Neurocomputing 174 (2016) 822–837

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Detection of stimuli from multi-neuron activity: Empirical study and theoretical implications

Nir Nossenson [a,*], Ari Magal [b], Hagit Messer [c]

[a] Department of Neurology, Massachusetts General Hospital & Harvard Medical School, 50 Blossom St. Boston, MA 02114, USA
[b] Sagol School of Neuroscience, School of Psychological Sciences, Tel Aviv University, Tel Aviv 69978, Israel
[c] School of Electrical Engineering, Tel Aviv University, Tel Aviv 69978, Israel

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form
17 September 2015
Accepted 1 October 2015
Communicated by A. Belatreche
Available online 13 October 2015

Keywords:
Stimulus detection
Gaussian signal in Gaussian noise
Electrophysiology
Multi unit activity
Decision making
Glutamate uptake rate

ABSTRACT

We report on detection results obtained in 20 experiments in which the presence of an external auditory stimulus had to be detected from observing electrophysiological multi-unit activity in the brain stem of rats. The performance of the optimal Gaussian-signal-in-Gaussian-noise (model-based) detector is compared to that of the energy detector which is widely used in electrophysiology as well as in many other disciplines with similar signal characteristics. It is shown that the optimal model based detector is indeed superior, but the performance gap in favor of the optimal detector is substantial mainly in very low probabilities of false alarm errors. The performance of the energy detector is close to optimum in moderate and high probabilities of false alarm error. Furthermore, the energy detector is shown to be more resilient to isolated and short, yet intense disturbances. We discuss a conjecture inspired by the model underlying the optimal detector and the empirical results, that the neural tissue itself executes a modified energy detection scheme, and we review experimental results from the literature that allegedly support this conjecture.

1. Introduction

Artificial detection of an external stimulus from observing the activity of neurons is of major interest in biomedical engineering and brain research because the nervous system itself executes stimulus detection tasks using neural signaling. According to its modern definition, detection is a procedure in which a single output is *selected* out of a *finite number of distinct choices* by using the data at hand alone (see e.g. [19]). The same definition also holds for several procedures attributed to the nervous system such as perception [54,56], decision making [19,54], pattern recognition [60] and more (e.g. hypothesis testing [19], classification [60]). The focus of this paper is given to the *binary* stimulus detection problem (selecting between two possible distinct choices) since it is a common problem by itself, and because binary detection can be used as a recurring building block for solving detection problems having a larger set of possible responses. In rehabilitation engineering, artificial stimulus detectors are needed in cases where the nervous system severely fails in selecting or executing the appropriate physical action or logical conclusion in response to the stimulus. For example, in some disorders, a weak or no stimulus results-in an exaggerated full-power response, whereas in other disorders, the stimulus does not lead to any response even when it is needed. An artificial stimulus detector that monitors neural signaling (but not the stimulus itself) is useful in cases where the response to the stimulus is normal up to a certain point in the neural path, but abnormal from that point on. In typical biomedical applications, the output of such a binary detector would be used for enabling (switching-on) a prosthetic device that bypasses the proceeding non-responsive neural segment, or for disabling (e.g. switching-off pharmacologically) an overly responsive segment. Other than biomedical applications, the question of event detection using neural activity has also broader interest to control engineers since in many daily life tasks, the nervous system still outperforms man made detectors in selecting (switching on) the appropriate response to a flow of incoming events, and it does so by using neural signaling. Thus, automatic artificial detection of stimulus presence through observation of neuron activity is a special intersection of control engineering and brain research, and is the main concern of this work.

The techniques for measuring neural activity are diverse, each reflecting different aspects of the processes occurring in the neural tissue. In this work we rely predominantly on our own electrophysiological multi-unit recordings from the pontine nucleus and the

---

[*] Corresponding author.
E-mail addresses: nnossenson@mgh.harvard.edu (N. Nossenson), poochoor@gmail.com (A. Magal), messer@eng.tau.ac.il (H. Messer).

http://dx.doi.org/10.1016/j.neucom.2015.10.007
0925-2312/© 2015 Elsevier B.V. All rights reserved.

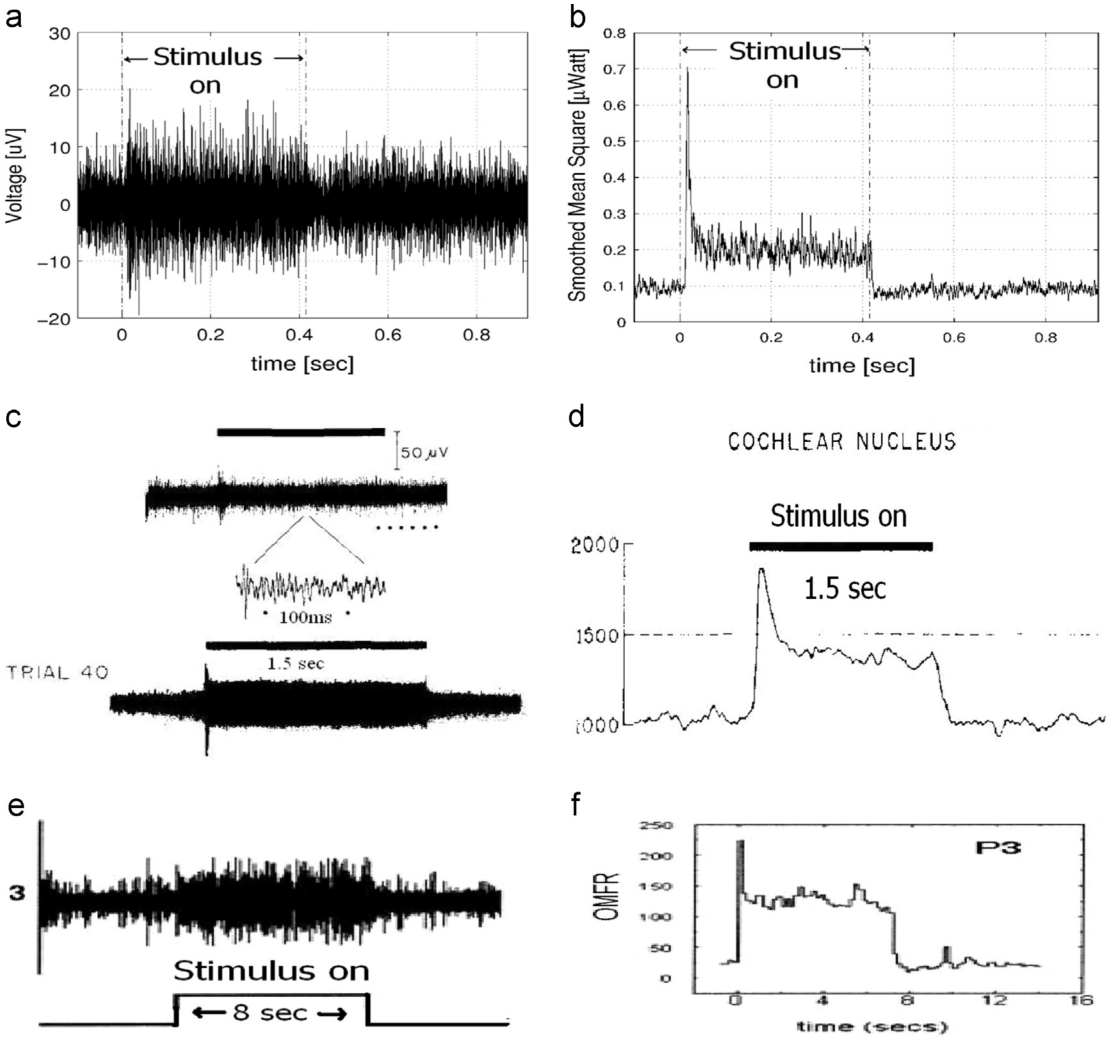

Fig. 1. Multi-unit response to a stimulus pulse. Left column shows examples of raw data of multi-unit activity in response to stimulus, and the right column is the corresponding multi-unit peristimulus histogram (PSTH): (a and b) Inferior colliculus response to auditory stimulus which was measured in our experiments. (c and d) Cochlear nucleus response to auditory stimulus as reported by Holstein et al. [23,24]. (e and f) Anterior parietal cortex response to somatosensory stimulus (vibrations), as reported by Tommerdahl et al. [58].

inferior colliculus of rats and also on similar reports by other researchers who recorded multi-unit activity in different locations (e.g. [23,24,45,58], see examples in Fig. 1). In multi-unit recordings, the electrode captures the activity of many cells as it is situated inside the tissue but outside the cells (extra-cellular recording). In our multi-unit recordings, as well as in the other recordings mentioned above, the electrode was located in a region that is *populated by many neurons that respond to the stimulus of interest*, and it captured the electrical activity of many stimulus responsive cells rather than the possibly unrelated activity of a single cell. Other than the activity of the stimulus responsive neurons, the electrode also captures the electrical activity of many more active cells in the background. It is empirically established though that this background activity is greatly reduced by high pass filtering above 300 Hz. The resulting filtered signal is often referred to as "multi-unit activity" (MUA) and consists of noisy fluctuations, that are somewhat more intense during the stimulus. Examples for a raw multi unit activity in response to various modalities of stimuli having a rectangular intensity are given in the left column of Fig. 1. Interestingly enough, the averaged intensity profile of multi-unit-activity in response to stimulus with a rectangular intensity has a consistent general form which was revealed in our tests as well as in research reports of others. As shown in the right column of Fig. 1, the intensity profiles exhibit a sharp magnitude rise on stimulus start, and as the stimulus continues the response decays exponentially until it settles to a new steady state value which is higher than the level in the absence of a stimulus but lower than the response following stimulus rising edge.

The common practical method for identifying responses to stimuli from multi-unit activity in densely populated regions is the "energy detection" method originally proposed in this context by Weber and Buchwald [64]. In this method, the signal is squared, integrated and finally thresholded to yield a clear cut decision. The method proposed by Weber and Buchwald is essentially heuristic and as such it does not guaranty optimality. Nevertheless, this method is supported by years of experience in neuroscience (see e.g. [1,3]) and in other fields such as radar [36], communications [13,59], quality control and seismology [4]. It is possible though, that further testing of an endless number of other detection schemes using a trial and error approach would yield a better detection scheme.

A different engineering approach for constructing a detection scheme is first to assume a probabilistic model which connects between the event to be detected (auditory stimulus in our case) and the observations (electrode voltage in our case), and then analytically derive a detection rule which minimizes the risk of an error. A particularly important class of probabilistic models that