Interacting Modalities through Functional Brain Modeling

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Abstract This paper proposes a concept for modeling modalities and understanding the interaction between modalities through functional brain modeling (FBM). FBM proves to be a powerful method for functional behavior prediction of a group of neuronal cells with equivalent functional behavior. An example of interacting groups of neuronal cells, utilizing FBM, in early vision is given. A broad setup of functional behavior and interaction between different groups of cells in early vision has similar conceptual properties as cells that process other sensory information or multi modal sensory information.

1 Introduction

Currently the chemical, biological, and functional structure and behavior of neurons are well understood. Nowadays desktop computing power also exceeds that of a fly's brain. Nevertheless there is no model or robotics system that is able to completely simulate its behavior. We propose to process sensory or cognitive data by functional brain modeling (FBM) to achieve better functional abilities than with existing simulations.

The aim of FBM is not to make a model of the brain on neural level from biological, electronic, chemical, and physical microscopic (molecular) level, but merely to model the functionality of a group of cells or even a complete area that have equivalent or similar functional behavior, and give the interaction between groups with different functional characteristics on macroscopic level.

FBM is aiming to reveal functional interaction mechanisms between different groups of neurons by simulation and predict behavior of cells in adjacent areas in the brain. Physical recordings of single (or a small number) of neurons, in practice, give a good insight in the functional behavior of a group of cells, but due to physical restrictions not all parts of the brain can be explored that way. Brain activity measurement methods, like EEG, fMRI, and PET, explain a lot about the interconnectivity of different areas in the brain, but are too crude to give detailed functional characteristics of a particular area or group of cells.

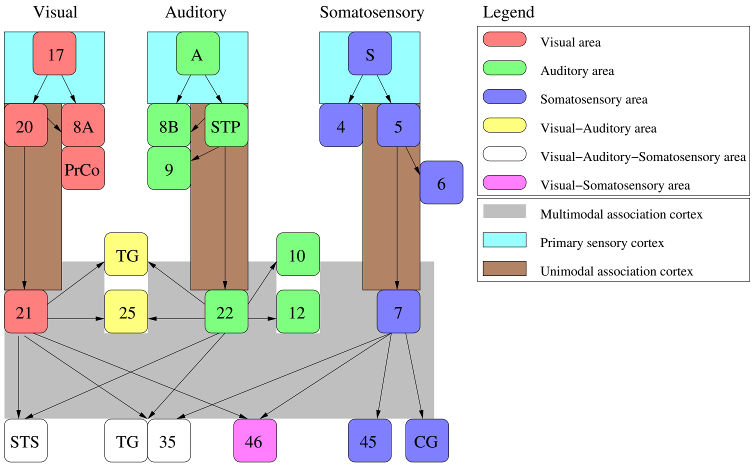

Figure 1. Schematic overview of visual, auditory, and somatosensory pathways. Adapted from [7]. Numbers and initials denote respective brain areas.

Functional brain simulations could be utilized to get a better insight in the behavior of certain brain areas.

We hypothesize that sensory data is processed, as illustrated in Figure 1, in a feedforward manner. Initially, the data in the stream is unimodal, but is progressively getting more abstract and converging on multi modal sensory areas. However, we suggest that the main importance of the hierarchy of the brain stems from bi-directional processing[3] based upon a brain architecture that consists of both an *archicortex* and a *neocortex*, which will be outlined in Section 2. Section 3 gives an overview of different cells in early vision from functional perspective. Section 4 shows, by example, how functional behavior of subsequent groups of cells in the feed forward data stream of early vision can be predicted. The paper finalizes with a discussion.

2 Integration of sensory areas

The cerebral cortex is anatomically divided into four (frontal, parietal, temporal, and occipital) lobes, and has functionally distinct regions. Most areas are primarily concerned with processing sensory information or delivering motor commands. Studies of afferent sensory pathways and association areas in the cortex have lead to three important principles of sensory information processing [7]:

1. Sensory data is processed in a series of relays along several parallel pathways from peripheral receptors through primary cortex and unimodal association cortex to the multimodal association cortex, see Figure 1.

[3] Bi-direction processing incorporates feedforward and feedbackward mechanisms that can be executed in parallel in multiple areas in the brain.

2. Sensory data representing different modalities converge upon areas of cortex that integrate the data.
3. The posterior association areas that process sensory data are highly interconnected with the frontal association area responsible for planning motor actions.

Unimodal sensory outputs converge on multimodal association areas in the *prefrontal*, the *parietotemporal*, and *limbic* cortices. Neurons in these areas respond to combinations of signals representing different sensory modalities by constructing an internal representation of the sensory stimulus concerned with a specific aspect of behavior.

However, data does not converge to a single highly specialized area [23], therefore one can state that the *feed forward* sensory streams should be interpreted as preprocessing for the cognitive brain areas, which include the archicortex and neocortex, where data is processed in a bi-directional way. The main reason of the hierarchy of the brain stems from bi-directional processing that consists of both an archicortex and a neocortex. Preprocessed sensory data feeds both cortices in a parallel manner. Where the areas, illustrated at the bottom part of Figure 1 can serve as input for the archicortex.

2.1 Feed forward data streams

Hubel and Wiesel did pioneering work in the cat's striate cortex. They explored various visual cortical areas with micro-electrodes and divided the recorded cells into four distinct classes (center-surround, simple, complex, and hyper complex cells) [5]. This division is based upon a building block architecture where center-surround type of cells form the input for the simple cells, simple cells in turn form the input for complex cells, and so on.

Currently, a subdivision into four classes would not suffice anymore, since many new types of cells have been found. FBM utilizes the concept of the building block architecture since it is very attractive from functional point of view. The building block concept will result in groups of cells that are all responsible for one or few specific features. Feature extraction yields a strong reduction of data (but moderate reduction of relevant information). Feature extraction in turn requires a processing mechanism to combine the features. As data progresses its representation is gradually becoming more abstract.

2.2 Bi-directional data streams

The human brain is evolved from the brain of other mammals having a special brain structure: the neocortex, which provides us strong cognitive abilities. Animals not having a neocortex achieve their highest cognitive processing in the archicortex [3]. The sensory pathways developed in the "old" archicortex are still active in the primate brain. They can process multimodal sensory data and provide basic cognitive skills, e.g., how to survive.

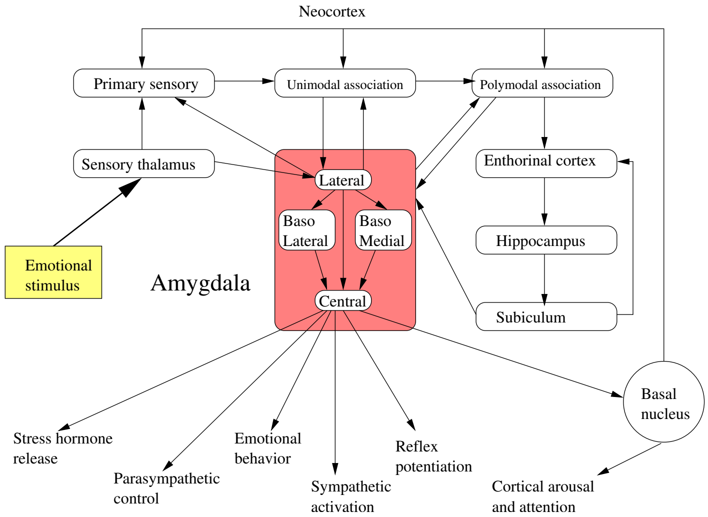

Figure 2. Schematic overview of emotional stimulus processing, from [18].

The *Amygdala*, known as center of many emotional processes, gets its sensory inputs not only from the neocortex but also from hypothalamus, thalamus, and brainstem [9,18], see Figure 2. Although the sensory input from thalamus activates the amygdala faster than input from neocortex [10,13], the quality of sensory processing is coarse because of the archicortex's relatively poor neuronal circuit. The fast and coarse poly-sensor processing in amygdala sending output to both unimodal association cortex and multimodal association cortex could be the top-down hypothesis on the feed-forward sensory stream to combine the relevant processes in the cortex by bi-directional connections [22]. Additionally, prefrontal cortex, anterior cingulated cortex, and hippocampus get input from amygdala [1,2,15,18], and could serve temporally dynamic integration of the neocortical processes.

Our aim is to utilize FBM to encapsulate the detailed neuronal interaction to elucidate the above described complex interaction within the archicortex.

3 Functional behavior of cells in early vision

Complex cells respond vigorously to lines and edges, but also to grating patterns of appropriate frequency and orientation. This response to grating patterns seems an artifact. However, grating cells receive inputs from complex cells, so therefore complex cells do respond to grating patterns too. Grating cells, most likely, play a role in both texture processing and figure-ground segregation [19,20,14]. From functional point of view it is expected that the complex type of cells segregate into a grating type of cell and a *complex type 2* type of cell that responds solely to lines and edges. Latter type of cell will receive excitatory input from the complex cells and inhibitory input from the grating cells.

A similar concept holds for junctions.[4] Endstopped cells respond well to all junctions (including line ends and corners), except to junctions where four lines end [4]. A typical four-line-end junction is a crossing of two lines. In the brain so-called crossing cells are found that respond to crossings only [16,17]. An important question to be solved is why end-stopped and crossing type of cells are found. It is expected that in one of the subsequent layers a *junction* type of cell is found, i.e., grouping of end-stopped and crossing responses takes place there. The junction type of cell responses is most easily obtained by a combination of end-stopped and crossing type of cells. If junction type of cells are found in one of the former layers, in the feed forward data stream, then it is likely that end-stopped and crossing type of cells play a different role in subsequent layers.

Utilizing the building block principle to subsequent groups of cells in a feed forward manner will at a certain moment lead to groups of cells that respond to highly specific features. It is clear from functional point of view that these cells, at a certain stage in the feed forward stream, will be fused to object like entities. For example, in the inferior temporal cortex cells have been found that strongly responding to face like stimuli [8].

4 Early vision simulation

Simulations of functional behavior of complex, endstopped, and grating cells give clear hints of the existence of other types of cells. Figure 3a illustrates an early vision simulation of complex, endstopped, and grating cells. The parameter settings that are used for the complex and endstopped cells have size $\sigma = 3.5$, wavelength $\lambda = 1$, spatial aspect ration $\gamma = 1$, and number of orientations $N = 8$. For mathematical details of the complex and endstopped cells we refer to [11,21]. For the grating cells the following parameters are used: $\sigma = 3.5$, $\lambda = 1$, $\gamma = 0.25$, and $N = 8$. Functional description and detailed properties can be found in [12].

Figure 3b is a synthetic stimulus that is created with the purpose to illustrate the need of strong interaction between different groups of cells. A grating pattern is used to partly mask a rectangle, but the setting is made such that a conflicting situation is created, i.e, until where the left vertical line belongs to the rectangle. The lines of the upper right corner of the rectangle are extended with the purpose to illustrate the behavior of endstopped cells. An early vision simulation (Figure 3a) using the input image of Figure 3b yield the results illustrated in Figure 4.

Complex cells respond to lines and edges of a specific orientation. In Figure 4a the results of a superposition of all N orientations of complex cells is illustrated. Since a grating pattern is made up of a set of alternating stripes, complex cells respond vigorously. From functional aspect such type of response is not desired because of its redundant character. It would be far more attractive to only have the boundaries of the grating pattern and to mark the interior as grating texture.

The fact that grating cells make up around 4 and 1.6 percent of the number of cells in monkey areas V1 and V2 [20], respectively, indicate that these cells

[4] A *junction* is a spatial coordinate where one or more lines or edges end.

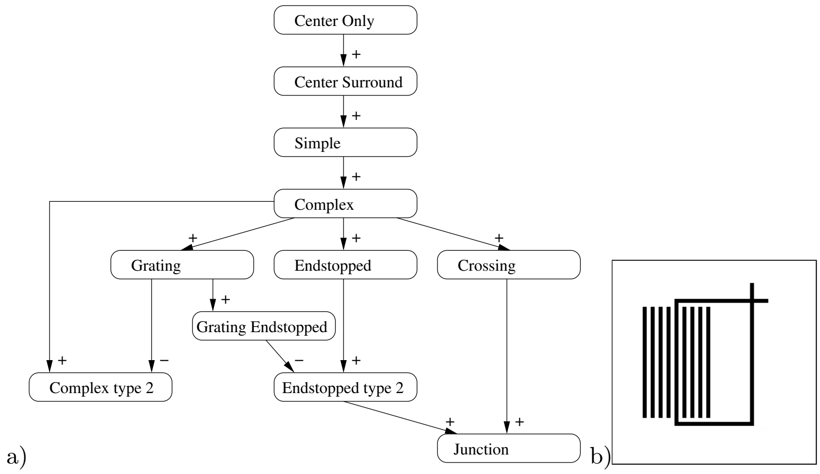

Figure 3. a) Early vision feedforward data processing network. The network includes simple, complex, endstopped, and grating cell responses. Complex type 2 cells respond strongly to edges and lines of a preferred orientation, while proposed junction cells respond strongly to all types of junctions. b) A synthetic input stimulus.

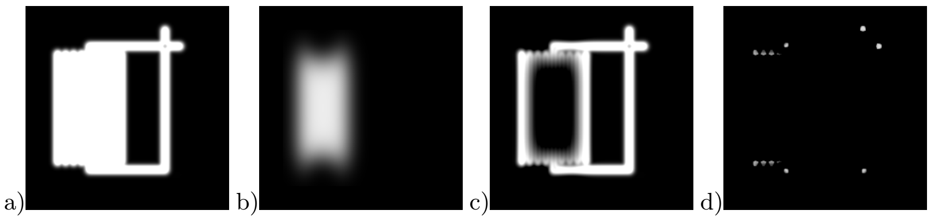

Figure 4. Responses of complex cells, grating cells, complex cells inhibited by grating cells, and endstopped cells, a-d, respectively. White denotes strong response, black no response.

play a prominent role in form segregation. Grating cells are highly orientation and frequency sensitive [19,20] which makes them most likely to be an inhibition mechanism for the complex cell responses rather than a texture processing mechanism [12]. Figure 4c illustrates the results of this inhibition mechanism. It is remarkable that the model for grating cells shows a slight drop in response at positions where the vertical line of the rectangle is masked by the grating pattern.

Endstopped cells respond to line ends, corners, and junctions, but not to crossings [4]. The model for endstopped cells shows that this is the case (Figure 4d). However, from functional perspective it is desirable to have all junction type of responses, as proposed in the feedforward data processing network of Figure 3a. Crossing type or double orientation tuning type of cells have been found in the cat striate cortex [16,17].

Endstopped responses also occur at the ends of the stripes in the grating pattern, this is a non-desired effect to endstopped responses. Endstopped type of grating cells have been found as well in monkey areas V1 and V2 [20]. It is likely that endstopped cells are inhibited by grating-endstopped type of cells, resulting in type 2 endstopped cells, and have excitatory connections with crossing type of cells to yield responses to all types of junctions, which is illustrated in Figure 3a as so-called junction type of cells.

5 Discussion

We proposed to process sensory and cognitive data by FBM. The aim of FBM is not to make a model of the brain on microscopic level, but merely to model, on macroscopic level, the functionality of a group of cells or even a complete area that have equivalent or similar functional behavior, and give the interaction between groups with different functional characteristics. From functional perspective the brain can be crudely divided into two types of data streams: a feed forward (sensory) data stream and a bi-directional (cognitive) data stream.

The disadvantage of FBM is its relatively static nature due to functional description and the assumption of data flow directions. The development and learning capacities are not as flexible as in the brain. Most of the primary sensory areas deal mainly with feature enhancement, extraction, and grouping. It is therefore not expected that primary areas need to adapt quickly or strongly. Hence, its sensory processing apparatus is doing similar work from functional perspective. Experiments performed by Hubel and Wiesel [6] give evidence that cat's primary visual sensory area is developed during the first weeks after birth, but at a later stage it hardly develops.

An early vision simulation utilizing FBM showed that resulting cell responses give strong insight in interaction between different groups of neuronal cells and one can predict the functionality of adjacent groups of neuronal cells.

References

1. D. G. Amaral and J. L. Price. Amygdalo-cortical projections in the monkey. *J. Comp. Neurol.*, 230:465–496, 1984.
2. S. T. Carmichale and J. L. Price. Limbic connections of the orbital and medial prefrontal cortex in macaque monkeys. *J. Comp. Neurol.*, 363:615–641, 1996.
3. J. P. Ewert, H. Buxbaum-Conradi, F. Dreisvogt, M. Glagow, C. Merkel-Harff, A. Röttingen, E. Schürg-Pfeiffer, and W. W. Schwippert. Neural modulation of visuomotor functions underlying prey-catching behaviour in anurans: perception, attention, motor performance, learning. *Comparative Biochemistry and Physiology*, A 128(3):417–461, 2001.
4. F. Heitger, L. Rosenthaler, R. von der Heydt, E. Peterhans, and O. Kübler. Simulation of neural contour mechanisms: from simple to end-stopped cells. *Vision Research*, 32(5):963–981, 1992.
5. D. Hubel and T. Wiesel. Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. *Journal of Physiology, London*, 160:106–154, 1962.

6. D. H. Hubel. *Eye, Brain, and Vision*. Scientific American Library, New York, 1988.
7. E. R. Kandel, J. H. Schwartz, and T. M. Jessell. *Principles of neural science*. Mc Graw Hill, fourth edition, 2000.
8. E. Kobatake and K. Tanaka. Neuronal selectivities to complex object features in the ventral visual pathway of macaque cerebral cortex. *Journal of Neurophysiology*, 70:856–867, 1994.
9. J. E. LeDoux. *Handbook of Physiology*, volume 5, part 1, chapter 1, Emotion, pages 419–459. American Physiological Society, 1987.
10. J. E. LeDoux. *The emotional brain: mysterious underpinnings of emotional life*. Simon & Schuster, New York, 1996.
11. T. Lourens. *A Biologically Plausible Model for Corner-based Object Recognition from Color Images*. Shaker Publishing B.V., Maastricht, The Netherlands, March 1998.
12. T. Lourens, H. G. Okuno, and H. Kitano. Detection of oriented repetitive alternating patterns in color images –a computational model of monkey grating cells. In J. Mira, editor, *Proceedings of the International Workshop on Artificial Neural Networks, IWANN 2001*, volume 1676, Part I of *Lecture Notes in Computer Science*, pages 95–107, Granada, Spain, June 2001. Springer-Verlag.
13. J. S. Morris, A. Ohman, and R. J. Dolan. A subcortical pathway to the right amygdala mediating "unseen" fear. *PNAS*, 96(4):1680–1685, 1999.
14. E. Peterhans. *Cerebral Cortex*, volume 12, chapter 8, Functional Organization of Area V2 in the Awake Monkey, pages 335–357. Plenum Press, New York, 1997.
15. A. Pitkänen, M. Pikkarainen, N. Nurminen, and A. Ylinen. Reciprocal connections between the amygdale and the hippocampal formation, perirhinal cortex, and postrhinal cortex in rat: a review. *Ann.s New York Academy of Sciences*, 911:369–391, 2000.
16. I. A. Shevelev, N. A. Lazareva, B. V. Novikova, A. S. Tikhomirov, and G. A. Sharaev. Double orientation tuning in the cat visual cortex units. *Neuroscience*, 61(4):965–973, 1994.
17. I. A. Shevelev, R. V. Novikova, N. A. Lazareva, A. S. Tikhomirov, and G. A. Sharaev. Sensitivity to cross-like figures in the cat striate neurons. *Neuroscience*, 69(1):51–57, 1995.
18. L. R. Squire, F. E. Bloom, S. K. McConnell, J. L. Roberts, N. C. Spitzer, and M. J. Zigmond, editors. *Fundamental Neuroscience*. Academic Press, second edition, 2002.
19. R. von der Heydt, E. Peterhans, and M. R. Dürsteler. Grating cells in monkey visual cortex: Coding texture? Visual Cortex. In B. Blum, editor, *Channels in the visual nervous system: neurophysiology, psychophysics and models*, pages 53–73, London, 1991. Freund Publishing House Ltd.
20. R. von der Heydt, E. Peterhans, and M. R. Dürsteler. Periodic-Pattern-selective Cells in Monkey Visual Cortex. *The Journal of Neuroscience*, 12(4):1416–1434, April 1992.
21. R. P. Würtz and T. Lourens. Corner detection in color images through a multiscale combination of end-stopped cortical cells. *Image and Vision Computing*, 18(6-7):531–541, April 2000.
22. M. P. Young, J. W. Scannell, G. Burns, and C. Blakemore. Analysis of connectivity: neural systems in the cerebral cortex. *Reviews in the Neurosciences*, 5:227–250, 1994.
23. S. Zeki. *A Vision of the Brain*. Blackwell science Ltd., London, 1993.