Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

SaD04.6

Neural Mass Model of Human Multisensory Integration

Rosalyn J. Moran, Richard B. Reilly* *Senior Member, IEEE.*

Abstract— **A neural mass model of interacting macro-columns is stimulated to reproduce unisensory, auditory and visually evoked potentials and multisensory (concurrent audio-visual) evoked potentials. These were elicited from patients conducting a reaction response task and recorded from intracranial electrodes placed on the parietal lobe. Important features of this model include inhibitory and excitatory feedback connections to pyramidal cells and extrinsic input to the stellate cell pool, with provision for hierarchical positioning depending on extrinsic connections. Both auditory and visually evoked potentials were best fit using a top-down paradigm. The multisensory response reconstructed from its constituent models was then compared to the actual multisensory EP. Fitting of the multisensory response from constituent models to the actual response required no significant changes to the architecture but did require a decrease in top-down feedback delay. This suggests that multisensory integration, and its related improvement in reaction behavior is not an automatic process but instead controlled by a central executive functioning.**

I. INTRODUCTION

Findings in multisensory integration research have implications across disciplines as diverse as psychiatry cognitive neuroscience and electrical engineering. The question of how information is synthesized in the human neocortex, the so-called "binding problem" has yet to be thoroughly explained at any level of anatomical or physiological organization. Disturbances in the ability to process sensory input and adapt responsively have been linked to common and serious disorders including schizophrenia and autism [1], [2]. [3].

While considerable advances have been made in animal studies of the anatomical role of midbrain structures (in the main, the superior colliculus) in multisensory integration, human studies have largely focused on behavioral data with tractable, abstract modeling [4]. The role of this integration is thus becoming better understood, however the anatomical and physiological mechanisms underlying the processing, is less clear. With current findings in multisensory integration research supporting both "top-down" and "bottom-up" facilitators [5] [6].

II. AIM

A recent neural mass model of the EEG has emerged that offers broad examination of both local neuronal populations and their relation to hierarchical cortical processing [7]. The aim of the research presented here was to extend this model based on real data, where sound anatomical and physiological correlates are manipulated to produce observed EEG output. Such a model would help provide a deeper understanding of the underlying physiology of multisensory integration. Moreover, multisensory models aid in the understanding of perception since they have unique constraints and provide unique results over traditional unisensory experimental paradigms.

III. JANSEN'S NEURAL MASS MODEL UNIT

The basic model unit [8] is an extension of the earliest lumped parameter model proposed by Lopez de Silva *et al.* [9] where anatomically plausible time constants and connectivities among interacting excitatory and inhibitory populations of neurons have produced the full spectrum of EEG activity, as well as evoked potential responses to transient stimuli. A cortical area is understood as an ensemble of strongly interacting macro-columns of granular and agranular cells, where the EEG is generated by their synchronous dendritic activity. The anatomical characteristics of the layered neocortex have been shown to be largely homogenous [10]. The supergranular (layers I-III) and infragranular layers (V-VI) comprise pyramidal excitatory cells whose dendrites branch profusely in layer 1. Due to the large size, number and regular orientation of layer III and V pyramidal cells, the EEG is assumed to be directly observed as the dendritic depolarization of this excitatory cell group, *y(t)* [11] . Inhibitory interneurons comprising smooth stellate cells and basket cells form the next part of the feedback loop with the pyramidal cells. Anatomically these also occupy, in the main, layers I-III and V-VI. In layer IV, the granular layer, spiny stellate cells receive extrinsic afferents

The state space equations regarding the population dynamics rely on two operators. The first transforms the mean pre-synaptic firing rate *m(t)* (this includes intrinsic and extrinsic inputs) into an average postsynaptic membrane potential *v(t).*

$$v = h \otimes m \tag{1}$$

$$h(t) = H\frac{t}{\tau}\exp(-\frac{t}{\tau})u(t) \tag{2}$$

h(t) is the impulse response of the excitatory and inhibitory populations. H_e, [12] and $\tau_{e,i}$ tune the maximum amplitudes

---

This work was supported in part by an IRCSET Fellowship

*R. J. Moran is with the Department of Electronic and Electrical Engineering, University College Dublin, Dublin 4, Ireland (e-mail: rosalyn.moran@ ee.ucd.ie).

R. B. Reilly, is with the Department of Electronic and Electrical Engineering, University College Dublin, Dublin 4, Ireland, and The Cognitive Neurophysiology Laboratory, St Vincent's Hospital, Fairview, Dublin, Ireland (e-mail richard.reilly@ucd.ie)

of post synaptic potential and rate constants of membrane and dendritic delays respectively.

The second transformation, S is an instantaneous sigmoidal function that transforms the average membrane potential to mean firing rate determined by voltage sensitivity parameters, e_o which determines the maximum firing rate of the neural population, v_o the PSP for which a 50% firing rate is achieved and r the steepness of the sigmoid transformation. Subpopulation interactions are characterized by the number of synaptic contacts present between pools in the feedback loop. *C1* represents the number of synaptic connections between the pyramidal cell group and the excitatory dendrites, *C2* the synapses from the excitatory population to the pyramidal cells, *C3* represents the synapses from pyramidal cells at inhibitory dendrites and *C4* the synapses from inhibitory to pyramidal synapses.

$$S_k(v) = \frac{c_k e_0}{1 + e^{r(v_0 - c_k v)}} \qquad (3)$$

IV. UNIT HIERARCHY

The Jansen model [7] has been embedded in a study of the hierarchical effects on event-related responses [6]. Three kinds of inter-area connectivity representing forward, backward and lateral signal transmission were constructed to enable mechanistic enquiries into the generation of evoked and induced responses. The model comprises heterogeneous and highly asymmetric coupling.

V. METHODOLOGY

A. Subjects

Data from three individuals with epilepsy are reported (ages 29, 35, and 45). The patients were implanted with subdural electrodes for evaluation of the foci of pharmacologically intractable epilepsy. Recordings were made after all clinical procedures related to seizure localization were completed. All recordings for the present study were made after subjects had been re- started on their medications.

B. Stimulation and Task

The auditory stimulus was a 1000 Hz tone presented over headphones. Visual stimulation comprised a red disk on a black background. Subjects were instructed to make button press responses when a stimulus (A, V or A+V) was detected, as quickly as possible without making errors.

C. EEG Recordings

Averages from -100msec to 250 msec around the stimulus were obtained for all three conditions. The electrode site from which data were analyzed was chosen based on the following criteria: a) it was over parietal cortex; b) both auditory and visual stimuli elicited a robust unisensory response at the site; c) and both the auditory and the visual responses were larger than the corresponding responses from the surrounding electrodes. Fig.1 displays all electrodes, they were placed over the left hemisphere in an 8x8 grid.

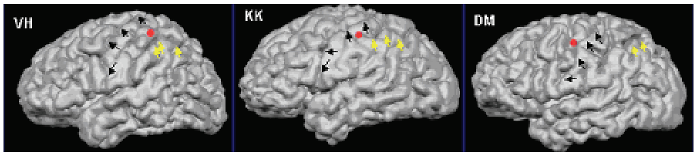

Fig 1. Parietal lobe electrode placement in three different subjects

D. Model Optimization

For both the auditory and visual evoked potentials hierarchy type was first examined (using standard unit model parameters). A simple bottom-up structure was constructed, with sequential bottom-up structures added until the first positive peak was accurately captured. Then, examination of the real ERP and the model output dictated whether a top-down or lateral connection was required to produce the trace post *P100* i.e. after the positive peak at 100msec. With the hierarchy decided, variable parameters were optimized using a genetic algorithm to optimize data fitting. Genetic algorithms are suitable for optimization problems that include multimodalities (many parameters) and non-linearities [13]. The extrinsic input for both audio and visual modalities are described by *p(t)*, these are presented to the system at 10 msec and 25 msec for audio and visual models respectively.

$$p(t) = q\left(\frac{t}{w}\right)^{n} e^{-t/w} \qquad (4)$$

where q=0.61, w=0.0013 and n=7.6. This transient was presented in [7] to produce an ERP with adequate amplitude relative to the background EEG.

VI. RESULTS

Behavioral

The electrode satisfying the criteria described above was found just anterior to the intraparietal sulcus over the superior parietal lobule. Behaviorally, the participants reacted most quickly to AV stimuli.

ERP Generation

The Auditory Evoked Potential P100was first arrived at via two bottom-up connections. Significant inhibitory afferents were excited via a top-down connection to produce the required N150 (Fig. 2). The Visual Evoked Potential P100 was arrived at via three bottom-up connections. Similar to the auditory EP, significant inhibitory afferents were excited via a top-down connection to produce the required N150 (Fig. 3) Optimisation terminated after 400 generations of the genetic algorithm.

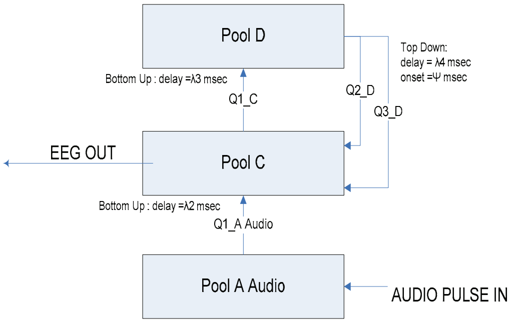

Fig 2. Audio Model of interacting macrocolumns.

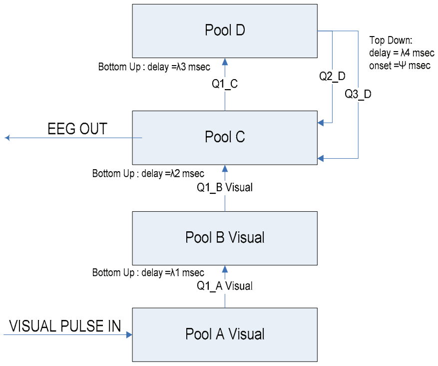

Fig. 3

Fig 3. Visual Model of interacting macrocolumns.

Multisensory Outputs

Using both audio and visual input pulses *p(t)* to Pool 1 and Pool 0 respectively, the model was simulated for multi sensory input, Fig. 4, with significant differences emerging in simulated and recorded ERPs at 70msec (Figs. 5,6 and 7).

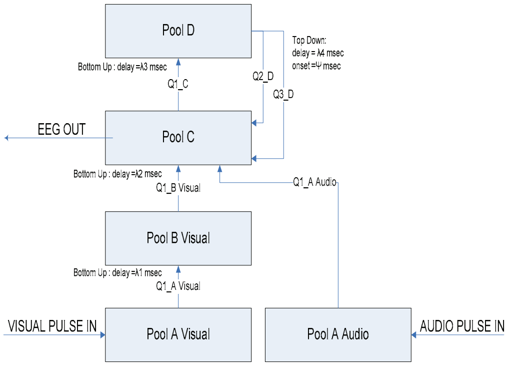

Fig 4. Component model for audio visual integration.

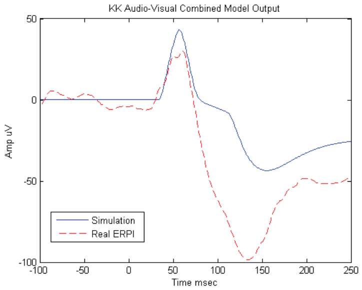

Fig 5. AV ERPs: Simulated and Recorded Subject KK

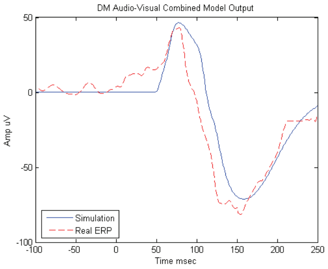

Fig 6. AV ERPs: Simulated and Recorded Subject DM

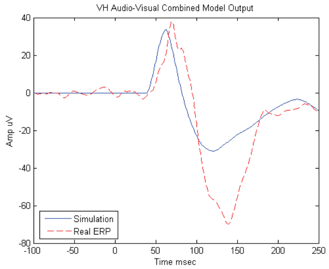

Fig 7. AV ERPs: Simulated and Recorded Subject VH

Optimization of intrinsic parameters produced no measurable difference in simulated ERPs. Similarly the addition of lateral and further top-down afferents did not affect the fitting properties of the simulated ERP. Optimization of extrinsic parameters, *Top-down onset* decreased from 100msec to 50msec, 95msec and 80msec produced significant improvements (Figs. 8, 9 and 10) for patients KK, DM and VH respectively.

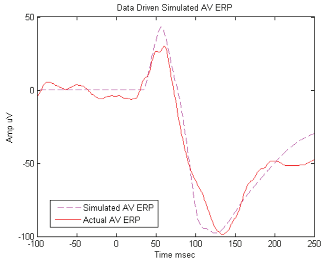

Fig 8. AV ERPs: Simulated and Recorded Subject KK

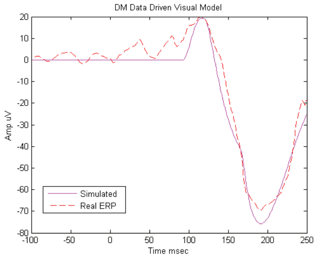

Fig 9. AV ERPs: Simulated and Recorded Subject DM

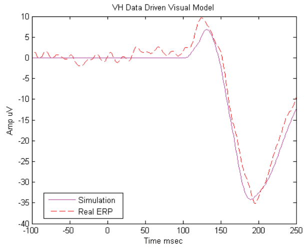

Fig 10. AV ERPs: Simulated and Recorded Subject VH

VII. DISCUSSION

For a bottom-up theory of multisensory integration, the complicated dynamics encompassed by the Audio+Visual model would be expected to produce the AV ERP adequately. However the vast fitting error observed in Figs 5,6 and. 7 produced by the audio and visual components suggest further dynamic behaviour beyond A+V amalgam. Investigations using genetic algorithms showed that the most significant parameter to induce the required changes was the top-down onset.

Several higher cortical areas have been identified as truly multisensory and may be implicated as those areas seen here to act earlier in processing multisensory stimuli. Such regions include the superior temporal sulcus and regions of the frontal cortex [14],[15]. The temporal resolution of EEG offers here an insight into the purpose of these regions. Top-down anatomical connections to supra and infra granular layers of lower level neuronal ensembles have been categorized as largely modulatory in their action [16]. That is, feedback causes weaker excitatory postsynaptic potentials than feedforward input [17] [18] but can raise the potential of the cell nearer to threshold so that it responds more quickly and more strongly to feedforward input. The psychophysical role of this modulation has been presented across the literature as an attention effect [19], [20]. An effect no more salient than say, increased contrast in a visual stimulus. However recent work presents a perceptual hierarchy with intelligent efficiencies [21]. Models of the visual stream have proposed that top-down modulations carry an expectation value that reduces the possible correct visual perceptions, in so far as feedback connections from higher to lower order visual cortical areas carry predictions of lower-level neural activities. The error signal between this prediction and the actual response is then sent back to the higher level via feedforward connections. The model presented here discriminates top-down from bottom-up experimental effects and in doing so offers Multisensory Integration as an interesting and tractable paradigm to test these larger perception hypotheses.

For multisensory research in general, this model implicates higher cortical regions, in producing a superadditive effect in behavioral response times.

ACKNOWLEDGMENT

The authors would like to acknowledge Dr Sophie Molholm, Dr Pejman Sehatpour and Professor John Foxe at The Nathan Kline Institute for Psychiatric Research in New York for data collection and physiological input.

REFERENCES

[1] M.E. Hertzig, H.A. Walker, “Symptom formation as an expression of disoedered information processing in schizophrenic children,.” *Journal of Autism and Developmental Disorders*, Vol. 5, No. 1, March 1975 pp 13-24.

[2] G. Dawson, R. Watling,”Interventions to Facilitate Auditory, Visual and Motor Integration in Autism: A review of the evidence,”*Journal of Autism and Developmental Disorders,* Vol. 30, No. 5, October 2000 pp 415-421.

[3] A. Fisher, E. Murray, A. Bundy, *Sensory Integration. Theory and Practice.*, Philadelphia, F.A. Davis Company.

[4] G. A. Calvert, T. Thesen,, ”Multisensory integration: methodological approaches and emerging principles in the human brain,,” *.Jpurnal of Physiology* Paris 1998, 2004, pp 191-205.

[5] D. Talsma, M. G. Woldorff, ”Selective Attention and Multisensory Integration: Multiple Phases of Effects on the Evoked Brain Activity”, *Journal of Cognitive Neuroscience*. 2005;17:1098-1114.

[6] B. E. Stein “Neural Mechanisms for synthesizing sensory information and producing adaptive behaviors,” *Experimental Brain Research,* Vol. 123, No. 1-2, October 1998, pp 124-135.

[7] O. David, L. Harrison, K.J. Friston,”Modelling event-related responses in the brain” *NeuroImage* 25, 2005, pp 756-770.

[8] B. H. Jansen, V.G. Rit, ”Electroencephalogram and visual evoked potential generation in a mathematical model of coupled cortical columns,” *Biological Cybernetics*, 1995, No. 73 pp 357-366.

[9] L da Silva, F. H. Hoek, A. Smits, L. H. Zetterberg,, “Model of brain rhythmic activity: the alpha rhythm of the thalamus” *Kybernetik*,1974, No. 15, pp 27-37.

[10] J. DeFelipe, L. Alonso-Nanclares, J.I. Arellano, ”Microstructure of the neocortex: comparative aspects,” *Journal of Neurocytology*. No. 31, 2002, pp 299-316

[11] E. Niedermeyer, F. Lopes, F. H. Da Sylva, “*Electroencephalography: Basic Principles, Clinical Applications and Related Fields.”* Lippincott Williams and Wilkins, 5th Ed. Nov 2004.

[12] A. Van Rotterdam, F. H. Da Sylva, ”A model of the spatial-temporal characteristics of the alpha rhythm”, Bull Math Biology, No. 44, 200, pp 283-305.

[13] L. Davis,*“Genetic Algorithms and simulated Annealing.*”, Morgan Kaufmann Publishers Inc. San Francisco, USA, 1987.

[14] L.A. Benevento, J. Fallon, B.J. Davis, M. Rezak, “Auditory—visual interaction in single cells in the cortex of the superior temporal sulcus and the orbital frontal cortex of the macaque monkey”, *Journal of Experimental Neurology*, Vol. 57, No. 3, Dec 1977, pp 849-872.

[15] G.A. Calvert, P.C. Hansen, S.D. Iversen, M.J. Brammers,”Detection of Audio-Visual Integration Sites in Humans by Application of Electrophysiological Criteria to the BOLD Effect”,*NeuroImage,* Vol. 14, 2001, pp 427-438.

[16] M.W. Spratling, “Cortical region interactions and the functional role of apical dendrites” *Behavioral and Cognitive Neuroscience Reviews,* Vol. 1, No. 3, pp 219-228, 2002.

[17] J.M.L Budd, “Extriate feedback to primary visual cortex in primates: a quantitative analysis of connectivity”, *Proceedings of the Royal Society of London, Series B,* 265 (1400), pp 1047-1044.

[18] Z. Shao, A. Burkhalter, “Different Balance of Excitation and Inhibition in Forward and Feedback Circuits of Rat Visual Cortex”, *Journal of Neurophysiology,* Vol. 16, No. 22, Nov 1996, pp 7353-7365.

[19] C. Buchel, K.J. Friston, “Modulation of connectivity in visual pathways by attention: cortical interactions evaluated with structural equation modeling and fMRI”, *Cerebral Cortex*, Vol 7 No. 8, 768-778

[20] R. Raizada, S. Grossberg, “Towards a Theory of the Laminar Architecture of Cerebral Cortex: Computational Clues from the Visual System”,*Cerebral Cortex*, Vol. 13, No. 1, 100-113, January 2003

[21] R. P. N. Rao, D. H. Ballard, “Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects”. *Nature Neuroscience*, Vol. 2 No. 1 Jan 1999 pp 79-83.