Cognitive Modeling of Event-Related Potentials

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Abstract

Cognitive modeling typically predicts the externally observable results of tasks and psychological experiments such as participant reaction times and error rates. To understand better the neural processes associated with cognition and behavior, it is necessary to model the internal processes. In this paper, we present a method of building a cognitive model of a simple visual selective-attention task, so that the brain electrical activity observed during the task can be simulated. Processes in the model were assumed to generate electrical dipoles in the brain and were found to provide an accurate fit to experimental data.

Keywords: Cognitive model, EEG, ERP, dipole.

Introduction

This paper describes ongoing research into building cognitive models of internal mental processes and using measurements made of electroencephalographic (EEG) data to validate the models. The data for the current work was obtained from a cognitive neuropsychology experiment, which measured the visual selective attention of children. EEG data was collected and analyzed as Event-Related Potentials (ERPs) to identify sources of electrical energy in the form of dipoles. These results were then used to build cognitive models that could reproduce the pattern and timing of EEG measured.

ACT-R

Cognitive models are computer simulations that attempt to predict and reproduce the behavior of human subjects in tasks and psychology tests such as categorization, mathematics, language, and decision-making. The models reproduce external manifestations of cognition such as response times, error rates, and decisions, but until recently there not have been attempts to link these results directly to underlying neural structures and events via modeling.

One widely used cognitive modeling system is ACT-R developed by John R. Anderson at Carnegie Mellon University (Anderson & Lebiere, 1998). In this architecture, cognition is considered to arise from the parallel interaction of several independent modules. However, top-down processes are directed by the Procedural Module, which is models procedural memory as a production system. Specifically, procedural memory contains production rules (i.e., if/then rules). Communication to and from the Procedural Module is managed by a system of buffers (see figure 1) and "chunks". Chunks in ACT-R are short lists of predicated information. For example a dog could be represented by the following chunk:

```
Isa:dog
Name:Fido
Color:brown
Size:large
```

Each buffer can contain one chunk at a time. Each module has at least one buffer, such as a visual buffer, an auditory buffer, or a declarative memory buffer. Modules receive instructions from their buffers and place the results of their activity into their buffers. Collectively, the buffers can be thought of as working memory; they can also be thought of as representing the current context of the task. Productions "fire" when their *if* condition matches the contents of the buffers. The *then* part of the production then alters the content of the buffers. Productions can only fire one at a time and each production takes 50 msec. Each module contains functions to determine how long it takes to return a result. For example, if a production places a request for a specific memory from the Declarative Memory Module the results will be delivered sooner if the memory is stronger. Therefore, ACT-R makes strong timing predictions about internal events.

Module Localization

This paper defines the term "module" as a function localized to an area and linked with a process in a task. This is distinct from Chomsky's language modules or Fodor's domain-specific modules, but is similar to Kosslyn's (1994) generalization. There has been considerable research using functional Magnetic Resonance Imaging (fMRI) to link the activity of the ACT-R modules to specific brain areas with results available on the ACT-R website (Anderson et al, 2011). The best estimates for the module locations are listed in Anderson (2004) while the functions of these brain areas

are described in Anderson (2007). For example, the caudate in the basal ganglia acts as the central coordinator of productions, the hippocampus controls declarative memory, while the anterior cingulated cortex controls attention to conflicting stimuli. Frontal cortex supports declarative memory, while visual processing takes place in the occipital lobe with further processing in the parietal (see Figure 1).
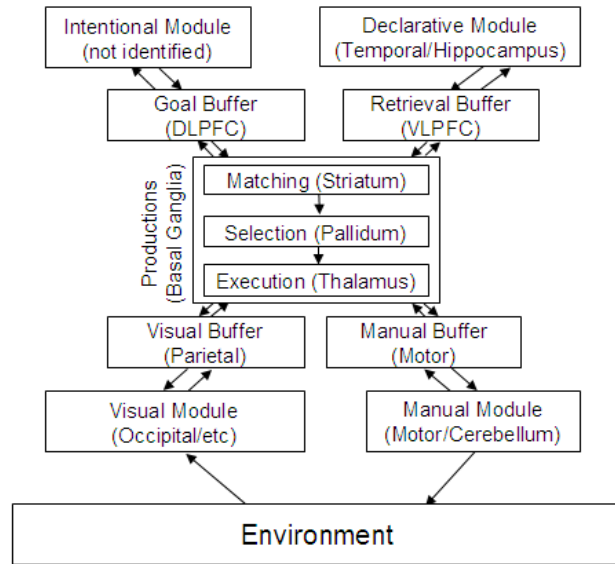

Figure 1: The organization of information in ACT–R 5.0.

In terms of localization, the use of fMRI is ideal. However, fMRI is too slow to detect events directly within the ACT-R time frame. Instead, Anderson estimates the BOLD (Blood Oxygen Level-Dependent) response from the time course of module activation (Anderson et al, 2003). However, this approach still requires a time delay mismatch between recorded activation and cognitive processing of several seconds. In this paper we use electroencephalography (EEG) with its superior time resolution (milliseconds) for similar purposes.

Electroencephalography

EEG is an alternative method of finding the location and timing of neural events and can provide independent, convergent results at low cost. Cassenti (2007, et al 2010) describes work using ERPs, to examine the N100 (a negative voltage at 100ms) and the P300 (positive at 300ms) relating these to events of perceptual encoding and context updating and using their timings to calibrate an ACT-R model.

The present work used a different approach to determine whether EEG recordings could be directly linked to the brain areas associated with defined ACT-R functions. Specifically, it used dipole analysis to locate areas of the brain that appear to originate the signals. A dipole is a physics term for a pair of closely spaced charges, one of which is positive and the other negative. A dipole can generate an electric potential (i.e. a voltage) at some distance from it depending upon its strength and orientation. A given section of the brain can have several thousand neurons all oriented in the same direction and firing together. This could be a cortical column, a nucleus in the lower structures, or a ganglion in the basal ganglia. These neurons produce a potential, of the order of microvolts, when they fire, which is measured in scalp electrodes as EEG (see Onton and Makeig, 2006, for a similar approach).

Experiment

An experiment was conducted with child participants, using a simple interactive technique to measure their attention. EEG measurements were made and used for estimating the parameters of a cognitive model.

Method

Participants Thirteen children (nine boys, four girls) aged from four to nearly seven attending daycare or preschool were recruited to take part in a selective-attention task. Subjects were excluded if they had known or suspected learning or developmental disability.

Apparatus For each participant, an electroencephalogram (EEG) was recorded following standard practice using an electro-cap designed for children by Neurosoft Inc. Signals were recorded at 1ms intervals from 11 scalp sites and the nose tip together with vertical and horizontal electro-oculograms. All electrodes were referenced to the nose tip and impedances kept below 5 kOhms. EEG recordings were made of the participant children while they performed several blocks of five-minute computerized behavioral tasks. EEG and response-time data was collected by the Neuroscan software supplied by Neurosoft.

Procedure For the selective-attention task, the children watched a computer monitor, which showed a picture every two seconds of either a duck or a turtle. The method followed the protocol of Akshoomoff (2002). The children were told to push a button every time they saw the duck and not to push when they saw the turtle (fig. 2).
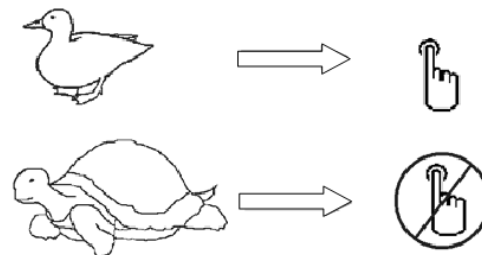

Figure 2: Duck and Turtle pictures and responses/no responses required.

The duck was shown 25% of the time and the turtle 75% of the time. The task required that children pay attention to the target stimulus (duck) while ignoring the irrelevant stimulus (turtle). Following 12 practice trials, each child was given 150 trials each. The task typically took 5 minutes to complete.

Analysis

The EEG data was analyzed using the software package EEGLAB from UCSD which runs on the proprietary MATLAB software (Delorme et al, 2004). Event-Related Potentials (ERPs) were then derived from the continuous EEG recordings. Behavioral measures of performance (accuracy and reaction times) showed that the children carried out the tasks well achieving an overall accuracy of 90% in pressing the button when appropriate.

Independent Component Analysis

The analysis continued with Independent Component Analysis (ICA), which is a mathematical technique of finding sets of separate functions that can explain all of the measurements in the most efficient way, as maximally independent signals. For example, the three posterior electrodes were found to react initially together in the ERP, so this was explained as a single component in the middle of the occipital area. The FASTICA algorithm was used, (Hyvärinen, 1998) as it produced the most consistent results. While the ICA method can calculate location and timings of components, it cannot estimate an absolute magnitude for them since there is an inherent ambiguity between the strength of the component and the attenuation from it to the measurement point.

Dipole Location

The DIPFIT routine of EEGLAB was then used to estimate a set of dipoles in the averaged ERP data that would explain the independent components extracted. Each dipole is assumed to be a region of cortex where several thousand neurons act together in parallel so that their combined electric potential is responsible for the EEG signal measured at the scalp. The DIPFIT software usually finds one or sometimes two dipoles for each of the specific regions that appear to produce the independent components. The EEGLAB spherical head model with standard coordinates was selected. For initial estimates, the data was combined for all of the subjects for both the duck and turtle cases.

Cognitive Model

The next stage was to create a model that reproduced the average ERP activity measured across participants. An ACT-R model of the process would, at the minimum, predict that the visual module (occipital) would be activated by the displayed picture and would place a representation of the picture in the visual buffer (parietal). Next, the representation would be used to retrieve the instruction about what to do for that animal from declarative memory (temporal), which in turn would be placed in the declarative memory buffer (frontal). At this stage of the work, the model was primarily built to reproduce the electrical activity measured rather than the behavioral results. This is to provide a proof-of-concept that can demonstrate that the method can be used consistently to describe internal neural activity. The goal is to define a set of process building blocks that are stable across diverse tasks and can be used to reproduce results from further tasks.

Electric-Potential Modeling

To model the electrical activity, each module in the cognitive model was assumed to be generating one or two dipoles in the locations identified in the dipole-fitting stage. The module was assumed to produce its electrical energy in a rising and falling wave. For modeling purposes, a simple triangular wave was assumed, which peaked in the middle of the module activity. The resulting potential (voltage) was then calculated at the surface of the head for each electrode.
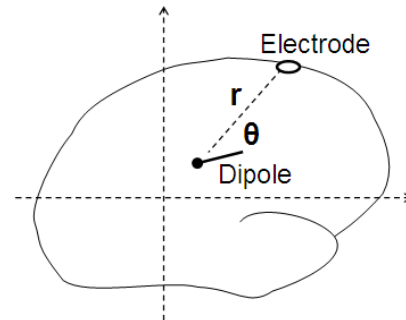

Figure 3: Calculating an electric dipole potential.

The effect of each dipole was estimated in the simulation as follows (see figure 3):
- Calculate the square of the distance r from the dipole to an electrode using Pythagoras.
- Calculate the cosine of the angle θ between the electrode and the dipole using vector dot product.
- Calculate the electric potential from the dipole at the electrode as $k.p.\cos(\theta)/r^2$, where p is the strength of the dipole and k is a constant. It is not necessary to know the value of the constant since relative magnitudes are used in the model.

Adding the potentials from all of the dipoles produced an estimate of the ERP signals at each electrode. The resultant estimates were then compared with the experimental measurements.

Results

Running the ICA routine on the experimental data produced eight independent components to account for the potentials measured. For example, a close dipole pair explained the strong occipital response at 100ms. These were located in the posterior of the head as expected for visual processing. The time course of the independent component was primarily a single spike at 100ms with little activity before or after. Thus, it could be modeled as a simple spike at 100ms, spread 50ms each side, and zero otherwise. Following the first occipital response at 100ms, a cascade of processes formed in the temporal, parietal, and frontal lobes, plus the basal area over the next 700ms. The independent components were found to be active only for a short time each. This facilitated modeling them as separate processes. The DIPFIT routine had shown that all of these components

could be accounted for by one or a pair of dipoles. These were then used as the basis for the modules in the cognitive model.

To simulate the activity, a computer model was constructed consisting of eight modules corresponding to the independent components found. Each module, when it was activated, was assumed to produce one or two dipoles lasting for its duration. This was modeled as rising linearly to a peak and then dropping at the same rate. It was assumed that the dipoles were generated at the location estimated in DIPFIT and which were consistent with the standard locations assumed in ACT-R. The brain regions that the locations corresponded to were found using the Talairach database (Lancaster and Fox, 2011). Table 1 lists the eight processes needed to simulate the ERP signals measured in the selective-attention experiment. Each line shows one module in the cognitive model with the source region of one or two electric dipoles. The times listed are the peaks of activity of each of those modules. Running the simulation produced output which closely reproduced the scalp electrical activity measured in the experiment. The third column shows the coefficient of determination (R-squared) of the simulation relative to the experimental data for that time over the spatial area of the scalp.

Table 1: Times and locations of modules in model.

Time (ms)	Region(s)	R^2
100	Occipital/Basal	95%
125	Parietal /Basal	87%
170	Occipital/Frontal	77%
220	Basal	98%
280	Parietal/Frontal	89%
320	Parietal/Temporal	96%
380	Parietal	91%
690	Occipital/Basal	70%

Figure 4 compares preliminary results of the simulation against the experimental results. The left-hand plots show contour lines of potentials averaged over the subjects measured in the selective-attention experiment at four of the eight times. The views are from above, with the nose at the top of the diagram and the ears at the side. Darker areas indicate more positive voltage responses in the ERP. The right-hand column shows the electric potentials calculated from the model for those four modules at their peak activity times. The locations of the dipoles responsible for the potentials are shown as small circles with lines indicating the direction of the positive voltage. A sensitivity analysis suggested that measuring the scalp EEG voltage to plus-or-minus 10% accuracy would result in localizing a dipole to within two or three millimeters.

The model showed a good agreement for the distribution of potentials measured in the experiment. Overall, the model accounted for 75% of the spatial and temporal variation of electrical potential measured in the experiment. As table 1 shows, at the peaks of activity, the agreement is generally

even higher. This is an excellent fit especially considering the many approximations and simplifications made in the calculations.
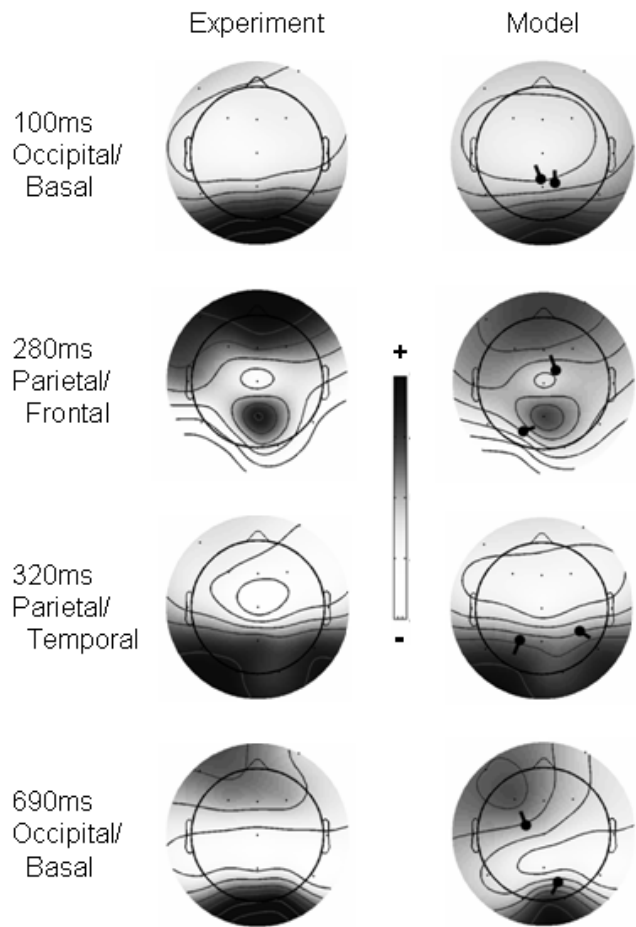

Figure 4: Comparison of experimental ERP results with model simulation for four times during the response.

Conclusion

The present work has suggested that EEG signals can be simulated using a cognitive model that assumes that each process generates one or two electric dipoles located at the center of functionality for that function. The standard ACT-R mappings of functionality proved very robust for use in EEG modeling.

Cognitive modeling has been typically used to reproduce the averaged outward behaviors of experiment participants such as response times and error rates. However, if the internal processes are to be simulated, the differences between participants must be taken into account. Data from the experiment revealed large variability between individuals, especially in the activity in their pre-frontal areas (see Griffiths, Yeh, D'Angiulli, A, 2009, and Yeh, Griffiths, and D'Angiulli, 2010). Such differences would need to be considered when modeling specific individuals. For example, ACT-R models usually only contain

productions that are related to the task at hand. To reproduce the overall brain activity during the task, other processes such as environmental checks taking place in the brain would need to be incorporated. For modeling, it will be necessary to keep tasks simple in order to be able to isolate consistent components. Despite the overall variability of EEG data, the technique of dipole analysis appears to be very promising to determine the localization, time course, and especially the sequencing of neural events.

Future Work

The next steps in this approach will be to identify the specific functionality of the processes postulated in the model that explain the EEG signals. This can be achieved by carrying out similar experimental manipulations that include or exclude various aspects of this protocol and thus enable the functions to be identified by a process of elimination. The work described in this paper used results from children to measure executive function. As the task was simple, it produced ideal data for modeling. Future modeling studies will use results from adults to provide a comparison to determine how the modules change during development. Models built from these results can then be used for investigation of neural processes and to explore patterns of neurocognitive development.

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