ACT-R Model of EEG Latency Data

Daniel N. Cassenti
Human Research and Engineering Directorate
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005

Anderson and Lebiere's (1998) modeling system ACT-R (Adaptive Control of Thought – Rational) has been a leading contributor to advances in cognitive science. Despite the modeling system's success there are areas in which it may be improved. The present research advocates a suggested approach to improving ACT-R's predictive capacity by using EEG (electroencephalography) latency data to predict the time it takes to achieve certain mental steps. A model is presented which successfully represents EEG data from a simple auditory experiment. Implications of this modeling approach to ACT-R and to the field of cognitive science are discussed.

INTRODUCTION

A problem that has faced experimental psychology since its inception is the inability to directly observe mental events (Gardner, 1987). This problem is greater in the field of cognitive modeling as model accuracy is inferred by its approximation to findings from empirical studies that have incomplete information about the nature of the individual mental events.

ACT-R

Anderson and Lebiere (1998) wrote that ACT-R (Adaptive Control of Thought – Rational) is intended to be a unified theory of cognition (Newell, 1990) which is a theoretical system that specifies the workings of the majority of cognitive processes. Ideally, ACT-R will evolve to a system that can accurately model any empirical data.

Successful ACT-R models should bring ACT-R closer to this goal and every unsuccessful model should help by indicating necessary improvements to ACT-R. Advocated here is another tactic to improving ACT-R – improving the model building process itself.

A modeler who wishes to match an ACT-R model's task execution time to the response time of the empirical data has two recourses. The more typical method is to add or subtract mental steps until model time equals response time. The other method is to adjust the time the model takes to complete individual mental steps from the default time attached to each mental step.

To execute the latter method, the modeler must estimate the time needed to perform certain mental steps. Ideally, the modeler assigns empirically-grounded intervals to every mental step. In practice, however this is impossible given that there is no single overt behavior for every mental step.

Productions are one type of mental step. Productions are if-then rules. ACT-R selects a production if the conditions specified in the "if" portion are satisfied. When the production fires, it will execute the actions listed in the "then" portion.

Productions work in concert with ACT-R's visual or auditory perceptual functions and ACT-R's manual and speech motor functions (Anderson, Bothell, Byrne, Douglass, Lebiere, & Qin, 2004). The perceptual functions may provide input to help match the conditions in a production and the motor functions may help produce responses in the action portion of a matched production. Productions may involve only mental steps (e.g., mental arithmetic) and these do not require perceptual or motor functions

A sequence of mental steps in ACT-R consists of production selection, production execution, and perceptual and motor mechanisms such as 165 milliseconds (ms) to encode an audio sequence (Anderson, et al., 2004). All of these consume an pre-defined, default amount of time or a modeler may set a different production time

EEG

As discussed above, production time assumptions in ACT-R raise questions about the accuracy of an ACT-R model's ability to predict time course, which appears to be an insurmountable problem given that there are no overt indications of when a test participant's mental processes occur. However, EEG (electroencephalography) studies represent a method for improving these estimates.

EEG is a method of measuring electrical activity from the brain. EEG researchers prescribe certain characteristic patterns of electrical activity with different mental processes, which can be matched to production firings in ACT-R models. EEG is known for its strong temporal acuity, which makes its temporal relationship with mental events fairly accurate.

The first of two most characteristic patterns from EEG studies is an initial strong negative polarity, typically called the N100 for its occurrence approximately 100 to 200 ms after the presentation of a stimulus. Skrandies and Rammsayer (1995) and others identify the N100 with perceptual encoding.

The second characteristic pattern from EEG studies is the P300 or a positive polarity that typically occurs 300 to 400 ms after the occurrence of a stimulus. Coles, Smid, Scheffers, and Otten (1995) and others match the P300 to context updating. Though there is debate about the meeing of the term context updating (see Polich & Kok, 1995), the position in the present study is the same as Donchin and Coles (1988) that context updating (signaled by the P300) is the time to encode or modify subjective probability of events.

MODEL

Experiment Description

Kerick, Oie, and McDowell, (submitted) conducted a simple auditory experiment. Five participants were asked to wear an EEG cap and press the button on a handheld response device when they heard a high pitched tone through headphones or to not press the button when they heard a low pitched tone. There were 20 high pitched tones and 80 low pitched tones (that occurred at a random time) per experimental block and six blocks of trials (30 total blocks across all participants).

Eleven of the blocks did not provide reliable EEG data because of EEG artifacts and were excluded from consideration. Overall there were 19 blocks of usable (75% or more readable EEG) data. Errors were under 1% of remaining data in every condition and were not considered in the model.

The mean and standard deviation (SD) of the N100, P300, and response time (RT) are presented in Table 1. An important feature of this data is that RT showed two different patterns for different groups of participants. Four participants (fourteen blocks) had an RT after the P300 and two participants (five blocks) had an RT before the P300. Clearly, the P300 and response do not proceed in a serial fashion. An assumption here is that individual differences account for the two response times (both groups completed the same task, so the difference must be attributed to the participants). Participants with a slower RT were more hesitant when pressing the button because only RT showed large differences between the two groups and not either of the EEG peaks. Figure 1 represents a visual depiction of the timing of N100, P300, and the two groups of RT.

Table 1. Empirical data including mean and SD of N100, P300, and two groups of RT. N100 and P300 values include the tone pitch.

Event	Mean (ms)	SD
N100 - High	155	22.03
N100 - Low	165	16.34
P300- High	384	42.03
P300 - Low	352	35.82
RT1	708	98.84
RT2	367	19.78

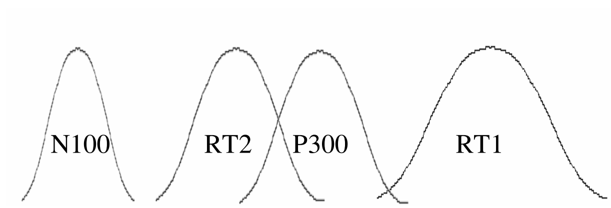

Figure 1. Depiction of time course of EEG events and RT (Groups 1 and 2).

Model Properties

The model employs six productions including: Encode Tone (ET, ET1 is production selection and ET2 is production firing, each of which take time in the model (presumably to allow time for sound detection, though typically selection and firing take place at the same time in ACT-R) to initiate sound encoding when a tone is detected; Retrieve Sound (RS) to identify the encoded tone as high or low pitched; Choose No Response (CNR) to not respond to a low tone; Choose Press (CP) to make a response for a high tone; Hold (H) to reset the goal and continue listening; and Press (P) to initiate a press motor response. Two of these productions also initiate perceptual-motor mechanisms. The ET production initiates a sound encoding auditory mechanism with a default of 165 ms. The P production initiates three motor mechanisms including Motor-Initiation (50 ms default), Output-Key (10 ms default), and Finish-Movement (90 ms default).

In addition to the productions and perceptual-motor mechanisms, the model also contained signals marking the time of the N100, P300, and RT. The N100 was triggered at the completion of the auditory encoding mechanism to correspond to perceptual encoding. The P300 represented updating the number of times CNR or CP fired. The P300 was initiated after CNR or CP production firing. Given that some of the participants pressed the response button before showing a P300, the P300 and response are not serial to one another. An assumption of the model is that this context updating takes an additional amount of time after choosing to press or not to press.

Therefore an additional amount of time drawn from a random normal distribution around a mean was added to the time of the P300 trigger to correspond to the amount of time it takes to update frequency after picking a response.

The RT corresponded to the amount of time it took to press the output key, which was the time recorded by E-Prime (Psychological Software Tools, Inc.), the experimental suite used in the empirical study. Figure 2 represents the model's time course.

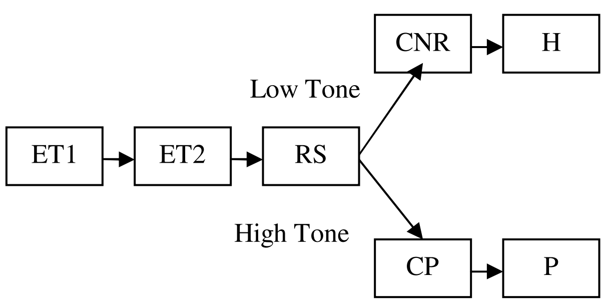

Figure 2. Time course of productions in model. Productions are represented in boxes with abbreviations as defined in text. The course of the productions changes depending on which tone the model hears.

Production times were changed from the 50 ms default (also considered the minimum production time for non-perceptual productions) with a mean and standard deviation to accommodate the time parameters of the EEG data. When a production is greater than 50 ms, it is assumed that the production takes longer to implement than other productions.

The productions, perceptual motor mechanisms, and the events (N100, P300, and RT) that follow them are presented in Table 2 for low tones and Table 3 for high tones. The tables also include model time and default ACT-R times.

Table 2. The steps, model time, default time, and event when the model hears a low pitched tone. Z indicates a random normal amount of time. +Z=P300 indicates an additional random amount of time has been added to calculate the P300 time. All model and default times are depicted in ms.

Step	Model Time	Default	Event
ET1	50	50	
ET2	Z	50	
Encoding	20	165	N100
RS	50	50	
CNR	50	50	+Z=P300
H	50	50	

Table 3. The steps, model time, default time, and event when the model hears a high pitched tone with same notation as described in Table 2. Mot.Init., Out.Key, and Fin.Move stand for Motor-Initiation, Output-Key, and Finish-Movement, respectively. All model and default times are depicted in ms.

Step	Model Time	Default	Event
ET1	50	50	
ET2	Z	50	
Encoding	20	165	N100
RS	50	50	
CP	50	50	+Z=P300
P	Z	50	
Mot.Init.	20	50	
Out.Key	10	10	RT
Fin.Move	90	90	

Tables 2 and 3 depict model times that have been converted to a random normal amount of time. The random normal times are based on the means and standard deviations found in the experimental data while accounting for the model steps that precede each event. Table 4 depicts the mean and standard deviation for each random normal time.

Table 4. The mean (ms) and standard deviation of the random normal times used to alter model step times to account for the N100, P300 and RT events at either a high or low tone. The two RT values indicate individual differences in response time.

Event	Tone	Step	Mean	SD
N100	Low	ET2	94.68	16.34
N100	High	ET2	85.43	22.03
P300	Low	After CNR	137.50	35.82
P300	High	After CP	178.96	46.99
RT1	High	P	404.55	98.84
RT2	High	P	56.38	19.78

The number of times that the default ACT-R parameters changed from default were restricted to production time and perceptual-motor mechanisms time changes that accommodated the N100, P300, and RT findings. The two perceptual-motor mechanisms changes were the Audio-Encoding time, which was reduced from 165 to 20 ms and the Motor-Initiation time which was reduced from 50 to 20 ms (because E-Prime only needed a downstroke and not the additional upstroke required by a typical punch movement). For Audio-Encoding, a high or low pitched tone is much less complex than other audio events (e.g., spoken words) and would therefore need less encoding time.

Model Results and Discussion

Nineteen runs of the model produced results that were a good approximation to the experimental results. Table 5 presents the model latency means, the experimental latency means, and the correlation between them.

Table 5. Comparisons between model and experimental results. Exp. Stands for Experimental and r represents the Pearson Correlation Coefficient.

Event	Tone	Model	Exp.	r
N100	Low	165	165	.969
N100	High	154	155	.968
P300	Low	352	352	.894
P300	High	380	384	.946
RT	High	590	600	.945

This model is the first of a potentially much wider class of models in which the time course of mental steps may be plotted. In particular, the time estimates of when perceptual encoding has taken place and a triggering point (i.e., choosing one or the other response) for context updating (i.e., the P300) were unique contributions of this model.

GENERAL DISCUSSION

The model presented here is the first to our knowledge that successfully modeled the results of EEG data within a major cognitive modeling system. The focus here was on a simple auditory experiment. The results conformed well to the experimental data.

Implications for ACT-R

The model presented here goes further than just being the first to model EEG data. More importantly, it contributes to ACT-R's progress towards becoming a unified theory of cognition. Prior to the present model, ACT-R modelers generally accepted the default production times (50 ms) and default perceptual motor mechanism times. The only overt indications of time course were the starting point with presentation of the stimulus and the end point, indicated by the response.

The advent of the present model allows expansion of the modeler's capabilities to more closely approximate the actual time course of mental steps. In particular, the modeler can estimate the time it takes to encode perceptual information with the N100 and can set a limit on how long it takes to reach productions that lead to context updating with the P300. In another case, the auditory encoding perceptual mechanism was adjusted to reflect the simplicity of tones compared to other types of sounds. The same types of consideration should be employed for other perceptual or motor mechanisms in future research.

Expanding this approach to other ACT-R models poses a challenge because of the present model's simplicity. In ACT-R many more productions may be necessary to simulate a task than the present model which only had four. Deciding where to change production times was mostly made by the nature of the production sequence (i.e., changing the ET production for N100, the parallel process time after CNR or CP for P300, and P for the response time). The advice to modeling with this approach is to approximate when in the process perceptual encoding, context updating, and response occurs and adjust the production time of those productions.

The P300 is a special case of event. The way in which it was used here was different from the

N100. Instead of occurring at the end of a production or perceptual motor mechanism, the P300 triggered after the model chose the response (in order to update response selection context) and included an extra amount of time. This simulated the time course of a parallel process, whereas the time course of mental steps in ACT-R is traditionally serial. Given that button presses occurred sometimes before the P300 and sometimes after the P300, including the P300 as a serial process was not an option. Whether the P300 signifies context updating or something else, the experiment presented here indicated that it is a parallel process which can occur before of after the response. However, since P300 always follows N100, we may assume that P300 is triggered at some point after stimulus encoding.

This method opens the door for new options in ACT-R for estimating the length of time for sub-symbolic processes such as context updating. Though productions and perceptual-motor mechanisms should remain serial, time course of parallel processes may be modeled using this method.

Our hope is that this model will also usher in a new class of ACT-R models for simulating EEG studies, in much the same way that Sohn, Ursu, Anderson, Stenger, and Carter (2000) did for fMRI studies. Sohn et al. (2000) began a large research effort (e.g., Anderson, Qin, Sohn, Stenger, & Carter, 2003) to relate ACT-R functions to spatial regions of the brain and the hope is that the present model will begin a research effort to relate ACT-R time course to EEG events.

Conclusions

The use of EEG techniques provides a useful tool for observing the timing of mental steps. This hypothesis motivated a model in ACT-R to simulate a simple auditory EEG experiment which showed that ACT-R can predict the latency of traditional EEG measures N100 and P300.

Though the high degree of relationship between model and data is not surprising given the use of mean and variability from the empirical data, the present model expands the capabilities of ACT-R and adds a new class of data to ACT-R's repertoire. ACT-R is a good candidate for a unified theory of cognition (Anderson & Lebiere, 1998) and this model may inspire new research on the time course of mental steps in ACT-R and cognitive modeling in general.

ACKNOWLEDGEMENTS

This research was completed at the U.S. Army Research Laboratory. I would like to thank Troy Kelley, Kaleb McDowell, Scott Kerick, Don Headley, Linda Pierce, and three anonymous reviewers for review of earlier drafts of this paper.

REFERENCES

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review, 111,* 1036-1060.

Anderson, J. R. & Lebiere, C. (1998). *The atomic components of thought.* Mahwah, NJ: Erlbaum.

Anderson, J. R., Qin, Y., Sohn, M-H., Stenger, V. A. & Carter, C. S. (2003) An information- processing model of the BOLD response in symbol manipulation tasks. *Psychonomic Bulletin & Review.* 10, 241-261.

Coles, M.G.H., Smid, H.G.O.M., Scheffers, M.K., & Otten, L.J. (1995). Mental chronometry and the study of human information processing. In M. D. Rugg & M. G.H. Coles (Eds.), *Electrophysiology of mind: Event-related brain potentials and cognition*. Oxford: Oxford University Press.

Donchin, E., & Coles, M.G.H. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Science, 11*, 357-374.

Gardner, H. (1987). *The mind's new science: A history of the cognitive revolution*. New York: Basic Books.

Kerick, S.E., Oie, K.S., & McDowell, K. (submitted). Assessment of EEG Signal Quality in Motion Environments.

Newell (1990). *Unified theories of cognition*. Cambridge, MA: Cambridge University Press.

Polich, J., & Kok, A. (1995). Cognitive and biological determinants or P300: An integrative review. *Biological Review, 41*, 103-146.

Skrandies, W., & Rammsayer, T. (1995). The perception of temporal structure and auditory evoked brain activity. *Biological Psychology, 40*, 267-280.

Sohn, M.-H., Ursu, S., Anderson, J. R., Stenger, V. A., & Carter, C. S. (2000). The role of prefrontal cortex and posterior parietal cortex in task-switching. In *Proceedings of National Academy of Science*, 97 (24), 13448-13453.