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Nonlinear analysis of saccade speed fluctuations during combined action and perception tasks

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HIGHLIGHTS

- Saccadic peak speed fluctuations are multifractal.
- Saccade multifractality strength differs in simple decision and dual decision task.
- Similar results for Lempel–Ziv analysis show different complexity measures.
- Multifractal parameter proposed for action–perception interaction in visual process.

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ABSTRACT

Background: Saccades are rapid eye movements used to gather information about a scene which requires both action and perception. These are usually studied separately, so that how perception influences action is not well understood. In a dual task, where the subject looks at a target and reports a decision, subtle changes in the saccades might be caused by action–perception interactions. Studying saccades might provide insight into how brain pathways for action and for perception interact.
New method: We applied two complementary methods, multifractal detrended fluctuation analysis and Lempel–Ziv complexity index to eye peak speed recorded in two experiments, a pure action task and a combined action–perception task.
Results: Multifractality strength is significantly different in the two experiments, showing smaller values for dual decision task saccades compared to simple-task saccades. The normalized Lempel–Ziv complexity index behaves similarly i.e. is significantly smaller in the decision saccade task than in the simple task.
Comparison with existing methods: Compared to the usual statistical and linear approaches, these analyses emphasize the character of the dynamics involved in the fluctuations and offer a sensitive tool for quantitative evaluation of the multifractal features and of the complexity measure in the saccades peak speeds when different brain circuits are involved.
Conclusion: Our results prove that the peak speed fluctuations have multifractal characteristics with lower magnitude for the multifractality strength and for the complexity index when two neural pathways are simultaneously activated, demonstrating the nonlinear interaction in the brain pathways for action and perception.

1. Introduction

Saccades are rapid eye movements initiated by activation of neurons widely distributed across the cerebrum, the cerebellum, and the brain stem. Study of saccades is popular since they can intermediate ways of studying motor control, cognition and memory. From saccade analysis it has been possible to identify distinct populations of neurons from brainstem to cerebral cortex that

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contribute to behaviors ranging from reflexive glances to memorized sequences of saccades during learned tasks (Leigh and Kennard, 2004). Saccade investigations are used both by neurologists and neuroscientists in order to develop models and schemes of circuit equivalence of different regions of the brain associated with specific behaviors (Wong and Shelhamer, 2013; Daye et al., 2013).

Gathering information about a scene requires both action and perception. However, in most experiments these are usually studied separately, so that how perception influences action is not well understood. In a dual task, where the subject looks at a target and reports a decision, subtle changes in the saccades might be caused by action/perception interactions.

New evidence of multiplicative interactions in cognitive performance suggests that cognitive processes at different scales of time and space are interdependent and interaction-dominant (Zheng et al., 2005; Ihlen and Vereijken, 2010; Kelty-Stephen and Mirman, 2013). In this context, recent development of nonlinear methods such as multifractal analysis or Lempel–Ziv complexity index can give new framework for analyzing and understanding the complex dynamics of different neuronal pathways involved in perception and action and also in the perception–action coupling. The neural circuits are regulated by complex dynamics that incorporate memory of past events, and the strength of this memory can be estimated by the Hurst exponent. Moreover, the degree of randomness in the dynamics of perception–action coupling is properly described by the algorithmic complexity function expressed by Lempel–Ziv metric.

Fractal and multifractal analysis has been extensively used in studies of the fluctuations in biological phenomena (Stan et al., 2013), neuroscience (Zheng et al., 2005), linguistic analysis (Ausloos, 2012; Suckling et al., 2008), EEG pattern (Wang et al., 2003; Dutta et al., 2014; Kumar et al., 2013), eye movement (Shelhamer, 2005; Ihlen and Vereijken, 2010; Schmeisser et al., 2001; Kelty-Stephen and Nixon, 2013; Astefanoaei et al., 2013).

Various implementations of the method use multifractal detrended fluctuation analysis (MF-DFA) (Kantelhardt et al., 2002), continuous wavelet transform modulus maxima (Muzy et al., 1993), structure function and singular measures formalisms (Yu et al., 2003; Tessier et al., 1996). Multifractal analysis by the MF-DFA method of neural activity was used by some authors (Kumar et al., 2013), who reported that optogenetically stimulated neural firings are consistent with a multifractal process. This computational procedure has shown that the generalized Hurst exponent exhibited dramatic changes that could differentiate neural activities during control phases and phases with chemically induced pain. According to other authors (Dojnow and Vitanov, 2008), numerical analysis with the Hurst generalized exponent of relatively short EEC data series revealed multifractal features in underlying processes; the authors claimed to develop a putative computational tool in the investigation of brain subsystems based on the neural activity mapping during cognitive task performance.

Multifractal characteristics in measured eye-tracking fluctuations were reported (Coey et al., 2012) with a focus on the influence of the eye-tracking instrument on the structure of measured signal variability. Their results provided evidence that the fractal structure in the variability of eye-movement data is not an artifact of the data recording device but an intrinsic behavioral trend in the subjects. It seems that whenever a subject executes saccades between fixation point and target, there are variations in eye position. Such trial-to-trial variation has usually been treated as purely experimental noise and cancelled out by averaging and smoothing over trials. Therefore fluctuations detected either in the eye movement (Coey et al., 2012) or fixation (Kelty-Stephen and Mirman, 2013) are still poorly explained.

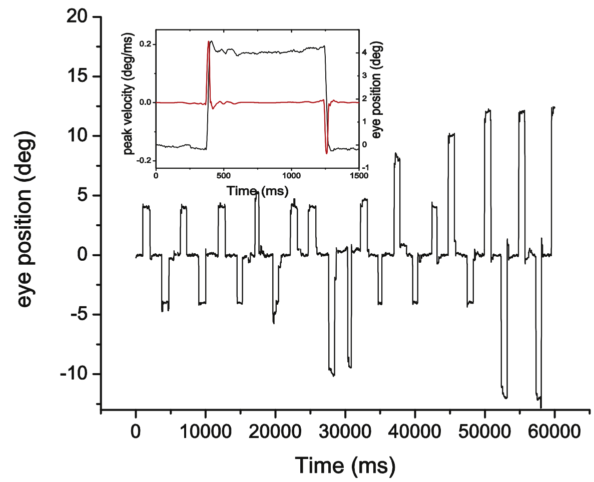

Fig. 1. Representation of eye saccadic response displayed for 60 s recording. Inset is an illustration of peak velocity computation.

The complexity of discrete-time signals of biomedical interest has also been investigated using the Lempel–Ziv analysis (Lempel and Ziv, 1976), proposed for the evaluation of the randomness in finite sequences of data as an extension of the algorithmic complexity function (Kolmogorov, 1965; Chaitin, 1966). The L–Z measure of complexity is related to the number of distinct substrings (i.e. patterns) and the rate of their occurrence along a given data sequence (Aboy et al., 2006). This measure has been used in biomedical research, such as in genomic sequence investigations for revealing patterns in DNA structure, in estimation of neural firing entropy and for describing neuronal responses induced in the visual cortex by different types of stimulation (Stan et al., 2013; Szczepaski et al., 2003; Amigo et al., 2004). The advantages of this method over correlation entropy from chaos theory were discussed by Hu et al. (2006), who studied the possibility of epileptic seizure detection from EEG data.

In the present study, we focus on the application of two complementary methods, multifractal analysis and the L–Z complexity to the identification of the nonlinear characteristics of saccadic visual exploration, by analyzing fluctuations in the peak speed eye movement during a simple action task and a dual action–perception task.

2. Methods

2.1. Data recording

Saccadic eye movements (Fig. 1) were recorded with a video-based eye tracker (iViewX Hi Speed, SMI) consisting in temporal series of angular shift values. Subjects' right eye movements were recorded at a sample rate of 1000 Hz. Only horizontal eye movements were analyzed. The subjects were nine healthy, adult volunteers who took part in an experimental research developed in the Laboratory of Sensorimotor Research, at National Eye Institute (NEI), National Institutes of Health (NIH), USA. The experiments conformed to the human subjects guidelines of the NIH for human subject research, and with the Declaration of Helsinki, were approved by the NEI institutional review board, and the subjects provided written, informed consent. Drug and alcohol influence was excluded in all subjects. Neuro-ophthalmological examination was carried out before the experimental saccadic study and no clinical, neurological pathologies nor visual impairment was found, except very mild refractive error in some cases (during the experiment the subjects worked without glasses). Visual stimuli were two