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Correlations between EEG signal components and ACT-R modules in Associative Recognition

Bachelor's Project Thesis

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Abstract: Since to date there is only limited data on the relation between ACT-R and EEG activity, we investigated whether the activations of ACT-R's modules were correlated with EEG activity in specific sets of electrodes during an associative recognition task. In this task, subjects had to learn sets of word pairs and correctly recall whether they had encountered word pairs presented in the testing phase before or not. A cognitive model was made in ACT-R that simulated the recall process, which consists of a perception, associative retrieval, decision and a response stage. We then examined whether there was any relation between the activation of these different modules and the set of EEG channels by means of logistic regression. Regression coefficients yielded from the logistic regression show positive and negative correlations for the EEG channels per module, and their implications for human information processing are discussed. Also, differences in ERP waveforms for these channels with respect to the task conditions are outlined and discussed.

1 Introduction

Human information processing has been a focus of both cognitive scientists and neuroscientists for a while now. Studying, theorising about, and modelling cognitive processes helps cognitive scientists create a better understanding of the way how a human brain handles the information processing during these tasks, and with it, a general idea how human cognition functions. Creating cognitive models, in particular, can help outlining cognitive processes. It's use in investigating the underlying mechanisms of human cognition has become increasingly important. For example, Meiran described a quantitative model suggesting the underlying mechanisms of cognitive control during task-switching (Meiran, 2000), and Salvucci was able to let a cognitive model show understanding of driver behaviour in order to predict and recognize distraction and behaviour during driving (Salvucci, 2006). The goal of these studies is to validate the theory of how human cognition handles the information processing during the studied cognitive task, through confirming correlation between the modelled results and the behavioural results, in multiple task conditions. The processes outlined by the model have to be considerably similar to the observed processes when humans are presented with the same task and stimuli. In general, the results yielded from the model can be compared with the results of people doing the same tasks (the behavioural experiment), according to traditional measures of cognitive psychology; reaction time, accuracy, and (more recently) neural data.

A more recent addition to this method of studying information processing is the incorporation of brain activity in the tests of the cognitive model. Van Vugt showed a cognitive modelling approach for investigating coherence between oscillations in distant brain regions and what they mean for information transmission (van Vugt, 2014). In addition, Borst and Anderson linked their proposed method for identifying processing stages in information processing with a cognitive model, and found indications for three major processing stages in the associative recognition task which were in agreement with the ones proposed in ACT-R (Borst and Anderson, 2015), which will be explained later.

Investigating the correlations between brain activity and cognitive models could give us insight in the brain areas responsible for certain aspects of cognition. A cognitive architecture is able to simulate EEG activity along with the behavioural data, by recording the activity of its respective modules.

In this study, the approach of comparing EEG-activity with activity of cognitive models will be done for the associative recognition task (discussed later). Any correlations between the EEG channels and the model's module activation during this task could lead to more insight in where the respective information processing takes place in the human brain. To investigate this correlation, existing data from the associative recognition task will be used alongside with an existing ACT-R model. The activity of the important modules of this cognitive model will be recorded, and compared with the EEG-data.

1.1 ACT-R

One approach to model cognitive processes is to use the cognitive architecture ACT-R(Anderson, Bothell, Byrne, Douglass, Lebiere, and Qin, 2004; Anderson, 2007). This is a theory about how human cognition works, and its constructs reflect assumptions about human cognition(Anderson, 2007). Such a cognitive framework is able to model new constructs that describe cognitive processes according to a proposed theory, with the theory following from research into different phenomena, which has been done for a range of processes. For instance, Anderson and Douglas used an ACT-R model to investigate the importance of goal-subgoal structures in problem solving during the Tower of Hanoi task, and found evidence for an effect of retention interval on retrieval time (Anderson and Douglass, 2001). In another study, Anderson et al. used the ACT-R theory to simulate a wide variety of effects in list memory paradigms, arguing that ACT-R is able to integrate many existing memory processing models proposed in earlier literature (Anderson, Bothell, Lebiere, and Matessa, 1998). Lebiere, Anderson, and Bothell applied the ACT-R theory to a simplified air traffic control task, yielding results matching a wide range of performance measures also observed in human participants of the task (Lebiere, Anderson, and Bothell, 2001).
ACT-R's operations are performed through several modules, buffers, and a pattern matcher. While the perceptual-motor modules and memory modules take care of operations needing to be performed, the buffers can hold encountered or retrieved information. The pattern matcher searches for a production that matches the current information that the buffer holds. This production can, in turn, alter the buffers and thus change the state of the system. The buffer and module activity recorded during the performing of an experiment by the ACT-R model can be used to compare to EEG-data recorded during the experiment, since they indicate activity of the basic cognitive processes simulated by the ACT-R architecture (van Vugt, 2012).

1.2 Associative Recognition

Associative recognition involves the processes of recognition memory, a subcategory of declarative memory. These processes comprise the ability to recollect the earlier experienced environmental content of an item in memory, along with the retrieval of this item. When this memory system is utilized, the environmental content of the item in memory can be retrieved, and it's connections in memory to other items in memory determine the ease of recollection of the item. The amount of occurrences in association with other items influence the connections to other memory items, which is observed in studies concerning the fan effect (Anderson and Reder, 1999).
The associative recognition task involves participants learning a set of associations between words, and are then tested on judging studied pairs, rearranged pairs, or new pairs. This tested association can consist of either a studied association of words (a target), words that are studied before in another association than the one presented (a re-paired foil), or a new association of new words (a new foil). There is an observed delay in reaction time, when the subject is presented with a re-paired foil, in this task, and it is due to the different memory systems involved (instantaneous and recognition memory) which are discussed above.
Earlier research investigating the influence of associations on item recollection by Anderson & Reder shows that the more associations an item in memory has, the longer the time is to retrieve this fact from memory(Anderson and Reder, 1999).

This study aims at investigating the correlation between ACT-R's module activity and EEG data from the associative recognition task. If an observable correlation between these two is present, the ACT-R model might identify interesting locations for information processing in the brain during the task, which can be used to investigate activity observed during EEG recording.

2 Methods

2.1 The associative recognition experiment

A behavioural experiment was conducted by Borst et al., which recorded reaction times, accuracy, and EEG-data during the associative recognition task that was discussed in the Introduction section (Borst, Schneider, Walsh, and Anderson, 2013). The first part of the experiment was the training stage, in which the participants had to learn 32 word pairs using a cued recall task. The next part of the experiment was the test phase, where participants needed to differentiate between the earlier discussed word pairs (targets, re-paired foils, and new foils). Borst et al. manipulated three factors in the associative recognition experiment, with the goal of altering cognitive processes during the task. Word length was first incorporated as a factor, although this has a minimal effect on reading speed(Spinelli, De Luca, Di Filippo, Mancini, Martelli, and Zoccolotti, 2005)(Juhasz and Rayner, 2003), it is known to alter the EEG signal in the occipital and pre-frontal region(Hauk and Pulvermüller, 2004). The next experimental factor is the associative fan, which influences the associative strength of words in memory, and refers to the amount of word pairs a particular word pair appears in. In this experiment, words could have a fan of 1 or 2, and both words in the word pair shared this fan. New word pairs were used with a fan of 1. The third experimental manipulation is the association type, which represented whether words were studied before and in which association they were studied in relation to the presented word pair. The three options were targets, re-paired foils, or new foils. These three probe types are illustrated in Figure 2.1 Since word length did not influence the retrieval process, these conditions were concatenated. Also, because the new foil always has a fan of 1, since it is never encountered before, the fan 2 condition for new foil was non-existent. This left us with 5 task conditions. Figure 2.2 provides an overview of a trial, and the part of the trial we are interested in analysing.

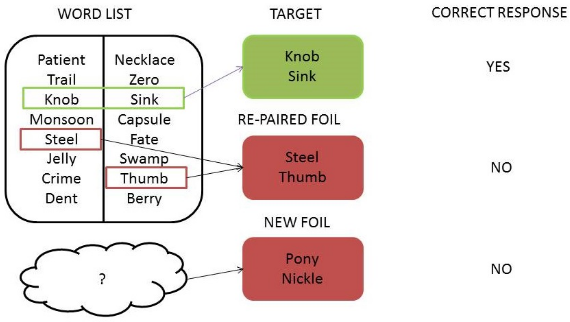

Figure 2.1: The three different kinds of word pairs that were presented in the test stage.

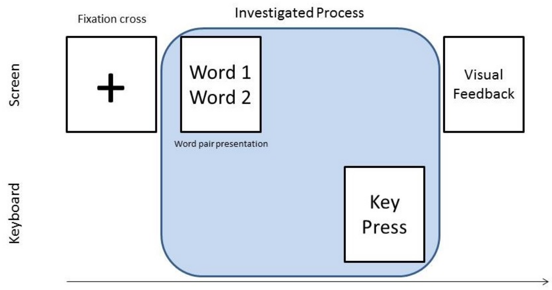

Figure 2.2: Overview of a trial in the Associative Recognition task. The processes we are interested in during this study range from the word presentation until the reaction.

2.1.1 Participants

The subjects participating in the experiments were 9 men and 11 women of the Carnegie Mellon University. The ages of the participants ranged from 18 to 40 years (mean age 26 years), and they were all right-handed. Not a single participant reported a history of neurological impairment, and all received monetary compensation for partaking in the experiment.

2.1.2 Procedure

The experiment started with the training phase (discussed above). The 32 word associations that had to be learned by the participants were presented on a screen (words above each other) for 5000 msec. After this presentation, a blank screen

followed for 500 msec. Participants had to focus on remembering the word pairs, and after the presentation a cued recall task had to be performed. This task consisted of the presentation of an earlier encountered word that was randomly selected. The participants then had to recall the associated word with the presented word. All participants completed three blocks of this cued recall task.
In the testing phase, participants were placed in the EEG recording chamber, in which they were presented with trials of word pair presentation. First, a fixation cross was presented with a variable duration (400 to 600 msec). Then, a word pair stimulus appeared on the place of the fixation cross until the participant responded.Targets required "yes"-responses on the keyboard (J key), and foils required "no"-respones (K key). After the response, feedback was presented whether they were right on the decision for 1000 msec. The trial ended in a blank screen of 500 msec, after which the next trial started. All participants completed 13 blocks with 80 trials, in which the 5 conditions occurred equally often in a random fashion. This resulted in 208 trials per condition per participant.

2.1.3 EEG recording

Also during the test phase, EEG data was recorded from 32 Ag-AgCl sintered electrodes (10-20 system) in an electromagnetically shielded chamber. In addition to the 32 electrodes, other electrodes were placed on the right and left mastoid (the right mastoid served as the reference node), and scalp recordings were algebraically re-referenced off-line to the average of these two mastoids. The horizontal and vertical EOG were recorded as the potential between electrodes placed at the external canthi, and the electrodes placed above and below the left eye, respectively. A bandpass of 0.1-70.0 Hz was selected for adjusting the EEG and EOG signals. This adjustment was done by a Neuroscan bioamplification system, and all electrode impedances were kept below 5 k Ω.

2.2 ACT-R Model

Borst et al. created an ACT-R model that was able to replicate the results of participants during the same associative recognition task (Borst et al., 2013). Different theories exist about the cognitive processes in the associative recognition task. The initial process has to be the encoding stage, in which the model recognizes a stimulus, and encodes in into its buffers for processing. The last stage is the response stage, where the model mimics the response given by a human based on its decision from the decision stage.
This ACT-R model assumes the computational process which accounts for associative recognition by assuming an associative retrieval stage and a decision stage, which both occur between the encoding and response stage. In the associative retrieval stage the model tries to recollect the best matching word pair from memory, using the encoded representation of the presented word pair. The decision stage follows, where it is decided if the retrieved word pair matches the presented word pair that is encoded into ACT-R's buffers, and the model will react subsequently according to this match.

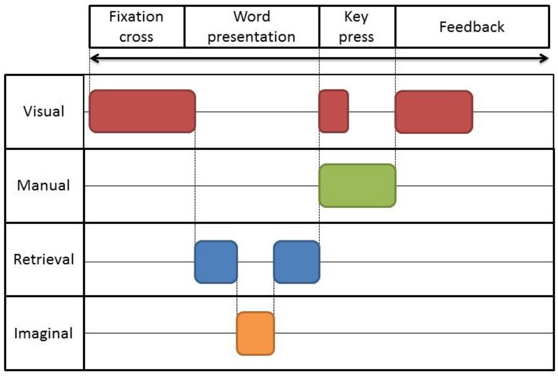

Figure 2.3: Module activity of the visual, manual, retrieval, and imaginal buffers during a trial of the associative recognition task.

When a trial is presented in ACT-R, the word pair is encoded and a representation of the word pair is put into the goal buffer. The detection of new foils involves the least processes, since these words are not known in the declarative memory. The model has procedures to check this fact, and react accordingly. In the other case, if words are present in the declarative memory, associative retrieval procedures check word pairs in memory. See Figure 2.3 for a visualization of how the created productions altered module activity during a trial.

Depending on the amount of associations of the presented words with other items in memory (the associative fan), this retrieval takes longer. Appropriate responses for all outcomes are given through productions that initiate a finger press correspondent to the decision from the model on a keyboard.
The output of the ACT-R model consists of behavioural results for every respective trial such as reaction time, accuracy, and a registration of the conditions of the trials, such as associative fan, and word-pair type. In addition to the behavioural results, for every trial the activation of every module during the trial was recorded, and denoted with a 0 for inactive and a 1 for active. The module activity data will be used for an analysis with the EEG-data.

2.3 Logistic Regression

In order to compare the EEG activity with the module activity data, a binomial logistic regression was used. The module activity was denoted with binary values, a 0 indicating the module being off, and a 1 indicating the module being on at that time point. The continuous EEG was concatenated for all participants, and correlations between the 32 channels investigated. Channels with correlations of 0.9 and higher with other channels were removed, in order of a descending amount of correlated channels to retain as much data as possible. This resulted in the discarding of 7 channels for the further analysis (F3, F4, FC3, FCZ, CP3, CP2, CP4). Subsequently, the remaining 25 channels were used as predictors in a binomial logistic regression, with the responses being each seperate module activity vector. This yielded 25 regression coefficient estimates for each channel per module and an intercept, indicating the predictive value per channel for that module. The logistic regression also returned p-values for each regression coefficient, over which a False Discovery Rate process was applied with a False Discovery Rate level of 0.01. This is a simple sequential Bonferroni-type procedure in order to correct for multiple comparisons (Benjamini and Hochberg, 1995). It controls the expected proportion of rejected null hypotheses that were incorrect rejections, or *false discoveries*. The new p-value thresholds per module were compared with the p-values of the regression coefficients, leading some channels to lose their predictive value. These channels were not taken into the further analysis.

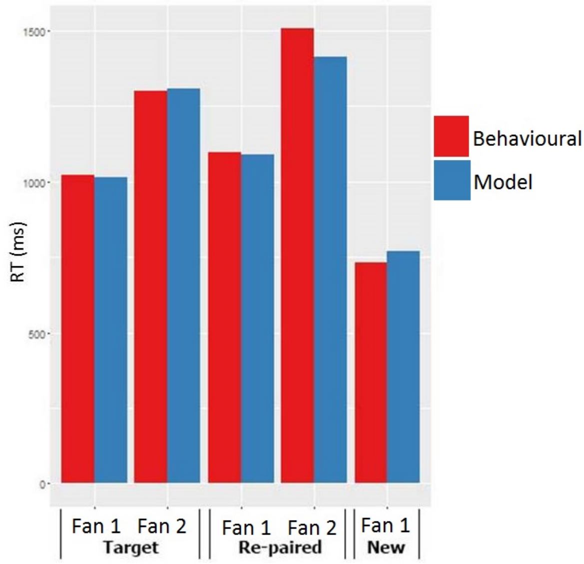

Figure 3.1: Comparison of reaction times of the behavioural data and model data for all task conditions.

3 Results

The test data were trimmed by removing 3.02% of the data with RTs more that 3 *SDs* longer than the mean correct RT for a given condition and participant. The mean correct RTs are shown in Figure 3.1. In order to investigate influences from the task conditions, the behavioural data was submitted to a repeated-measures ANOVA with Fan, Length, and Pairtype as factors. Word Length at this stage was already neglected, so trials with these conditions were concatenated. RT was longer for Fan 2 word pairs compared with Fan 1 word pairs, reflecting a main effect of Fan on RT, $F(1,19) = 67.3$, $p < 0.001$. RT was longer and the fan effect on RT was larger for re-paired foils than for targets, reflecting a main effect of probe, $F(1,19) = 47.21$, $p < 0.001$, and an interaction between Probe and Fan, $F(1,19) = 39.25$, $p < 0.001$. This interaction indicates the increase in reaction time when a fan of 2 is paired with a re-paired foil, which can be seen in Figure 3.1. There were no other significant effects on RT

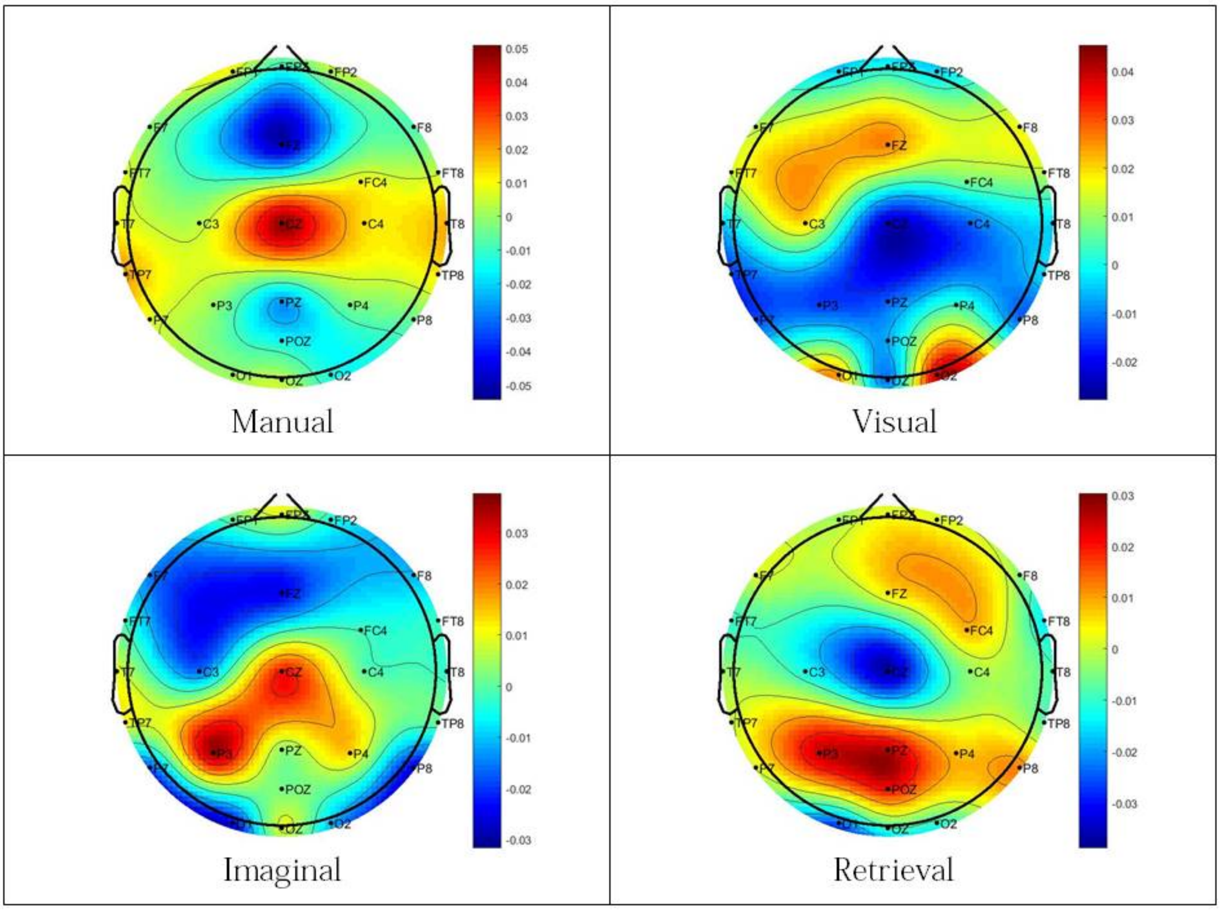

Figure 3.2: Regression coefficients per module mapped onto the scalp. Note that a blue color indicates negative regression coefficients, and that correlated channels are removed (F3, F4, FC3, FCZ, CP3, CP2, CP4).

or error rates.

The logistic regression discussed before was performed for every module. In the plots in Figure 3.2, the regression coefficients per module can be seen, mapped onto the scalp. This illustrates the EEG channels with the most predictive value for the respective modules. Per module, the channels with p-values above the renewed p-value threshold that was calculated with the FDR-process as described in the method section were removed.

The manual module shows a clear positive coefficient for the channel at site Cz, and a negative coefficient for parts of the frontal lobe. Milder positive regression coefficients can be observed at the lateral sites of the temporal lobe (channels T7 and T8) and at the junctions of the temporal lobe with the frontal lobe (channels FT7 and FT8) and with the parietal lobe (channels TP7 and TP8). A mild negative regression coefficient is present at the parietal lobe.

The visual module has positive correlations for the channels at the O1 and O2 sites, and parts of the frontal lobe, the first two channels having the strongest positive coefficients. This module also has a negative coefficient for the EEG sites at the parietal lobe. Furthermore, milder regression coefficients (with respect to the aforementioned channels) are seen at the left part of the frontal lobe and at the junction at the frontal lobe with the temporal lobe (at the left).

The retrieval module and imaginal module both show strong positive coefficients for the channel sites that are associated with the parietal lobe. The main difference is that where the central site of the

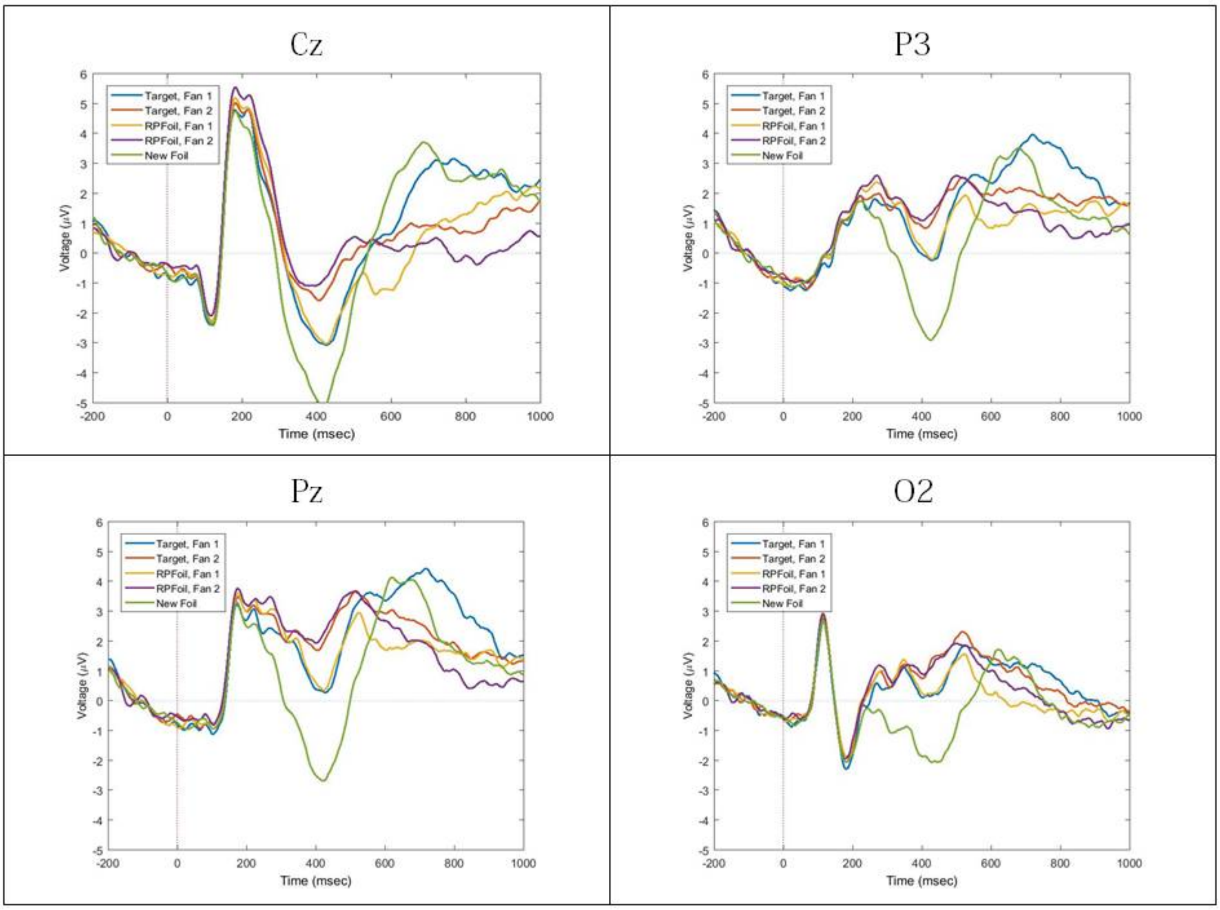

Figure 3.3: Event-related potentials of probe-locked data for the channels with the highest regression coeffecient per module; Cz for the manual module, P3 for the imaginal module, Pz for the retrieval module and O2 for the visual module.

EEG system has a positive regression coefficient for the imaginal module, this is a negative coefficient for the retrieval module. In addition, the frontal lobe mainly has negative regression coefficients for the imaginal lobe, whereas these are positive for the retrieval module. These are indications for dipoles at the parietal lobe for the imaginal module and at the parietal and frontal lobe for the retrieval module.

Figure 3.3 shows the ERP waveforms during a stimulus presentation of the channels with the highest regression coefficients per module. The first graph of the Cz channel (the channel with the highest coefficient for the manual module) shows a greater inhibition of this channel at around 400 msec when a new foil was presented with respect to the other task conditions. The ERP waveforms of this channel also suggest a grouping of waveforms for the task conditions with fan 1 or fan 2. During the inhibition, task conditions with the same fan follow the same pattern, and the conditions with fan 2 have a lower activity at the end of the trial than the task conditions with fan 1 do.

The waveforms in channel P3, which is the channel with the highest coefficient for the imaginal module, show a large inhibition of the activity of task conditions when a new foil was presented, whereas the other task conditions only experience a small peak followed by a small inhibition. It has to be mentioned again that the pattern followed by the waveforms during this inhibition show resemblance with respect to fan. After the inhibtion, the waveform of the new foil condition seems to join the other waveforms again in the pattern. When comparing this general pattern for all the task conditions at channel Pz, the channel with the highest regression coefficient for the retrieval module, roughly the same pattern can be seen. All waveforms experience a peak at around 200 ms, followed by a small inhibition for the target and re-paired foil conditions and a large inhibition for the new foil condition. Also, the same coherence in waveforms during this inhibition is seen for task conditions with the same fan.

The channel with the highest coefficient for the visual module, O2, shows a roughly shared waveform for all the task condition in the peak and inhibition. However, the waveform for the new foil condition gets disinhibited less than the other conditions, but later follows the descending pattern that the other waveforms follow.

4 Discussion

When looking at the regression coefficients mapped onto the scalps, several interesting observations were mentioned in the previous section. However, what do these observations tell us? It is well known that although the temporal resolution of EEG recordings is excellent, the spatial resolution is not very good. One thus has to be careful when making assumptions using data implying spatial differences in brain activity that is yielded from EEG recordings. However, certain observed differences in Figure 3.2 do appear to agree with what we already know about where certain cognitive processes are executed in the brain. The manual module, for example, shows a high positive regression coefficient at site Cz. The regression coefficients also show negative values for parts of the frontal and parietal lobe, indicating a dipole at the highly correlated site, Cz. This would be expected, because the manual module is active when a key press is executed. Since the model and the behavioural data have similar reaction times on average, this simulated key press is in accordance with the actual key press. The primary motor cortex is the part of the brain that, in association with other motor areas (premotor cortex, posterior parietal cortex, supplementary motor area), is responsible for the coordination of motor actions, such as a key press. It's location is at the dorsal portion of the frontal lobe, which is in accordance with the location of the Cz site in the EEG system.

A second observation that can be made from Figure 3.2 is that the highest positive regression coefficients seem to be in the occipital lobe, and are surrounded with negative regression coefficients. These negative regression coefficients are again indicators for a dipole at the occipital lobe. The primary visual cortex is responsible for the registration of visual stimuli, and is present at both hemispheres. The primary visual cortices in both hemispheres process visual stimuli of the contralateral site of the visual field. Thus, when visual stimuli are presented, these areas become active, which is in accordance with the activation of the visual module, which registers the simulated visual stimuli.

The retrieval module is used for extracting information from the declarative memory in ACT-R, whilst the imaginal module is responsible for the matching of information (in our case holding the two words to check if they form a word pair). Both modules show strong positive coefficients for the channel sites that are associated with the parietal lobe. This part of the brain is mainly associated with sensory information, spatial sense and navigation, which are not processes that the imaginal and retrieval module simulate. However, brain areas such as the hippocampus that are located below the cortices at these locations are often associated with human information processing. The hippocampus is especially believed to be associated with declarative memory, which is a process that is handled by the retrieval module in the ACT-R model. It is located in the medial temporal lobe, and since EEG processing does not provide a good spatial resolution (especially with respect to depth), it is possible that this high coefficient is a precursor for hippocampal stimulation. In addition, the brain areas comprising the fronto-parietal network that are assumed to be coherently active during cognitive control functions such as working memory and declarative memory retrieval (Borst and Anderson, 2013) seem to have high values for the regression coefficients. This is especially apparent at the regression coefficients for the retrieval module, the module responsible for the retrieval of declarative memory items. However, the poor spatial resolution of EEG recordings has to be emphasized again, implications that are made from the regression coefficients may be speculations until confirmed with other research methods, such as

fMRI.
Regarding the ERP waveforms of the channels mentioned in the results, it is also dangerous to make absolute inferences from this data. However, certain differences and coherences do point to some speculations which seem logical when considering the different task conditions. Firstly, the new foil task condition is the only case where words are presented in the test phase that were never encountered before, not during the trials nor during the study phase. In all the channels that are presented in Figure 3.3, the ERP waveform for this task condition seems to be inhibited more, after which it experiences a higher peak than the other waveforms. Although it is hard to say what this implies, it seems to be logical for this waveform to show less activity at sites that we assume to be a good precursor for the retrieval of items in memory, and comparing these items. This is because the words that are presented can be discarded fairly quickly (also observed in the reaction times, see Figure 3.1) and little to no retrieval and comparison is needed. For the EEG sites that we believe to be precursors for manual and visual activity, it is hard to say what this larger inhibition implies. The other largely observed effect for all these channels is that the waveforms of task conditions that share the same fan seem to follow the same pattern during the inhibition. The task conditions with a fan of 1 get inhibited more at this time, which is roughly around 400 msec, while the task conditions with a fan of 2 get inhibited less. Again, it is hard to exactly pinpoint what this implies, but it does highlight a large difference between the task conditions, which is also present in the reaction times.
Overall, the model seems to replicate the behavioural data fairly good, and its module activity creates some implications in the logistic regression that are comparable to what we know about human information processing. However, when looking at specific locations of information processing during the associative recognition, precaution has to be taken with these conclusions. Further research using methods with a higher spatial resolution would be an effective addition to these implications. Furthermore, the research does have some other points for improvement. For instance, the EEG recordings used in this analysis only consists of probe-locked data, which runs for 1000 msec after the presentation of a stimulus. Not all trials were completed within this time frame, and it would be interesting to look at the processes that occur later in the trial with the inclusion of the reaction for every trial. In addition, all processes could be outlined clearer when exact data from the moment of stimulus presentation until the reaction would be used, since the module activity could be adjusted based on these time trials. When exact time series corresponding to each length of a trial are used, the module activity would represent the hypothesized processes more. In this case, the activity of the modules that are responsible for the information processing and information retrieval are of a fixed length per trial. When longer or shorter trials occur for a condition, the module activity could reflect the lengthened or shortened processes more. Information processing would be more in accordance with the imaginal and retrieval module, which could lead to making clearer assumptions about these processes.

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