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The effects of memory load and stimulus relevance on the EEG during a visual selective memory search task: An ERP and ERD/ERS study

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Abstract

Objective: Psychophysiological correlates of selective attention and working memory were investigated in a group of 18 healthy children using a visually presented selective memory search task.

Methods: Subjects had to memorize one (load1) or 3 (load3) letters (memory set) and search for these among a recognition set consisting of 4 letters *only* if the letters appeared in the correct (relevant) color. Event-related potentials (ERPs) as well as alpha and theta event-related synchronization and desynchronization (ERD/ERS) were derived from the EEG that was recorded during the task.

Results: In the ERP to the memory set, a prolonged load-related positivity was found. In response to the recognition set, effects of relevance were manifested in an early frontal positivity and a later frontal negativity. Effects of load were found in a search-related negativity within the attended category and a suppression of the P3-amplitude. Theta ERS was most pronounced for the most difficult task condition during the recognition set, whereas alpha ERD showed a load-effect only during memorization.

Conclusions: The manipulation of stimulus relevance and memory load affected both ERP components and ERD/ERS.

Significance: The present paradigm may supply a useful method for studying processes of selective attention and working memory and can be used to examine group differences between healthy controls and children showing psychopathology.

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Keywords: Selective attention; Working memory; Children; ERP; Alpha; Theta; Event-related desynchronization/synchronization

1. Introduction

It is commonly accepted that *selective attention* and working memory play essential roles in human information processing. Traditionally, selective attention refers to the ability of the processing system to select certain (relevant) information for further processing and to ignore irrelevant information. *Working memory* is commonly viewed as a limited capacity system that is capable of storing and manipulating information (Baddeley, 1986, 1996). Since working memory and selective attention are at the core of information processing, deficits in these areas may lead to serious problems in human functioning. For example,

several authors have related deficits in selective attention and working memory to developmental disorders like *attention deficit hyperactivity disorder* (ADHD) and *pervasive developmental disorder not otherwise specified* (PDDNOS) (American Psychiatric Association, 2000) (Althaus et al., 1996a,b; Pennington and Ozonoff, 1996).

1.1. Psychophysiological measures in studying information processing: ERPs

It is not surprising that, in trying to shed more light on healthy human information processing, much psychophysiological research has concentrated on the effects of selective attention and working memory on various task measures. Studies of event-related potentials (ERPs) from the human electro-encephalogram (EEG) have investigated

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the effects of both selective attention (for reviews see (Wijers et al., 1996) and (Hillyard and Anllo-Vento, 1998)) and working memory (e.g. Gevins et al., 1996; Grune et al., 1996; Kiss et al., 1998; Kok, 2001; Mulder et al., 1984; Ruchkin et al., 1990, 1992, 1995, 1996) on several ERP components. Because of the high temporal resolution of the ERP, the outcome of these studies gives us more insight in the time course of normal human information processing. Moreover, the acquired knowledge can be applied to research on groups showing psychopathology, which may, in turn, contribute to a better understanding of possible deficiencies in information processing of the malfunctioning mind.

1.2. Psychophysiological measures in studying information processing: ERD/ERS

The ERP reflects ‘stimulus driven’ or *evoked activity* that is both time- and phase-locked to the event. *Induced activity*, on the other hand, can be considered as rhythmic background activity that is modulated by external or internal events and is time-, but not necessarily phase-locked. Due to the averaging procedure in computing the ERP, *non-phase* locked activity is cancelled out of this measure. With the method of event-related desynchronization/synchronization (ERD/ERS), however, this activity can be maintained (Bastiaansen and Hagoort, 2003) because the amplitudes are squared before averaging. Here, an event-related change in power of a given frequency band is expressed as the percentage of the power in a specified reference period. A decrease of power is called event-related desynchronization (ERD) (Pfurtscheller, 1977; Pfurtscheller and Aranibar, 1977) while an increase is referred to as event-related synchronization (ERS) (Pfurtscheller, 1992). Thus, ERD/ERS has the advantage that it contains information that is cancelled out of the ERP (i.e. non-phase locked activity). On the other hand, this entails that a differentiation between evoked and induced activity is not possible with this method. Since both ERPs and ERD/ERS may reflect different neurophysiological processes (Bastiaansen, 2001; Pfurtscheller and Lopes da Silva, 1999), the current study used both methods.

The frequency bands that have acquired most attention in ERD/ERS research are the theta (4–8 Hz) and alpha (8–10 Hz) bands, both of which have been found to be sensitive to variations in task demands (for reviews see Bastiaansen and Hagoort (2003) and Klimesch (1999)), especially to manipulations of memory load.

Theta activity has been reported to be most pronounced over midline frontal electrode sites (Gevins and Smith, 2000) and has repeatedly been related to processes involved in learning and memory (Bastiaansen and Hagoort, 2003; Klimesch, 1999). Studies in humans indicating that the hippocampus mediates in the generation of theta activity (Arnolds et al., 1980; Halgren et al., 1978; Tesche and Karhu, 2000) corroborate this hypothesis as it is widely

established that the hippocampus plays an essential role in learning and memory.

Although still little is known about the origin of alpha activity in the brain (Steriade, 2000), it has been hypothesized on the basis of animal studies and studies in humans (Feige et al., 2005; Steriade, 2000) that the alpha rhythm is related to thalamo-cortical activity. Alpha can be seen most clearly in an eyes-closed condition of relaxed wakefulness being most pronounced over occipito-parietal sites. A common finding is that alpha activity is suppressed in attention demanding tasks (Klimesch, 1999).

1.3. Child studies

Most research on psychophysiological correlates of visual selective attention and working memory has been carried out on adults, but there is also a considerable amount of literature on ERP studies in normally developing children (e.g. Courchesne, 1978; Ridderinkhof and Van der Molen, 1995; Taylor and Pang, 1999; Van der Stelt et al., 1998). Studies using time frequency analysis, however, are smaller in number (Krause et al., 2001; Van der Stelt et al., 1998; Yordanova and Kolev, 1996, 1997). It is known that the immature brain is subject to developmental changes in information processing. Consequently, as compared to the mature brain, it may show differences in electrophysiological responses to incoming stimuli, which may be related to either cognitive growth or brain maturation (Ridderinkhof and Van der Stelt, 2000). Therefore, prior to studying clinical groups of children, we investigated selective attention and working memory in a group of healthy children by adopting a visual ‘selective memory search’ task. Both memory load and selective attention were manipulated in order to specify their effects on ERPs as well as on event-related alpha and theta power. Our main purpose was to identify valuable task-related EEG measures on which later comparisons could be made between a control group and clinical groups.

1.4. Processes of attention and memory in the current experiment

Memory load was manipulated by presenting the children either one or 3 letter(s) they had to memorize (the ‘memory set’) and subsequently compare with 4 letters in the following display set (‘recognition set’). Selective attention was manipulated by depicting the recognition set in either the same (relevant) or in a different (irrelevant) color as the letter(s) the child had to remember. The child had to decide whether the stimuli matched *only* if both sets were presented in the same color.

In response to the presentation of the memory set, the subject has to store the letter(s) in working memory and keep them actively in mind until the presentation of the imperative recognition set. This interval of storage and ‘sustained retention-rehearsal effort’ has been extensively

investigated by Ruchkin et al., (1990, 1992). In the ERPs, the authors found two slow waves, the amplitudes of which increased with verbal working memory load. First, a parietal positive slow wave appeared that was later followed by a left anterior negativity. The authors proposed that the first wave might be related to storage and the second to rehearsal of phonological information.

After the occurrence of the imperative recognition set, the subject decides if the letters in the display are relevant on the basis of their color, indicating whether a comparison has to be carried out among them. In the event-related potential, the effect of selectively attending to a specific stimulus category is commonly investigated by comparing the response to relevant (to be attended to) stimuli with the response to irrelevant (to be ignored) stimuli. In adult studies investigating selective attention to color, between 150 and 200 ms an early frontal selection positivity (FSP) and an early, occipitally maximal, selection negativity (SN) have repeatedly been found in the ERP, which are often followed by a more central N2b between 250 and 300 ms (Harter and Aine, 1984; Hillyard and Anllo-Vento, 1998; Smid et al., 1999; Wijers et al., 1989ab, 1996,). These components have also been found in a developmental study by Van der Stelt and colleagues (Van der Stelt et al., 1998) who used a visual (color) selective attention paradigm as well. However, in comparing different age groups ranging from 7 to 24 years, they found component latency, topography and amplitude to vary as a function of age. In their youngest age groups (7–9 and 10–12 years), FSP onset was delayed and SN was hardly or not visible. The N2b component also showed delayed onset latency for the younger children and was distributed more fronto-temporally, whereas this component is more centrally distributed in older children and adults.

If the recognition set has been categorized as relevant, the subject is supposed to search for (one of) the target letter(s) in the display—hereby comparing each letter in the recognition set with the letters in the memory set until (one of) the target letter(s) is found. This search process is supposed to be controlled, capacity-limited and serial in nature (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977) and has been found to be reflected by a negative going long latency wave (300–600 ms post-stimulus), reaching a maximum at Cz (Okita et al., 1985; Wijers et al., 1989b). In adults, this search-related negativity (SRN) is present only for attended stimuli and is enhanced in situations of higher memory load.

Another attention-related component is the P3 or P3b (Hillyard and Picton, 1979). This component is characterized by a large occipito-parietal positivity to target stimuli as compared to nontarget stimuli. In healthy adults, P3b amplitude is larger in response to attended stimuli whereas its amplitude decreases when memory load is higher (Kok, 2001; Mulder et al., 1984; Wijers et al., 1996). Van der Stelt et al., found age-related changes concerning this component as well. Like in adults, the P3b in the study by Van der Stelt

was most pronounced at Pz. Its topography, however, changed with age from occipital maximum amplitude in the youngest age groups to a parietal maximum in the older groups. Furthermore, its latency onset decreased as a function of age.

Finally, we examined the effects of memory load and attention on theta and alpha activity. Theta reactivity has been investigated in several paradigms using the method of ERD/ERS as well as on the basis of spectral power analysis. Repeatedly, it has been demonstrated that theta activity is enhanced in conditions where higher demands are made on (working) memory as compared to conditions of lower cognitive load (Bastiaansen et al., 2002; Gevins and Smith, 2000; Gevins et al., 1997; Krause et al., 2000; McEvoy et al., 2001). In children, theta synchronization has also been demonstrated by Krause and co-workers (Krause et al., 2001). Using an auditory memory task, they found theta to be enhanced during especially the retrieval interval. This theta ERS was, however, delayed and smaller in amplitude than in adults.

In contrast to theta, alpha generally shows desynchronization in situations of higher task demands (Boiten et al., 1992; Krause et al., 2000; Stipacek et al., 2003) although Jensen et al. (2002) found alpha power to increase with the number of items held in memory. In their study on children, Krause et al., (2001) also found alpha ERD, however, smaller than in adults.

1.5. Objectives

In the present study, we investigated both ERPs and ERD/ERS in theta and alpha activity in a group of healthy children. Our main objective was to determine the sensitivity of these various measures to the manipulation of selective attention and memory load. We expected to find effects of these manipulations on both ERPs and ERD/ERS that are comparable to the effects generally found in adults, as described above. An eventual differential influence of the task manipulations on the ERPs on the one hand and alpha/theta ERD/ERS on the other, might provide more insight into whether the same or different functional processes underlie these effects. Here, we did not have specific hypotheses. To our knowledge, this is the first study in which the method of ERD/ERS is used together with the analysis of ERPs while at the same time manipulating both selective attention and memory load in one single task.

2. Methods

2.1. Subjects

Participants were 15 boys and 4 girls between 8 and 12 years of age. Because the error percentage of one boy was at about chance level, the data of this child were left out of the analyses. Thus, the data of 18 children (mean age: 10.4

years ± 1.5) were examined. We included more boys than girls in our study because, in subsequent studies, we will focus on the comparison of groups of children with ADHD problems and children showing problems in the autism spectrum. The prevalence of these problems is known to be about 4 times as large among boys as among girls. The children were recruited from regular primary schools and were fully informed about the experiment. They had no history of major medical or psychiatric illness or special education and had normal or corrected-to-normal vision. IQ's were assessed by a short form of the WISC-RN (Dutch version) (Van Haasen et al., 1986; Wechsler, 1974), including the subtests Information, Similarities, Picture Arrangement and Block Design. Mean IQ was 110.4 (SD ± 16.7). Each participant received a small amount of money at the end of the experiment.

2.2. Stimuli and design

The experiment consisted of 640 trials presented in 20 blocks containing 32 trials each. After each block, a 40 s resting period followed. Halfway the experiment, i.e. after 10 blocks of trials, the subject was given a 10 min break.

All stimuli were uppercase consonants presented against the black background of a computer monitor. Every block of trials was preceded by a white fixation cross appearing for 2000 ms in the middle of the screen. The first trial started with a *memory set* consisting of 3 consonants presented in juxtaposition for 1700 ms (see Fig. 1). These letters were either red or blue and either all the same or all different, i.e. memory load was either one or 3 letters. The subject's task was to memorize these letters and the color in which they were presented. After the memory set, the fixation cross reappeared and remained on the screen until the next trial. Seven hundred milliseconds after the reappearance of the fixation cross, it became accompanied by 4 consonants constituting the *recognition set*. These letters were either red or blue as well, and were presented in an imaginary square around the fixation cross. After 1500 ms, the recognition set disappeared and after another 1500 ms the next trial began.

The recognition set contained either one target letter or none. If a target letter was present, the child was expected to respond by pressing a button *only* when the letters in the recognition set were depicted in the same color as the memory set. Otherwise, no button had to be pressed. Our task manipulations resulted in 3 task variables: *memory load* was varied by displaying 3 letters in the memory set, which were either all the same ('load1') or all different ('load3'). *Relevance* was varied by depicting the memory set and the recognition set in either the same (relevant) or in different (irrelevant) colors. With the target being present or not (*Target/Nontarget (T/NT)*), this led to 8 stimulus categories which were all presented equally often and at random.

2.3. Procedure

The children visited our department twice with at most 1 week in between. During their first visit they underwent a training session in which the whole task was practiced to familiarize the child with the test situation and to minimize the effect of learning during the actual experiment. No EEG-measurements were made. After this training session, a short break was given followed by the IQ test. During the second visit, the actual experiment took place. This started with a brief introduction after which the child practiced another 3 blocks of trials in the presence of the experimenter. As soon as the experimenter was convinced that the child performed at an adequate/optimal level, the electrodes were placed on the head and connected to the measurement equipment. The child was asked to fixate at the center of the screen, to blink as little as possible and to respond fast but accurately.

2.4. Electrophysiological recording

Using the left earlobe as a reference, we recorded the electroencephalogram (EEG) with 7 tin electrodes attached on the midline of the scalp (Fz, Cz, and Oz) and at parietal positions (P3, P4, P7, and P8) according to the official extended 10-20 system (American Electroencephalographic Society, 1994). The EOG was recorded with one electrode placed above the eyebrow and another on the outer canthus of the left eye. We placed the ground electrode at the breastbone and kept electrode impedance below 5 k Ω . Using the DAP data acquisition system (developed by Instrumentatiedienst Psychologie (IDP), University of Groningen), the EEG and EOG were amplified with a 10 s time constant and a 200 Hz low pass filter, sampled at 1000 Hz, digitally low pass filtered with a cut-off frequency of 30 Hz and online reduced to a sample frequency of 100 Hz. EEG recording was restricted to the task execution resulting in approximately 58 min of total EEG registration time.

Fig. 1. Time sequence of a trial. (A) Example of a relevant target load1, (B) example of an irrelevant nontarget load3.

2.5. Data processing

The EEG signals were further processed using Brain Vision Analyzer to obtain both ERPs and ERD/ERS. Trials in which a wrong response was given or in which reaction times were either exceptionally low (below 200 ms) or high (above 2500 ms) were excluded from further analysis. Furthermore, recordings with EEG deflections exceeding 200 μ V or EOG deflections exceeding 500 μ V were removed. The remaining epochs containing eye movements were corrected using the regression procedure of Gratton (Gratton et al., 1983). Further processing of the EEG in order to obtain ERPs and ERD/ERS was carried out separately and will be described in the following sections.

2.5.1. ERPs

The EEG signal was segmented in 2500 ms epochs encompassing the memory set and in 1600 ms epochs encompassing the recognition set, both starting 100 ms before the appearance of the memory set and the recognition set, respectively. Being aligned to a 100 ms prestimulus baseline, the epochs covering the memory set and the recognition set were averaged for each subject, electrode position and stimulus category. Thus, ERPs were obtained for the ‘memory interval’, in which the memory set presentation was embedded, for the load1 and the load3 stimulus categories. For the ‘recognition interval’, covering the presentation of the recognition set, ERPs were derived for each of the 8 stimulus categories, i.e. relevant target load1, relevant nontarget load1, irrelevant target load1, irrelevant nontarget load1, relevant target load3, relevant nontarget load3, irrelevant target load3 and irrelevant nontarget load3.

2.5.2. ERD/ERS

In agreement with the commonly accepted frequency ranges for theta and alpha, we defined the theta frequency band as ranging from 4 to 8 Hz and the alpha band from 8 to 12 Hz.

After artifact detection, the data were bandpass filtered for the specified theta and alpha frequency ranges, squared and low pass filtered with a cut-off frequency of 4 Hz. The data were epoched and averaged for each stimulus condition separately. Here, the 500 ms time window preceding each trial was considered as a reference period. Finally, the trial was divided into 18 segments of 250 ms for each of which ERD/ERS was calculated as the percentage of increase or decrease in power relative to the reference interval. Positive values indicated ERS, whereas negative values indicated ERD.

2.6. Statistical analysis

2.6.1. Behavioral data

Subjects had to respond only if a relevant target appeared. Responses to these stimuli were considered as

hits if the button was pressed within the 350 (load1) or 450 (load3) to 4700 ms time window after the appearance of the recognition set. For all stimulus conditions, the percentages of hits, false rejections, correct rejections and false alarms were computed. Mean reaction times were computed for responses to relevant targets in load1 and load3 separately and analyzed with a repeated measures-analysis (GLM, SPSS) using Load as factor. Error rates were analyzed with a Load $\times$ Relevance $\times$ Target/Nontarget repeated measures-analysis.

2.6.2. ERPs

In order to explore the effects of Load within the memory interval, repeated measures analyses were carried out for each mean amplitude value of 50 ms time segments from 0 to 2400 ms post-stimulus time interval. Separate analyses were performed for the midline electrodes (Fz, Cz and Oz) and parietal electrodes (P3, P4, P7, P8) using Load and Lead as within-subject factors together with Hemisphere for the analysis of the parietal electrodes.

To investigate the effect of Relevance in the recognition interval, mean amplitude values of 20 ms time segments from 100 to 500 ms post-stimulus interval were entered as dependent variables in a repeated measures design. Here, we used smaller time segments because, in general, effects of Relevance are short lasting. Again, separate analyses were performed for the midline and parietal electrodes using Load, Relevance, Target/Nontarget, Lead and—for the parietal electrodes—Hemisphere as within-subject factors.

Using 50 ms mean amplitude values from 0 to 1000 ms post-stimulus time interval as dependent variables, similar analyses were performed to investigate later effects of Relevance and Load. As larger effects in ERP-amplitudes were expected here, larger time segments were used than for the earlier effects of Relevance.

In the current experiment, we used multiple analyses, thereby increasing the risk of capitalization on chance. As 48 mean amplitude values were tested for the memorization interval, for each factor there was a chance of 48×0.05 that one of the intervals showed an effect. To solve this problem, we considered an effect as significant *only* if values smaller than 0.05 were found in at least 3 consecutive time segments for the analyses in the memorization interval and in *two* consecutive time segments in the recognition interval. The significance criterion for one interval was set at 0.05. Using a criterion of 3 consecutive significant intervals in the analyses on the memorization interval, this chance was reduced to 0.006 ($46 \times 0.05 \times 0.05 \times 0.05$) which is far lower than the significance criterion of 0.05. For both kinds of analyses on the recognition interval (using 20 mean amplitude values of either 20 ms time segments and 50 ms time segments), the chance was reduced to 0.048 ($19 \times 0.05 \times 0.05$). If significant effects in successive time segments were found, we reported the largest *P*-value and the largest and smallest *F*-values.

In all analyses mentioned below, we used two-sided tests of significance. Whenever an interaction effect with Lead was found, post-hoc analyses for separate electrodes were performed in order to explore whether an effect of task manipulation was confined to a specific location. In case of violations of the sphericity assumption (Mauchly's test), either Huynh–Feldt (if Huynh–Feldt $\varepsilon \geq 0.75$) or Greenhouse–Geisser (if Huynh–Feldt $\varepsilon < 0.75$) corrections were applied to the degrees of freedom (Quintana and Maxwell, 1994). If necessary, effect sizes were mentioned in terms of partial eta squared (η_p^2).

The results will be reported on the basis of the ERP components described in the introduction.

2.6.3. ERD/ERS

The values of ERD/ERS that were computed for each of the 18 time segments were entered as dependent variables into repeated measures analyses. For the memory interval, Load was used as the within-subjects factor and for the recognition interval, load, relevance and target/nontarget were used as within-subject factors. The analyses were confined to the electrode positions that displayed the most pronounced load-related effects. α was set at 0.05 and we described the largest P -value along with the largest and smallest F -values. Effect sizes are mentioned in terms of partial eta squared (η_p^2).

2.6.4. Correlations

If significant effects were found on the ERP components and/or on ERD/ERS, the differences between the amplitudes engendered by the task manipulations were computed for each subject in the intervals for which significant effects were found. For example, if a main effect of Load was found on the P3 amplitude, the magnitude of this effect was calculated as the mean difference between load3- and load1-stimuli over the time segments for which a significant effect was found. To this end, the mean amplitude values of all stimulus categories in load3 were subtracted from the mean amplitude values of all stimulus categories in load1. If an interaction of, for example, Load $\times$ Relevance was found, indicating that for only relevant stimuli an effect of Load existed, the effect of Load was calculated only for the relevant stimuli. Analogously, effects on the other ERP components and alpha/theta ERD/ERS were calculated. The obtained values were entered as dependent variables in a Pearson product-moment correlation with reaction times, errors, age and IQ. Furthermore, for alpha and theta, correlations were also computed for the total amount of ERD/ERS for each stimulus category if significant ERD or ERS was found. Finally, correlations were computed of mean theta and alpha power in the reference interval with reaction times, errors, age and IQ.

In Section 3, only significant correlations will be summarized.

3. Results

3.1. Performance data

As expected, reaction times in load3 were significantly slower than in load1 ($F_{\text{Load}}(1.17) = 392.53$; $P \leq 0.000$, $\eta_p^2 = 0.96$). Stimuli in load3 also elicited more wrong responses than stimuli in load1 ($F_{\text{Load}}(1.17) = 34.13$; $P \leq 0.000$, $\eta_p^2 = 0.67$) (see Table 1). Furthermore, more errors were made in response to relevant stimuli as compared to irrelevant stimuli ($F_{\text{Relevance}}(1.17) = 21.43$; $P \leq 0.000$, $\eta_p^2 = 0.56$) and to target stimuli as compared to nontarget stimuli ($F_{\text{T/NT}}(1.17) = 28.66$; $P \leq 0.000$, $\eta_p^2 = 0.63$). The interaction Load $\times$ Relevance $\times$ T/NT ($F(1.17) = 34.12$; $P \leq 0.000$, $\eta_p^2 = 0.40$) reveals that the former effects were mainly brought about by the relevant targets in load3 eliciting most errors, i.e. misses. Although the foregoing suggests that the children were able to ignore irrelevant stimuli, they still made errors in this category; they made more false alarms in response to irrelevant targets than to irrelevant nontargets as is reflected by the contrast on irrelevant targets versus irrelevant nontargets ($F_{\text{T/NT}}(1.17) = 10.78$; $P = 0.004$).

3.2. ERPs

3.2.1. Memory interval: effect of memory load

Except at Fz, the memory set containing 3 different consonants (load3) elicited an overall larger long-lasting positivity as compared to the set containing 3 identical consonants (load1). For the midline electrodes, this effect of Load nearly reached significance between 650 and 900 ms and, from then on, became significant until 1350 ms after stimulus onset ($F_{\text{Load}}(1.17) = 4.95$ – 10.76 ; $P \leq 0.040$). Interaction effects for Load $\times$ Lead within the same time window ($F_{\text{Load} \times \text{Lead}}(2.16) = 3.98$ – 8.56 ; $P \leq 0.028$) as well as subsidiary analyses per lead confirm this effect to exist for Cz ($F_{\text{Load}}(1.17) = 4.76$ – 9.37 ; $P \leq 0.043$) and Oz ($F_{\text{Load}}(1.17) = 4.91$ – 14.61 ; $P \leq 0.041$), but not for Fz. Main effects of Load were also found for the parietal electrodes between 250 and 400 ms ($F_{\text{Load}}(1.17) = 5.01$ – 15.46 ; $P \leq 0.039$) and between 550 and 1550 ms ($F_{\text{Load}}(1.17) = 4.64$ – 33.21 ; $P \leq 0.046$). The interaction Load $\times$ Hemisphere ($F_{\text{Load} \times \text{Hem}}(1.17) = 5.08$ – 8.11 ; $P \leq 0.038$) revealed that the effect of Load is larger over the left than over the right hemisphere (see Fig. 2).

Table 1

Means and standard deviations (in parentheses) of reaction times (rt) and errors in load1 and load3

		Load1		Load3	
		Target	Nontarget	Target	Nontarget
Relevant	rt	846.25 (143.23)			1241.57 (168.73)
	% Errors	2.36 (2.74)	0.56 (0.77)	14.32 (9.24)	4.58 (3.59)
Irrelevant	% Errors	2.22 (2.63)	0.21 (0.64)	4.72 (7.25)	0.49 (1.15)

Fig. 2. Grand average ERPs in response to the memory interval at P3 (left) and P4 (right) for both load conditions.

3.2.2. Recognition interval: effects of Relevance on SN, FSP and N2b

In Fig. 3, the grand average ERPs to relevant and irrelevant nontarget stimuli are plotted, collapsed over both load conditions. The ERPs to nontarget stimuli were depicted, because here, the P3 component, being largest in response to target stimuli, will show the least interference. At parietal electrodes, we expected the ERP to relevant stimuli to be more negative than to irrelevant stimuli (SN). However, as the figure shows, the actually occurring effect tends to be exactly the opposite. A significant main effect of Relevance occurred from 280 ms until the end of the analyzed interval (until 500 ms) ($F_{\text{Relevance}(1.17)} =$

4.61–14.64; $P \leq 0.047$) indicating a more positive going signal for the relevant stimuli during this whole interval. The effect appeared to be larger for the P3/P4 electrode pair as compared to the P7/P8 pair (140–220 and 260–500 ms: $F_{\text{Relevance} \times \text{Lead}(1.17)} = 5.59–14.43$; $P \leq 0.047$).

At Fz and Cz, a small negative deflection followed by a larger positive peak at about 210–220 ms can be distinguished for the relevant as well as for the irrelevant stimuli. In the analyses over the midline electrodes, a main effect of Relevance ($F_{\text{Relevance}(1.17)} = 9.05–28.16$; $P \leq 0.008$) was found from 220 ms onwards indicating a more positive signal for the relevant stimuli over these electrode positions. The interaction Relevance $\times$ Lead (180–300 ms:

Fig. 3. Grand average ERPs in response to the stimulus set for relevant versus irrelevant nontargets collapsed over load1 and load3.

$F(1.17)=4.60$ – 1.96 ; $P\leq 0.019$) indicates this effect to differ between the electrode positions. Because we expected the FSP and N2b to occur at the more frontal electrodes only, separate analyses were performed on data from Fz and Cz.

At Fz, significant main effects of Relevance were found between 180 and 340 ms and between 400–440 ms (180–340 ms: $F(1.17)=4.87$ – 39.52 ; $P\leq 0.041$; 400–440 ms: $F(1.17)=6.13$ – 7.15 ; $P\leq 0.024$) demonstrating a selection positivity with a clear peak at about 220 ms followed by selection negativity that may be related to the N2b described in Section 1.

For the Cz electrode, effects of Relevance were found between 200 and 360 ms ($F(1.17)=5.60$ – 22.36 ; $P\leq 0.030$) and between 440 and 500 ms (440–500 ms: $F(1.17)=11.97$ – 20.35 ; $P\leq 0.003$). Here, relevant stimuli elicited a more positive signal than irrelevant stimuli. Possibly, the late effect of Relevance (between 440 and 500 ms) is caused by the onset of the P3 whose amplitude is larger in response to relevant as compared to irrelevant stimuli (see below).

The effects of Load and Target will be reported in the sections on the SRN and the P3.

3.2.3. Recognition interval: effects of Relevance and Load on SRN and P3

3.2.3.1. Search-related negativity. Visual inspection of our data, as well as previous studies showing that the SRN is most pronounced at Cz (Okita et al., 1985; Wijers et al., 1989b), led us to confine further analyses to the Cz lead. Here, we found a main effect of load between 250 and 700 ms ($F_{\text{Load}}(1.17)=5.61$ – 12.89 ; $P\leq 0.030$). The interaction Load $\times$ Relevance ($F_{\text{Relevance}\times\text{Load}}(1.17)=5.58$ – 45.83 ; $P\leq 0.033$) between 350 and 700 ms suggests that for the relevant stimuli a large effect of load existed whereas for the irrelevant stimuli, this effect was very small (see Fig. 4). Further analyses carried out over the irrelevant and relevant stimuli separately, confirmed this observation, i.e. we found a main effect of Load for the relevant stimuli between 150 and 800 ms ($F_{\text{Load}}(1.17)=5.65$ – 28.49 ; $P\leq 0.029$) while no such effect was found for the irrelevant stimuli.

3.2.3.2. P3. As can be inferred from Fig. 5, target stimuli elicited a larger positivity roughly from 400 to 800 ms, this effect being larger for relevant stimuli and stimuli in load1. A repeated measures-analysis over the midline electrodes yielded main effects of Load (300–650 ms: $F_{\text{Load}}(1.17)=5.21$ – 11.04 ; $P\leq 0.036$), Relevance (200–750 ms: $F_{\text{Relevance}}(1.17)=5.56$ – 26.89 ; $P\leq 0.031$), T/NT (350–700 ms: $F_{\text{T/NT}}(1.17)=4.63$ – 17.96 ; $P\leq 0.046$) and Load (nearly the entire interval: $F_{\text{Load}}(2.16)=7.58$ – 95.09 ; $P\leq 0.004$). Successively, these effects imply that the P3 was slightly suppressed in response to the high load condition as compared to the low load condition, that relevant stimuli elicited a larger P3 than irrelevant stimuli, that targets elicited a larger amplitude than nontargets did, and, finally, that the P3 amplitude differed for each electrode site. Furthermore, a significant T/NT $\times$ Load interaction was found between 400 and 800 ms ($F_{\text{T/NT}\times\text{Load}}(2.16)=5.97$ – 31.50 ; $P\leq 0.007$) suggesting the T/NT effect to be largest at Oz. A subsidiary analysis confined to data from the Oz-electrode revealed a T/NT $\times$ Load interaction between 450 and 500 ms ($F_{\text{T/NT}\times\text{Load}}(1.17)=6.10$; $P=0.024$) confirming the observation that the T/NT effect is larger for load1 than for load3. Furthermore, the task effects of Load and T/NT are less pronounced in the irrelevant category than in the relevant category, as the interactions T/NT $\times$ Relevance between 450 and 550 ms ($F_{\text{T/NT}\times\text{Relevance}}(1.17)=9.85$ and 6.91 ; $P=0.006$ and 0.018) and Relevance $\times$ Load between 400 and 550 ms ($F_{\text{Relevance}\times\text{Load}}(1.17)=5.68$ – 11.03 ; $P\leq 0.029$) demonstrate. Finally, there was no significant interaction of T/NT $\times$ Relevance $\times$ Load, although medium effect sizes for the intervals between 550 and 650 ms ($\eta_p^2=0.094$ and 0.096) suggest that there was hardly or no effect of T/NT for irrelevant stimuli in load3.

3.2.4. Theta

As can be inferred from Fig. 6a, there was a short enhancement of theta immediately after presentation of the memory set ($F_{(0-750\text{ ms})}(1.17)=7.82$ – 25.05 ; $P\leq 0.012$) which disappeared in the course of the memory interval and reappeared in response to the recognition interval ($F_{(100-2100\text{ ms})}(1.17)=19.24$ – 35.49 ; $P\leq 0.000$). During

Fig. 4. Grand average ERPs in response to relevant targets and nontargets (left panel) and irrelevant targets and nontargets (right panel) measured at Cz. In the irrelevant category, the ERP in response to load1 was virtually the same as in response to load3, whereas in the relevant category, the ERP in response to load3 showed negativity as compared to the ERP to load1.

Fig. 5. Grand average ERPs at Oz in response to load1 stimuli (left panel) and load3 stimuli (right panel).

Fig. 6. (a) Mean theta (4–8 Hz) ERD/ERS values at Fz during the entire trial for both memory load conditions (load1 and load3). The vertical dashed line indicates the onset of the recognition interval; (b) mean theta (4–8 Hz) ERD/ERS values at Fz during the recognition interval. Each line represents a different stimulus category.

the latter interval, theta ERS lasted longer than during the memory set and was enhanced for load3 as compared to load1 ($F_{\text{Load}(850-4500 \text{ ms})}(1.17) = 13.00-20.00$; $P \leq 0.002$). There was no main effect of Load during presentation of the memory set.

Theta ERS in the recognition interval was larger for relevant as compared to irrelevant stimuli ($F_{\text{Relevance}(350-600; 1350-2100 \text{ ms})}(1.17) = 5.57$; $P = 0.030$) and for nontarget as compared to target stimuli ($F_{\text{T/NT}(1600-1850 \text{ ms})}(1.17) = 6.87$; $P \leq 0.018$). As Fig. 6b illustrates, the latter effect seems to have been established largely by the relevant nontargets in load3 which elicited most synchronization ($F_{\text{T/NT} \times \text{relxload}(1850-2100 \text{ ms})}(1.17) = 7.17-9.58$; $P \leq 0.016$); $F_{\text{Load} \times \text{rel}(1600-1850 \text{ ms})}(1.17) = 18.97$; $P \leq 0.000$; $F_{\text{Load} \times \text{T/NT}(1600-2100 \text{ ms})}(1.17) = 5.07-6.48$; $P \leq 0.038$; ($F_{\text{T/NT} \times \text{rel}(1350-2100 \text{ ms})}(1.17) = 4.77-7.73$; $P \leq 0.043$).

3.2.5. Alpha

Overall, there was an initial, but nonsignificant, short increase in alpha power after presentation of the memory set, which was followed by a long-lasting desynchronization ($F_{(500-2000 \text{ ms})}(1.17) = 5.25-11.14$; $P \leq 0.035$). As Fig. 7a illustrates, alpha ERD was less pronounced by the end of the memorization period and became significant again after presentation of the recognition set ($F_{(350-2100 \text{ ms})}(1.17) = 5.99-21.78$; $P \leq 0.026$) showing slightly more desynchronization than during memorization. In response to the memory set, the display consisting of 3 dissimilar letters (load3) elicited significantly more alpha ERD than the lower load condition ($F_{\text{Load}(1500-2000 \text{ ms})}(1.17) = 5.47-6.68$; $P \leq 0.032$). In the initial phase of the recognition interval, load1 shortly evoked more alpha ERD than load3 ($F_{\text{Load}(100-350 \text{ ms})}(1.17) = 5.03$; $P = 0.039$). After that, virtually the same amount of ERD existed for both load conditions.

During the first segment after presentation of the recognition set (see Fig. 7b) alpha was more desynchronized in response to irrelevant stimuli than to relevant stimuli ($F_{\text{Relevance}(100-350 \text{ ms})}(1.17) = 5.49$; $P = 0.032$). At 600–850 ms, the effect became reversed with the relevant stimuli eliciting more ERD ($F_{\text{Relevance}(600-850 \text{ ms})}(1.17) = 8.07$; $P = 0.011$). In the same time segment, there also was a main effect of T/NT ($F_{\text{T/NT}(600-850 \text{ ms})}(1.17) = 5.49$; $P = 0.026$) that

Fig. 7. (a) Mean alpha (8–12 Hz) ERD/ERS values at Oz during the entire trial for both memory load conditions (load1 and load3). The vertical dashed line indicates the onset of the recognition interval; (b) mean alpha (8–12 Hz) ERD/ERS values at Oz during the recognition interval. Each line represents a different stimulus category.

almost reached significance in the following time segment (850–1100 ms) with a high effect size ($\eta_p^2 = 0.154$), indicating that target stimuli elicited more ERD than nontargets did.

3.2.6. Correlations

Correlations demonstrated that, with increasing age, fewer false alarms were made in response to irrelevant targets ($r = -0.54$, $P = 0.020$) and higher IQ's were associated with a lower amount of misses ($r = -0.52$, $P = 0.026$) as well as with lower reaction times in load1 ($r = -0.68$, $P = 0.002$).

Concerning the psychophysiological data, we only found a significant correlation between IQ and theta ERS for irrelevant nontargets in load3 ($r = -0.54$, $P = 0.021$), indicating that children with lower IQ's showed more

synchronization in response to these stimuli. Contrary to what might be expected on the basis of previous studies, age was correlated with neither ERP-amplitudes nor with ERD/ERS.

4. Discussion

Our study describes the behavioral and EEG measures we obtained while a group of 18 healthy children performed a visual selective memory search task. We manipulated the task variables memory load and relevance in order to find useful measures on which, in a subsequent study, comparisons may be carried out involving 3 groups of children with developmental psychopathology. The results demonstrate that the manipulation of load as well as of relevance differentially affected a number of measures.

4.1. Performance data

Reaction times and the number of errors were enhanced in load3 as compared to load1. Furthermore, most errors were made in the relevant condition. This latter finding suggests that the children were, up to a certain level, able to ignore irrelevant stimuli. However, children still made false alarms in response to irrelevant stimuli with the targets eliciting most errors. Probably, the targets in the irrelevant category were difficult to ignore completely.

4.2. ERPs

Effects of relevance and load were also found on the amplitudes of several ERP components. Starting with the memory interval, we found a positive slow wave being larger in response to the higher load condition. In agreement with Ruchkin and colleagues (1992), we suppose that this memory load effect is associated with the encoding of information into a working memory store. The memory load effect was most pronounced at P3/P4 and was slightly larger over the left compared to the right hemisphere. This lateralization is probably due to the phonological nature of the stimulus information, which is generally processed in brain areas located in the left hemisphere (Awh et al., 1996; e.g. Ruchkin et al., 1990, 1992).

The manipulation of selective attention was manifested in relevance-related effects on the ERPs to the recognition interval. Here, we found an early (between 200 and 340 ms) relevance-related frontal positivity and a later (between 400 and 440 ms) relevance-related negativity at Fz. We suggest these attention-related components to be comparable to, respectively, the FSP and N2b frequently found in adults engaged in similar tasks (Harter and Aine, 1984; Hillyard and Anllo-Vento, 1998; Wijers et al., 1989a,b, 1996). Comparable to findings in children and adolescents by Van der Stelt et al., (1998), the latencies of the components in our study had a later onset than those found in adult studies.

The N2b-like negativity was small and emerged at Fz and not at Cz. This is also in agreement with the findings by Van der Stelt and colleagues who found an age-related shift in topography demonstrating a more pronounced N2b at the more frontal sites for their younger age groups. An early selection negativity like the SN, generally found in adults and small or absent in the Van der Stelt et al. study, was not found. All in all, we conclude that the manipulation of stimulus relevance was successful in that it elicited selection-related components in the ERP. Evidently, although quite some false alarms were made in response to irrelevant stimuli, these components demonstrate that the children were able to select relevant information in a rather early stage of information processing.

Within the relevant category, a prolonged negativity occurred at Cz for stimuli in load3 relative to stimuli in load1 between 200 and 800 ms. Partly overlapping in time, from about 400 to 800 ms, target stimuli elicited a substantially larger P3 than nontarget stimuli. This ‘T/NT’ effect was most pronounced at Oz and slightly suppressed for stimuli in the load3 condition. Furthermore, these effects of Load and T/NT were less pronounced in the irrelevant category than in the relevant category.

The observation that the load-related negativity at Cz occurred for relevant stimuli and not for irrelevant stimuli, further illustrates that the children were able to filter relevant information from irrelevant information. On the other hand, although the P3 T/NT effect was larger in the relevant category than in the irrelevant category, the fact that there still was a T/NT effect in the irrelevant category once again suggests that the children were engaged in some processing of stimuli they were supposed to ignore. In fact, because the ERPs were derived from trials in which only correct responses were given, we may assume that the children were aware of the irrelevance of these stimuli. Apparently, they were not able to completely ignore them. In their experiment investigating non-spatial visual attention in 5-, 7- and 9-year-old children, Wijker and colleagues (see for a review Ridderinkhof and Van der Stelt, 2000; Wijker, 1991) did not find an N2b while they did find a P3b for irrelevant stimuli as well as for relevant stimuli. From this, the authors inferred that younger children are not capable of filtering out irrelevant information in early stages of information processing. The children in our study were older than the children in the study by Wijker and colleagues and they did show relevance-related effects in their ERPs (i.e. an SN and an N2b-like negativity) as well as a T/NT effect on the P3 for irrelevant stimuli. Therefore, we conclude that our subjects were indeed able to select relevant information for further processing, as illustrated by the early selection effects in the ERP, but that they could not completely suppress some processing of the irrelevant information, as demonstrated by the T/NT effect for irrelevant stimuli. Here, it might be speculated that the children use a different cognitive strategy in that their orientation to the target/nontarget dimension precedes or is

run in parallel with the color-based selection of stimulus relevance. However, the fact that the effects of Relevance emerged considerably (about 200 ms) earlier in time than the onset of the T/NT effects further illustrates the assumption that stimulus selection on the basis of color takes place before the target selection.

4.3. ERD/ERS

With regard to ERD/ERS, we found theta ERS in response to both the memory set and the recognition set. During the presentation of the memory set, theta ERS was not affected by task load. This implies that, during the process of encoding, theta was not susceptible to the number of items to be stored in memory. In response to the recognition set, where the child had to compare each item on the display with each item kept in memory, theta ERS lasted longer than during the memory set. Besides that, ERS was larger as the stimulus category demanded more processing. Accordingly, the relevant nontarget stimuli in load3, i.e. the attended stimuli on which a search had to be carried out that, moreover, was exhaustive in nature, elicited most theta synchronization.

The finding that theta synchronization was more pronounced during the recognition set than during the memory set, corresponds with findings by Klimesch and colleagues (Klimesch et al., 1999) who also found more ERS during retrieval than during the encoding of episodic information. It has been argued that the sustained ERS during retrieval may either reflect the actual retrieval of an episodic memory code for which a memory trace is present (Burgess and Gruzelier, 2000; Klimesch, 1997, 2001) or the attempt to retrieve this code (Klimesch et al., 2001). Our finding that the relevant nontargets in load3 elicited most ERS corroborates the latter explanation. If theta ERS in this interval were related to the actual retrieval of a memory trace, the targets would have elicited most ERS. Obviously, this was not the case. As the increase in theta activity was larger in response to higher task demands, we consider this increase in theta to reflect an enhanced amount of cognitive effort the children had to invest in the task. More specifically, this amount of effort may be invested in operations carried out in working memory that are related to serial search and comparison.

In an *n*-back spatial memory task, Gevins and Smith (2000) found good performers to show more theta enhancement in a higher load condition than bad performers. The authors explain their findings also in terms of effort. They suggest that the good performers may be better able to invest more effort and maintain attention in order to meet higher task demands than those who performed worse. Among our subjects, we did not find a relation between task performance and alpha or theta ERD/ERS. What we did find was a negative correlation between theta synchronization for irrelevant nontargets in load3 and IQ. Probably, children with lower IQ's had difficulty

ignoring irrelevant information. However, very few errors were made in this category. A possible explanation may be that children with lower IQ's did pay some attention to irrelevant information—as theta ERS indicates—while this did not always end up in an overt response. In other words, these children may have more difficulty in directing their attention, but they can control their eventual motor response.

For alpha, an initial short-lasting ERS immediately after the appearance of the memory set was followed by a sustained ERD. This ERD was larger for stimuli in load3 than for stimuli in load1 and became less pronounced by the end of the memory interval. The load-effect on alpha is in accordance with the common assumption that alpha power attenuates with increased stimulus load (Klimesch, 1999). For example, in a variety of research paradigms and with different methods, it has been found that alpha desynchronizes with the allocation of attention (Dujardin et al., 1993; Marrufo et al., 2001) and with increasing task complexity (Boiten et al., 1992; Krause et al., 2000). Moreover, in several studies a load-related attenuation of spectral power has been found (Gevins and Smith, 2000; Gevins et al., 1997) as well as load-related desynchronization (Stipacek et al., 2003). However, it must be mentioned that in some studies, alpha synchronization has been found during the retention of auditorily presented information (Krause et al., 1996, 1999) as well as an increase in spectral power during retention in a modified Sternberg task.

After the presentation of the recognition set, alpha became even more desynchronized than in response to the memory set. A similar pattern was found by Krause and colleagues (Krause et al., 1996, 1999). While in their studies a significant alpha ERS was found during auditory encoding, the authors found, like in our study, a significant alpha ERD during the retrieval interval. From our data, we may infer that searching for the target letter among the letters in the recognition set makes higher demands on attentional resources than the process of storage and sustained retention-rehearsal, leading to more ERD in the recognition interval. Notably, while for theta activity the most difficult stimulus category clearly elicited the largest response, this was not the case for alpha reactivity. For alpha, we only found small effects of Relevance, T/NT and Load. The early and short-lasting effect of Load may indicate that alpha ERD for load1 had an earlier onset than for load3, whereas the effects of Relevance and T/NT may indicate that relevant stimuli and target stimuli received slightly more attention than irrelevant and nontarget stimuli, respectively.

Finally, apart from the correlation with IQ, no further correlations were found between ERD/ERS and ERPs, behavioral data or age. Earlier studies have demonstrated

that relative theta power decreases with age while relative alpha power increases (Clarke et al., 2001; Gasser, 1988), the study by Clarke and colleagues using the same age groups as in our study. As relative theta and alpha power changes with age, it might be plausible that both theta and alpha *reactivity* would change with age as well. For example, in response to auditorily presented stimuli, Krause and colleagues (Krause et al., 2001) found ERD/ERS for both adults and children, but for the children ERD/ERS was of smaller magnitude. Nevertheless, in our opinion, the fact that we did not find a significant correlation between age and ERD/ERS, does not imply that there is no relation at all. The age range in our study may have been too small and/or the effects on ERD/ERS may not have been large enough, leaving little variation for correlations to become significant.

4.4. Conclusions

In our study on visual selective attention and memory processes in children, effects of stimulus relevance and memory load were found on behavioral and psychophysiological measures. The effects of relevance and load generally seen in adults were detectable in both ERPs and ERD/ERS measured in a group of 18 healthy children. While alpha ERD was mainly affected by stimulus load, theta ERS proved to be highly sensitive to the other task manipulations as well. Theta demonstrated most synchronization in response to relevant nontargets in the highest load condition, which might suggest that theta ERS is related to serial search processes. In the ERP, the P3 was affected by all task manipulations as well. However, it demonstrated a pattern of effects engendered by the various task manipulations that was quite different from that of theta ERS. Whereas theta ERS showed a linear increase with higher task demands (see Fig. 6b), the P3 amplitude was suppressed in response to the higher load condition while, on the other hand, an enhancement was found for target stimuli versus nontarget stimuli and for relevant stimuli versus irrelevant stimuli. Thus, although all task manipulations affected ERPs as well as ERD/ERS, these effects are likely to reflect different functional processes. The fact that the ERPs show a different scalp distribution than ERD/ERS may further indicate that different neural mechanisms are involved in the establishment of the ERPs and ERD/ERS, respectively. We therefore conclude that the information obtained with ERD/ERS provides complementary information in addition to the information derived from ERPs.

Finally, the successful manipulations of task load and relevance indicates that the current task offers a reliable paradigm in assessing effects of selective attention and memory load in children. Therefore, we consider the described measures as useful instruments in further research involving group comparisons between clinical groups and a control group.

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