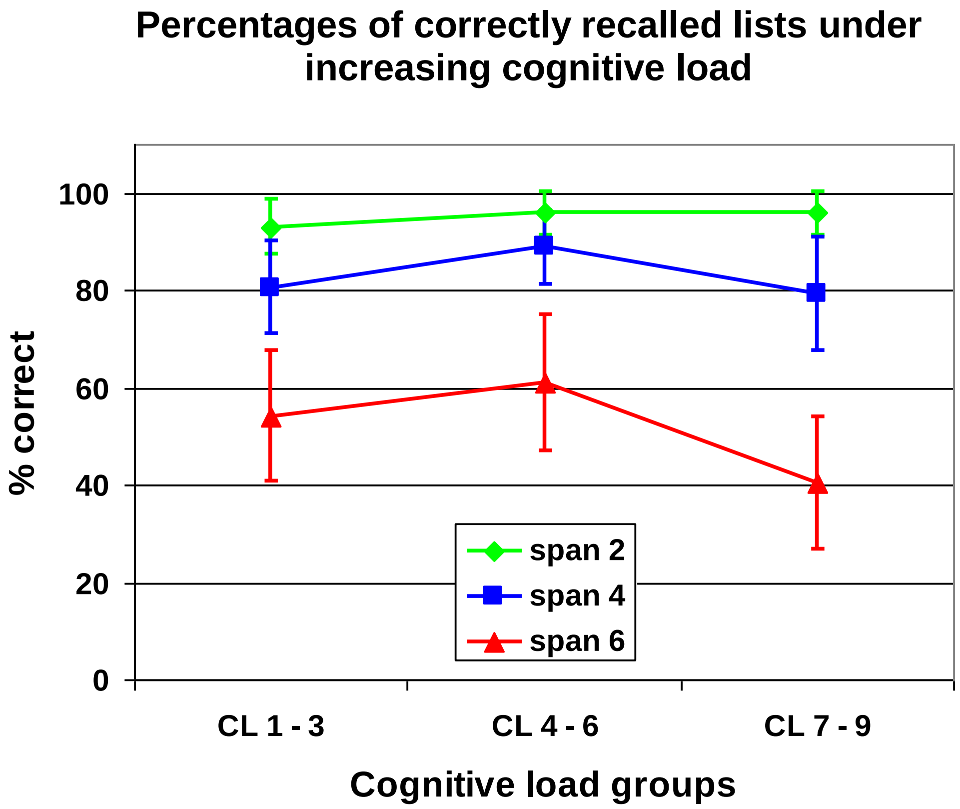

**Figure 7** Mean percentages and 95% confidence intervals of correctly recalled lists of each list length in the different cognitive load groups

A Friedman test on the mean percentage of correctly recalled lists did not show a significant statistical dependence on cognitive load in any of the three list lengths (see Table 5).

**Table 5** Statistical values from a Friedman test on the dependence of the percentages of correctly recalled lists on cognitive load

| list length | $X^2(2)$ | p-value |
|---|---|---|
| span 2 | 0.875 | 0.646 |
| span 4 | 2.100 | 0.350 |
| span 6 | 5.583 | 0.061 |

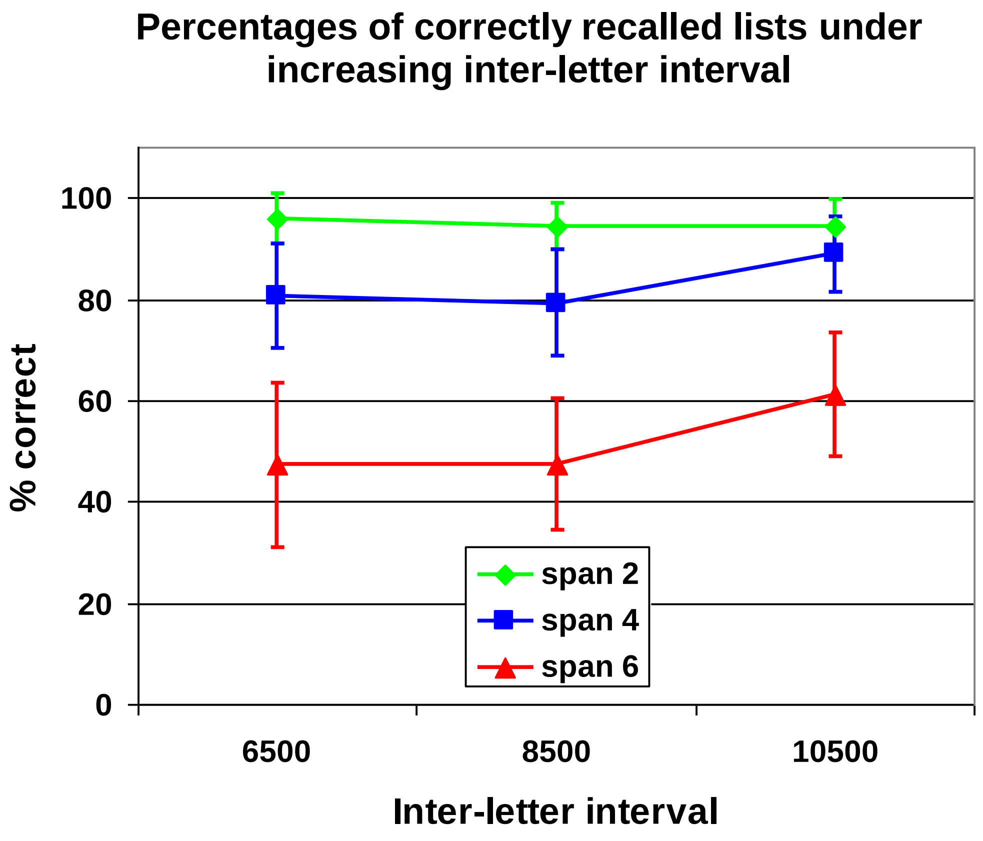

**Figure 8** Mean percentages and 95% confidence intervals of correctly recalled lists of each length with different inter-letter intervals

A Friedman test on the mean percentages of correctly recalled lists showed a statistical dependence on inter-letter interval only with lists of length 6 (see Table 6).

**Table 6** Statistical values from a Friedman test on the dependence of the percentages of correctly recalled lists on the inter-letter interval

| list length | $X^2(2)$ | p-value |
|---|---|---|
| span 2 | 0.500 | 0.779 |
| span 4 | 2.952 | 0.229 |
| span 6 | 7.913 | 0.019 |

Within the results of list length 6, the significances between conditions were tested with paired Wilcoxon tests, after the Bonferroni correction had been applied. The results indicated that lists with an inter-letter interval of 10500 ms might be better recalled than those with intervals of 6500 ms and 8500 ms ($Z = -0.708$; $p = 0.045$ and $Z = -0.789$; $p = 0.026$, respectively). However, after the Bonferroni correction, these results are not statistically significant. Recall with intervals of 6500 ms and 8500 ms did not differ from each other ($Z = -0.037$; $p = 0.916$).

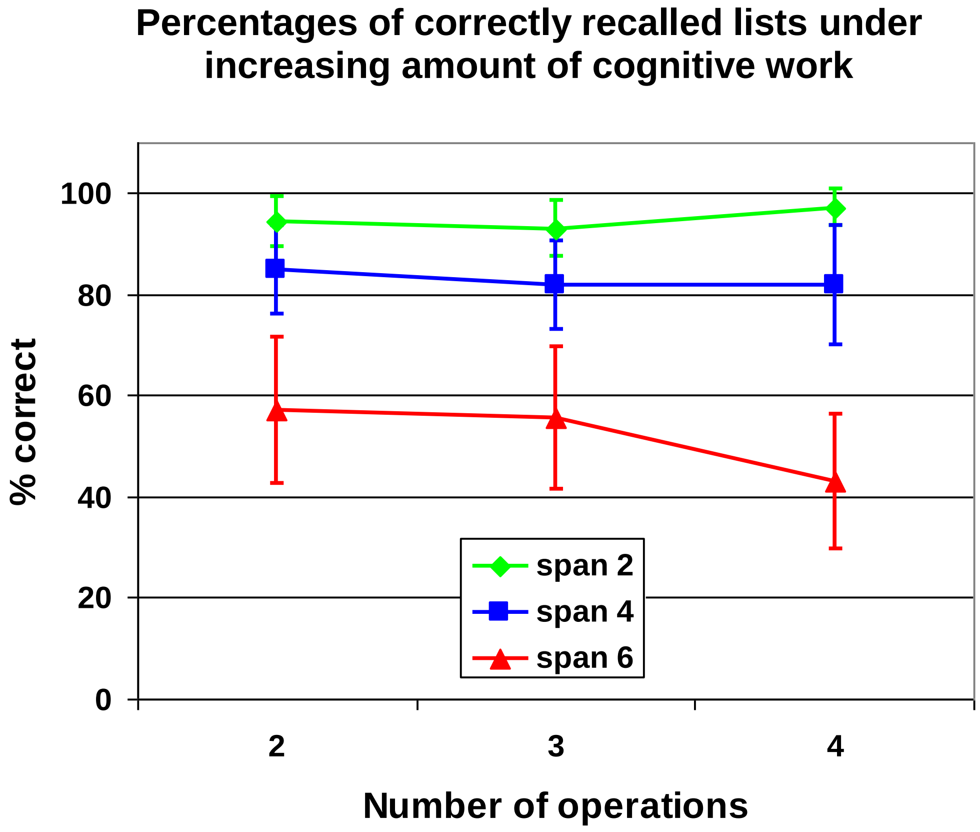

**Figure 9** Mean percentages and 95% confidence intervals of correctly recalled lists of each list length with different amounts of total cognitive work

A Friedman test on the mean percentages of correctly recalled lists did not show an effect of the total amount of cognitive work with any of the list lengths (see Table 7).

**Table 7** Statistical values from a Friedman test on the dependence of the percentages of correctly recalled lists on the amount of cognitive work

| list length | $X^2(2)$ | p-value |
|---|---|---|
| span 2 | 0.353 | 0.838 |
| span 4 | 0.700 | 0.705 |
| span 6 | 2.960 | 0.228 |

### 7.1.2 Results for the processing task

For analysing the dependence of the percentage of, and mean response time for correctly verified results on cognitive load and list position, the results from list positions 5 and 6 were pooled together in order to form a number of observations comparable to the results from list position 1. Comparisons were made only within the conditions of no concurrent memory load (list position 1) and heavy concurrent memory load (list positions 5 and 6), and between the two.

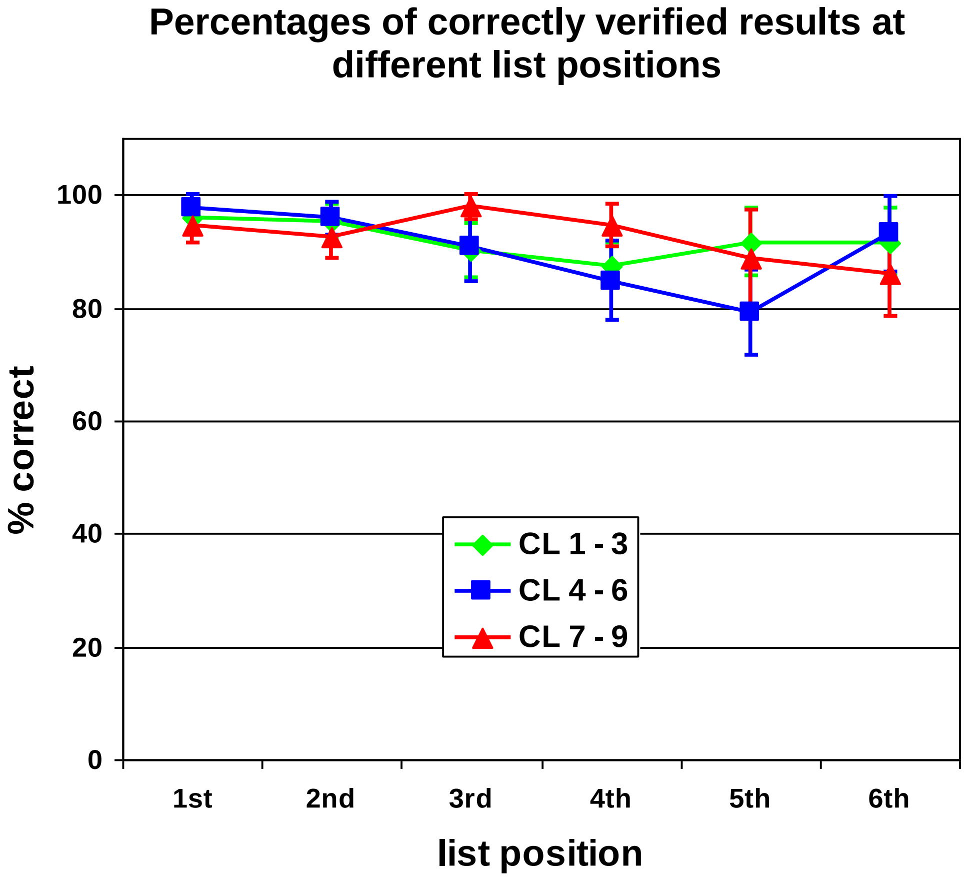

**Figure 10** Mean percentages and 95 % confidence intervals of correctly verified results in the three cognitive load groups at each list position

A Friedman test on the mean percentages of correctly verified operations did not show a significant effect for cognitive load under both no memory load at all and heavy memory load (see Table 8).

**Table 8** Statistical values for a Friedman test on the mean percentage of correctly verified operations did not show a significant dependence on cognitive load at the beginning of the task or the last operations of the task, i.e. no concurrent memory load and heavy concurrent memory load

| list position | $X^2(2)$ | p-value |
|---|---|---|
| 1st | 3.931 | 0.140 |
| 5th and 6th | 3.769 | 0.152 |

A paired Wilcoxon test showed a significant effect for list position on correctly verified results, with operations calculated more accurately under no concurrent memory load (list position 1) than when under heavy concurrent memory load (list position 5 and 6) ($Z = -2.383$; $p = 0.017$).

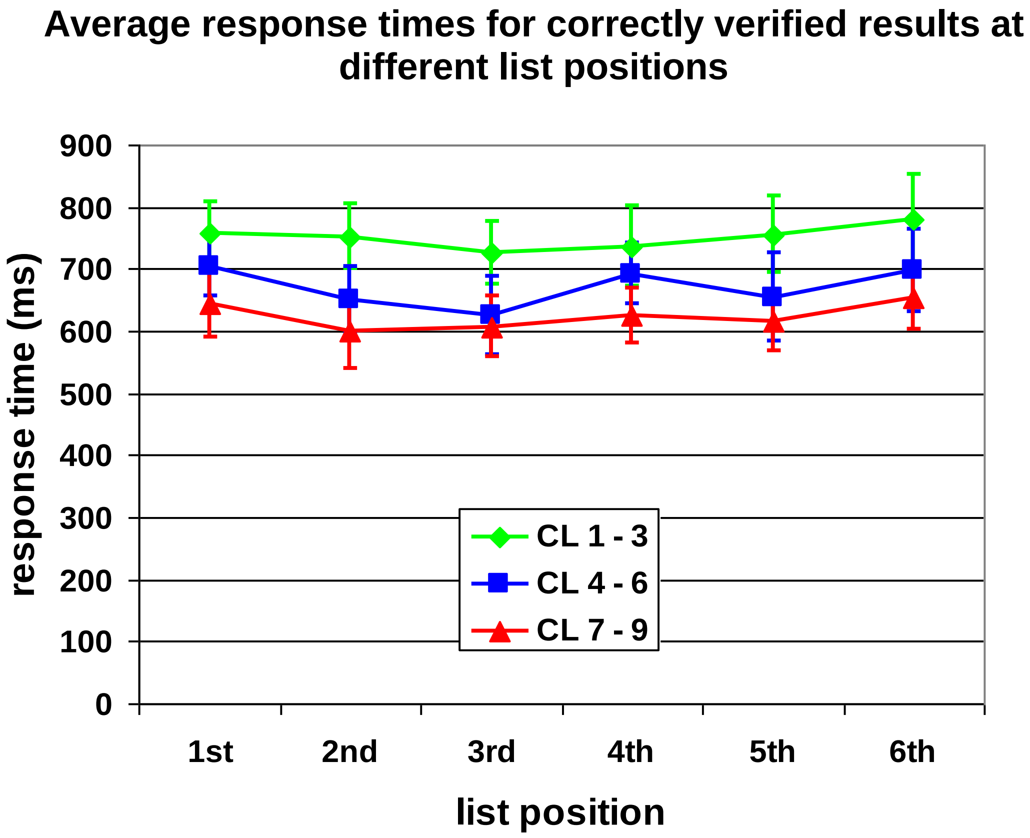

**Figure 11** Mean response times and 95 % confidence intervals for correctly verified results in the three cognitive load groups at each list position

The mean response times showed a similar, strongly significant effect for cognitive load, with responses given faster under greater cognitive load. This effect was significant for both conditions with no memory load at all and conditions with heavy memory load (see Table 9).

**Table 9** Statistical values from a Friedman test for the dependence of the mean response times of correctly verified results on cognitive load at the beginning of the task and the last operations of the task, i.e. no concurrent memory load and heavy concurrent memory load

| list position | $X^2(2)$ | p-value |
|---|---|---|
| 1st | 10.750 | 0.005 |
| 5th and 6th | 12.250 | 0.002 |

A paired Wilcoxon test did not show an effect for list position on mean response times under no concurrent memory load (list position 1) as compared to heavy concurrent memory load (list position 5 and 6) ($Z = -0.560$; $p = 0.575$).

## 7.2 Physiological results

The ERP elicited at the Fz electrode site by the presentation of a correctly recalled target letter shows a clear effect for concurrent memory load on the encoding process with heavier memory load increasing negative activity throughout the time window (see Figure 12a). Cognitive load does not seem to affect encoding (see Figure 12b).

The ERP elicited at the Pz electrode site by the presentation of a correctly verified result suggestion shows no effect for concurrent memory load on categorization of the result suggestion (see Figure 13a). A clear effect for cognitive load on categorization was found, with increased cognitive load increasing negative activity throughout the time window (see Figure 13b).

**Effects of concurrent memory and cognitive load on the encoding of correctly recalled target letters**

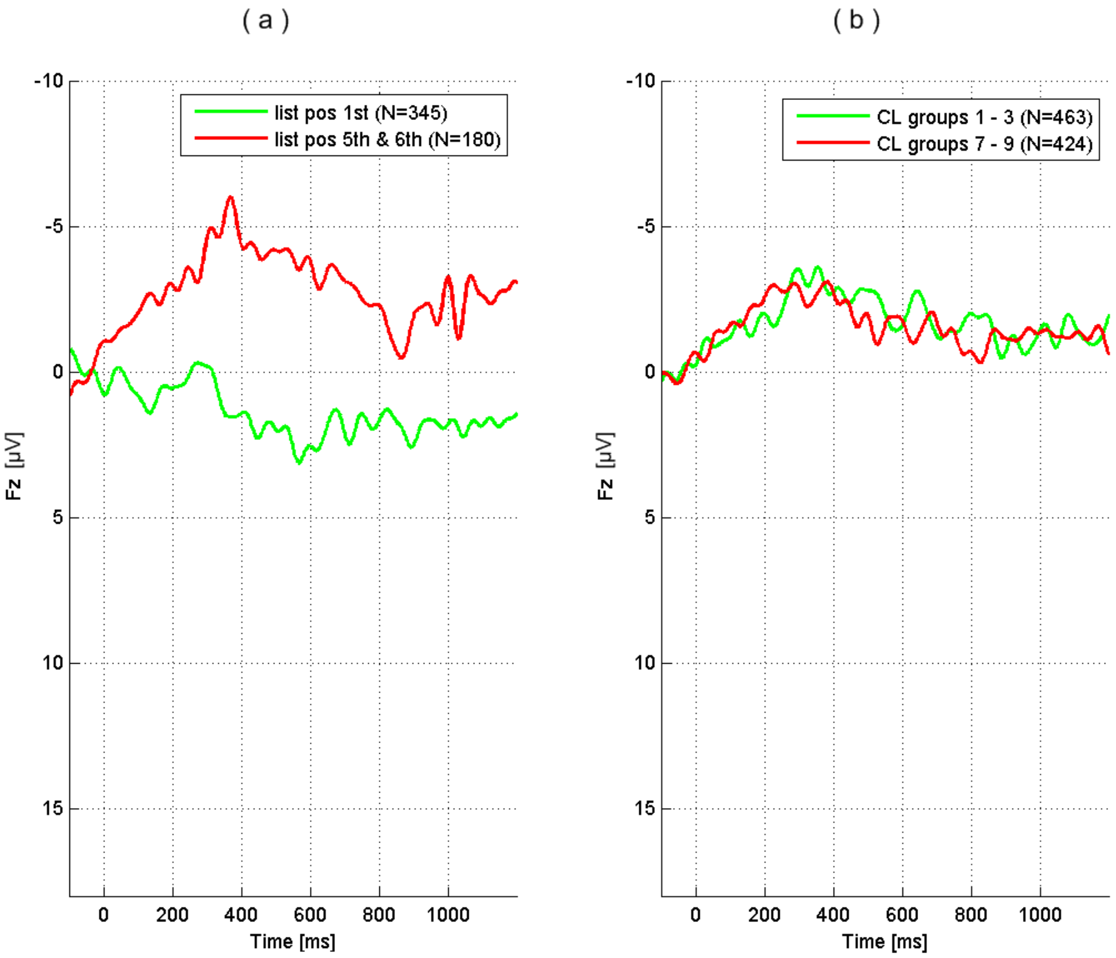

**Figure 12** Effects of concurrent memory load (a) and cognitive load (b) on grand average event-related potentials from the Fz electrode site for the encoding of correctly recalled target letters triggered at target presentation.

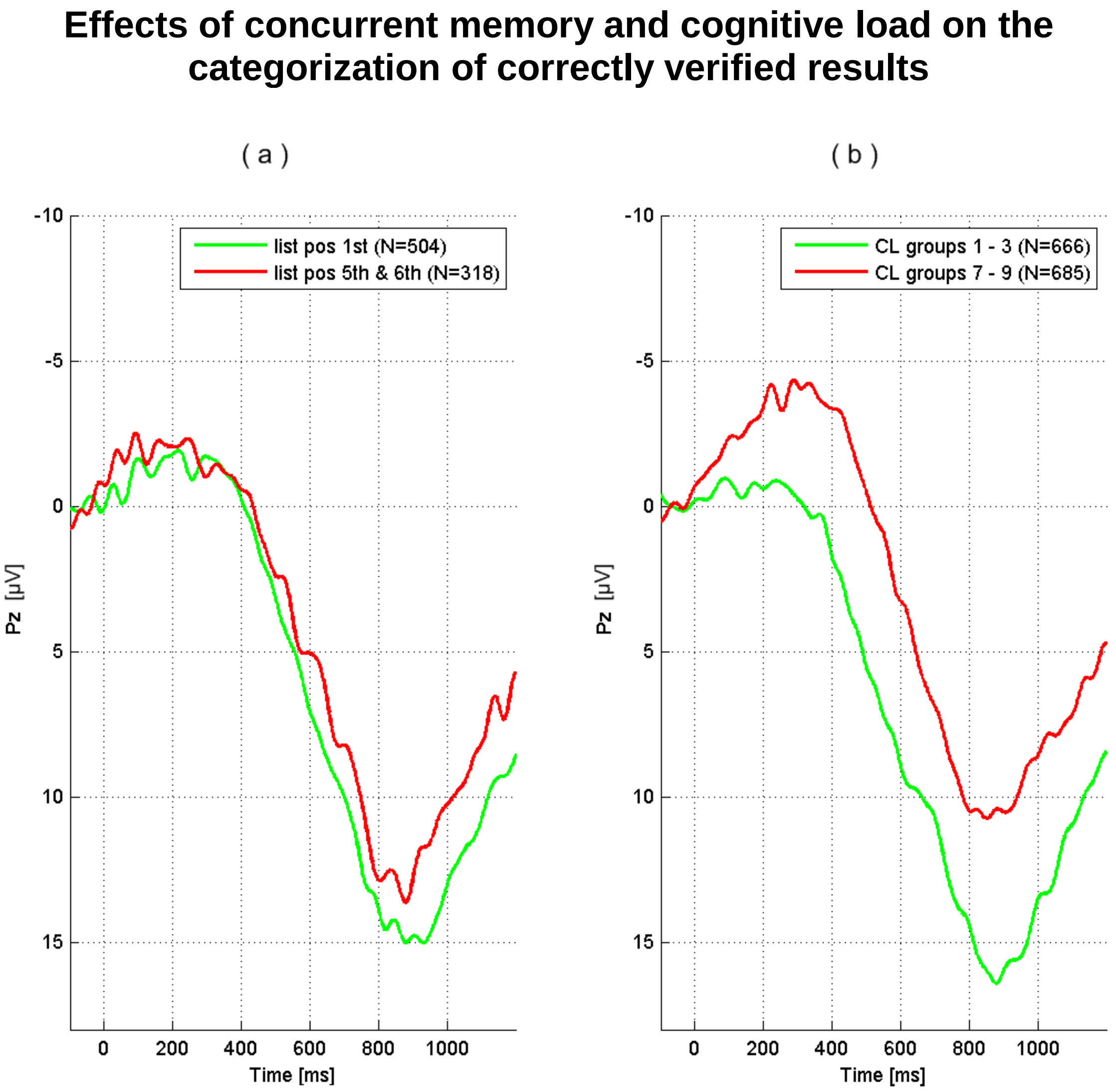

**Figure 13** Effects of concurrent memory load (a) and cognitive load (b) on grand average event-related potentials from the Pz electrode site for the correctly verified results triggered at presentation of result suggestion.

A Wilcoxon test on the amplitudes of the late positive peaks under light and heavy cognitive load (see Figure 14) showed a statistically significant effect for increased cognitive load decreasing the amplitude of the peak (Z = -2.240; p = 0.025).

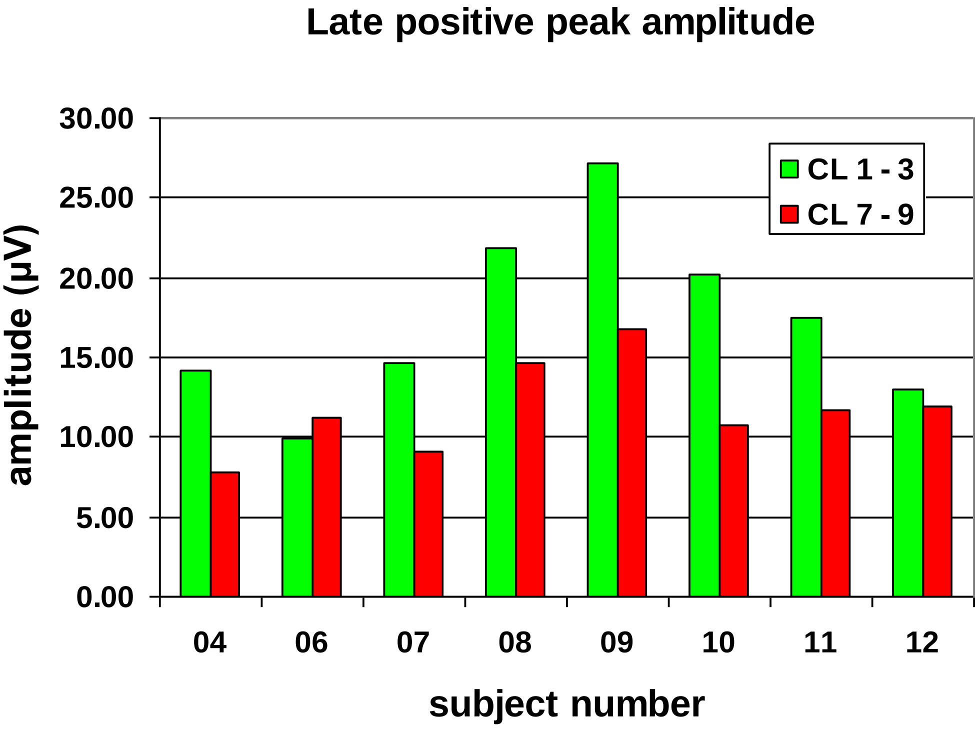

**Figure 14** Late positive peak amplitudes of each participant for the peak elicited by the presentation of correctly verified result suggestions under light (green) and heavy (red) cognitive load

A Wilcoxon test on the latencies of the late positive peaks under light and heavy cognitive load (see Figure 15) did not show any effect for cognitive load on latency (Z = -0.280; p = 0.779).

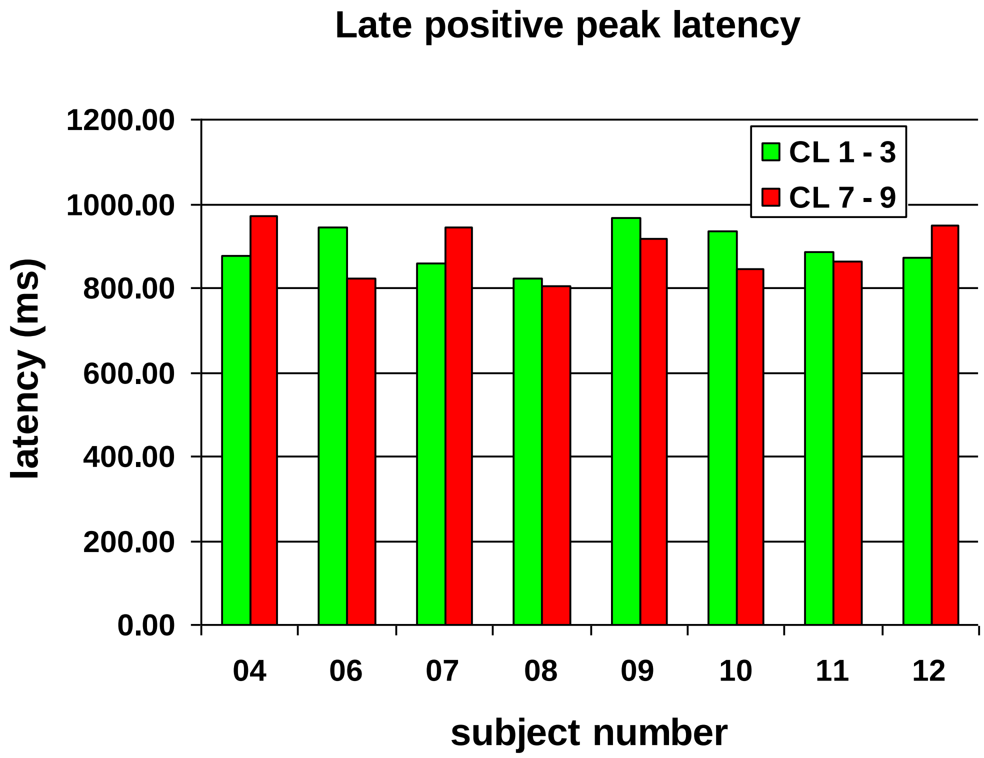

**Figure 15** Late positive peak latencies of each participant for the peak elicited by correctly verified result suggestions under light (green) and heavy (red) cognitive load

# 8 Discussion

In this chapter, I will first examine the behavioural and physiological results and compare the differences and similarities between them, the results of the original experiment of Barrouillet et al. (2004), and our own predictions. Then I will hypothesize and discuss possible explanations for the differences observed. Finally, I will sum up the conclusions of the experiment, and propose some necessary and interesting topics for future research.

## 8.1 Behavioural predictions and results

We were unable to replicate the behavioural results of Barrouillet et al. (2004) to any extent. In fact, the participants in our study showed no indication of a trade-off between processing and maintenance, and performed significantly better under conditions of even double the retrievals / time -ratio as compared to those in the original experiment.

Under medium cognitive load, i.e. the same retrievals / time -ratio as in the original experiment, the mean span of the participants in our study was much higher (4.92, SD = 1.44) than the mean span observed in the original experiment (2.60, SD = 0.63). Moreover, even under heavy cognitive load the mean span in our study was much higher (4.31, SD = 1.81) than the mean span under lighter cognitive load in the original experiment. It should also be noted, that the true working memory capacity of the participants in our study could be higher than the span scores obtained: Our aim was not to determine the accurate continuous operation spans, but how the increasing cognitive load affects maintenance, and hence we only included list lengths up to six items. As some participants were able to recall most of the lists of length six even in the heaviest cognitive load group, they might have been able to recall also lists of greater length, thus resulting in an even greater span score.

Increasing cognitive load did not affect performance in the arithmetic processing task, and throughout the different cognitive load cases the participants achieved a high rate of correct responses. This indicates that the participants did not sacrifice performance in the processing task for more resources to be available for performing the maintenance task. In fact, an increase in the cognitive load of the processing task decreased response times, thus resulting in better performance if response quickness is considered as a factor. However, the participants were instructed to perform both tasks accurately, not as quickly as possible. I would attribute the decrease in response times to the pacing effect of the shorter presentation time of each operation.

Furthermore, our results were not in line with the predictions of either the cognitive space model of Case et al. (1982) or the memory decay model of Towse and Hitch (1995). Increasing the total amount of cognitive work did not show a statistically significant deteriorating effect on memory performances. Increasing the inter-letter interval showed a trend towards shorter intervals decreasing performance in the maintenance task, opposite to the prediction of the memory decay model. In our experiment, the only factor that affected memory performance in a clear and consistent way was the length of the list to be remembered.

## 8.2 Physiological predictions and results

The physiological results do not show any clear effect for cognitive load during the encoding process, for which no predictions were made due to lack of research on the topic. In contrast to the predictions regarding concurrent memory load, no effect on the ERP elicited by the result categorization process was found. This implies that in this type of task, there is no processing and maintenance trade-off. The grand average waveforms are nearly identical for target letter encoding under light and heavy cognitive load. The same applies for result categorization under no memory load at the beginning of the task and a heavy memory load of 4 or 5 items. However, the cognitive demand of the processing task, i.e. the cognitive load itself has a clear effect on the result categorization, with heavier cognitive load showing a near constant negative deflection in the grand average waveform for the whole time window of 0 - 1000 ms. During the memory encoding process (i.e. in the ERP elicited by the presentation of a new target), a similar negative deflection is observed with heavy memory load, as compared to conditions with no memory load.

The grand average waveforms elicited by the presentation of the result suggestion show a clear positive peak at 800 - 900 ms post-stimulus. In the individual results the latency of this peak is consistent throughout participants, and in six of the eight participants its amplitude decreases with increased cognitive load. If regarded as the P300, this decrease in amplitude is in line with the predictions of more resources having to be allocated to performing the tasks. However, the long delay throws the classification of this peak as the P300 under questionable light.

The ERP elicited by the presentation of correctly recalled targets also shows a small negative peak at 400 ms post-stimulus with the increase in concurrent memory load (see Figure 12a). The N400 component has generated a large amount of research, and is widely recognized as being related to semantic processing in language comprehension (Holcomb 1993), for instance the concreteness or imageability of words (Nittono et al. 2002). Semantic processing of words is not applicable to the experiment in this study, as consonants were used as targets. I have not found any research regarding the behaviour and role of the N400 component as related to memory load and dual task processing, and in the scope of our study it is likely to rise from a different cognitive process altogether.

## 8.3 Possible explanations for the differences and underlying phenomena

The fact that memory performance was not significantly impaired even with the highest loads could be interpreted as a ceiling effect: the demands of the task were well within the participants' ability to perform such a task. However, this is rather surprising, as the cognitive load in the most demanding case was twice the load used in the original experiment by Barrouillet et al. (2004), and the participants in both experiments are from a similar age group and have comparable academic backgrounds.

The only difference between the two experiments is that in ours the participants did not articulate the continuous operations. Still, they were required to perform the same amount of cognitive arithmetic work. As the TBRS model postulates, processing tasks that occupy the central bottleneck of retrieval should hamper maintenance greatly as it prevents refreshing the decaying memory traces. The bottleneck should be occupied by the memory retrieval of the result of the operation itself, not the articulation of the operands. In fact, Baddeley (1986) has shown that articulation involves no cognitive load at all, but affects spans by preventing subvocal rehearsal. However, rehearsal should also be prevented by the retrieval of the result from memory, as the bottleneck permits only one retrieval at a time. Does this difference imply that articulation is a more demanding process than is generally assumed? Or that overt articulation is slower than covert articulation, and thus occupies the bottleneck for a longer period of time, causing longer delays in refreshing the memory traces?

The long latency of the slow positive peak in our analysis could be explained by the idea of rapid switching between tasks that the TBRS model is based on. The experimental setup does not force the participant to pay attention to the result suggestion immediately when it is presented. The participant may be engaged in a covert rehearsal of the letter list after the presentation of the previous operation, when the result appears on screen. As the time allowed for verifying the result is relatively long (1000 + 500 ms), the participant may opt to finish rehearsing the list, and then switch attention to the processing task. On the other hand, the fact that the participants' mean response times for result categorization are shorter than the observed peak latencies, is a strong indication that the peak is completely unrelated to response categorization: In order to achieve such high rates of correct answers, categorization has to be performed properly before the answer is given.

The near constant negative deflection observed in heavier cognitive load cases might be explicable in terms of the late positive components of the ERP that are related to executive functions of working memory, and the switching process on which the TBRS model is based on. If rapid switching between tasks takes place throughout the performance of the continuous operation span task, the activity rising from this process should also be visible throughout the task, not only at a fixed period after stimulus presentation. In conditions of lighter cognitive load, more opportunities to switch between the tasks are available, and thus executive control activity would be increased.

As the results of Garcia-Larrea and Cézanne-Bert (1998) and Kusak et al. (2000) indicate, both working memory updating and retrieval are likely to elicit a positive late component in the ERP waveform upon the presentation of a new item. However, our results show correlation between a negative deflection and concurrent memory load, a phenomenon for which I have not found prior literature. All in all, the physiological results are somewhat unorthodox, and similar findings are rare at best. Then again, the waveforms and the descriptive measures of the peaks are coherent and observed throughout the data. There is no indication that the findings are flawed or due to imprecise measurement. Neurophysiological studies of traditional working memory span tasks are rare, and investigating EEG activity in them is an undocumented, but interesting topic for future research.

## 8.4 Prospects for future research

In the future, the first step towards deepening our understanding of working memory functions and the accuracy of the models describing them is to see whether we are able to reproduce the results of Barrouillet et al. (2004) by replicating their experiment. If we are able to confirm their results with an identical setup, the role of speech will provide a titillating opportunity for further research, as the only difference in our setup was the introduction of the result verification stage to eliminate the need for speaking out loud.

The neurophysiological phenomena observed in our study also call for further investigation. The activity patterns found do not completely correspond to components that have been earlier recognized and documented in ERP research. A much larger number of participants need to be measured in order for significant conclusions to be drawn, but the results of the present study provide several research questions regarding the role of the P300, the N400, and the late positive components and their relation to the long-lasting positive and negative deflections in our data.

From the neurophysiological data in our study it can be clearly seen, that increasing cognitive and memory load both affect the ERP. However, cognitive load affected only processing, and memory load only encoding, no effect between them was found. This is perplexing, as the idea the continuous operation span task is based on is that there is a trade-off between processing and maintenance. This trade-off effect is also convincingly established in the behavioural results of Barrouillet et al. (2004). Why this trade-off effect did not show in our results, is an issue that demands further investigation.

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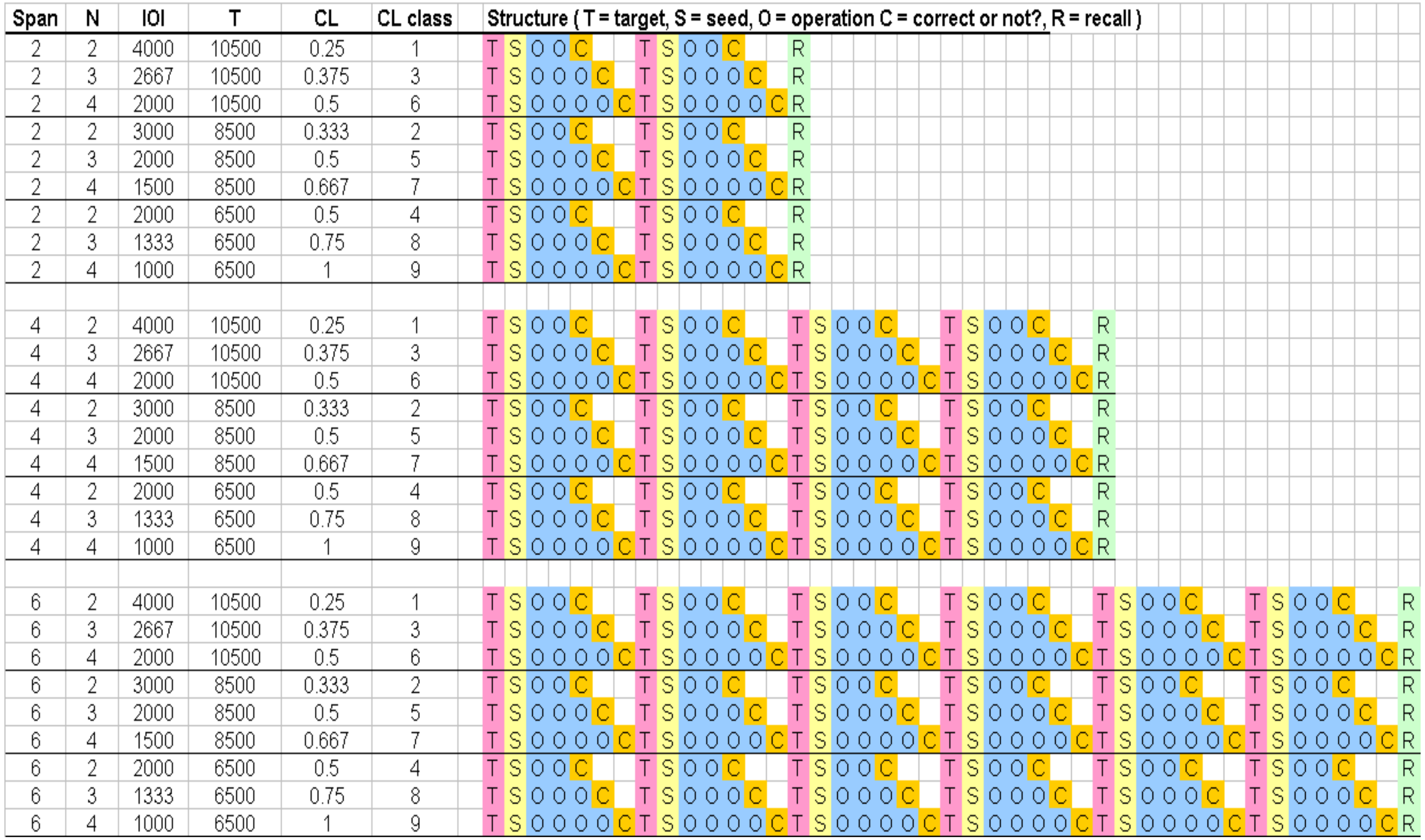
# Appendix A

## COMPLETE EXPERIMENTAL DESIGN



| Span | N | IOI | T | CL | CL class | Structure ( T = target, S = seed, O = operation C = correct or not?, R = recall ) |
|---|---|---|---|---|---|---|
| 2 | 2 | 4000 | 10500 | 0.25 | 1 | T S O O C T S O O C R |
| 2 | 3 | 2667 | 10500 | 0.375 | 3 | T S O O O C T S O O O C R |
| 2 | 4 | 2000 | 10500 | 0.5 | 6 | T S O O O O C T S O O O O C R |
| 2 | 2 | 3000 | 8500 | 0.333 | 2 | T S O O C T S O O C R |
| 2 | 3 | 2000 | 8500 | 0.5 | 5 | T S O O O C T S O O O C R |
| 2 | 4 | 1500 | 8500 | 0.667 | 7 | T S O O O O C T S O O O O C R |
| 2 | 2 | 2000 | 6500 | 0.5 | 4 | T S O O C T S O O C R |
| 2 | 3 | 1333 | 6500 | 0.75 | 8 | T S O O O C T S O O O C R |
| 2 | 4 | 1000 | 6500 | 1 | 9 | T S O O O O C T S O O O O C R |
| | | | | | | |
| 4 | 2 | 4000 | 10500 | 0.25 | 1 | T S O O C T S O O C T S O O C T S O O C R |
| 4 | 3 | 2667 | 10500 | 0.375 | 3 | T S O O O C T S O O O C T S O O O C T S O O O C R |
| 4 | 4 | 2000 | 10500 | 0.5 | 6 | T S O O O O C T S O O O O C T S O O O O C T S O O O O C R |
| 4 | 2 | 3000 | 8500 | 0.333 | 2 | T S O O C T S O O C T S O O C T S O O C R |
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| 4 | 4 | 1000 | 6500 | 1 | 9 | T S O O O O C T S O O O O C T S O O O O C T S O O O O C R |
| | | | | | | |
| 6 | 2 | 4000 | 10500 | 0.25 | 1 | T S O O C T S O O C T S O O C T S O O C T S O O C T S O O C R |
| 6 | 3 | 2667 | 10500 | 0.375 | 3 | T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C R |
| 6 | 4 | 2000 | 10500 | 0.5 | 6 | T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C R |
| 6 | 2 | 3000 | 8500 | 0.333 | 2 | T S O O C T S O O C T S O O C T S O O C T S O O C T S O O C R |
| 6 | 3 | 2000 | 8500 | 0.5 | 5 | T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C R |
| 6 | 4 | 1500 | 8500 | 0.667 | 7 | T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C R |
| 6 | 2 | 2000 | 6500 | 0.5 | 4 | T S O O C T S O O C T S O O C T S O O C T S O O C T S O O C R |
| 6 | 3 | 1333 | 6500 | 0.75 | 8 | T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C T S O O O C R |
| 6 | 4 | 1000 | 6500 | 1 | 9 | T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C T S O O O O C R |