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Multifractality and non-Gaussianity of eye fixation duration time series in reading Persian texts

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HIGHLIGHTS

- Evidence shows human behavior to be fractal and multifractal.
- We study the fractality of eye movements while reading Persian text.
- Fixation durations are multifractal regardless of reading goal or text familiarity.
- Multifractality appears to be intrinsic to human behavioral dynamics.

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ABSTRACT

There is growing evidence that cognitive processes may have fractal structures as a signature of complexity. It is an ongoing topic of research to study the class of complexity, and how it may differ as a function of cognitive variables. Herein, we explore the eye movement trajectories generated during reading different Persian texts. Features of eye movement trajectories were recorded during reading Persian texts using an eye tracker device. We show that fixation durations, as the main components of eye movements reflecting cognitive processing exhibits multifractal behavior. This indicates that multiple exponents are needed to capture the neural and cognitive processes involved in decoding symbols to derive meaning. We test whether multifractal behavior varies as a function of two different stimuli including fonts, and familiarity of the text for readers during four different reading procedures concerning silent and aloud reading and goal-oriented versus non-goal-oriented reading. We find that, while mean fixation duration is affected by some of these factors, the multifractal pattern in time series of eye fixation durations did not change significantly. Our results suggest that multifractal dynamics may be intrinsic to the reading processes, and the lognormal distribution properly describes the statistics of the fixation duration time series for all the stimuli in our reading experiments.

1. Introduction

Reading task is a process of integrative information processing; from attention to word identification and to comprehension. This process establishes a connection between eye movements, and attention to the written text, to acquire new

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information [1]. The perceptual process of reading is reflected in reaction times or eye movements, and a cognitive outcome is text comprehension [2]. Therefore, studying eye movement characteristics is helpful in understanding the underlying dynamics that involves during the reading task.

The vast majority of research on reading have focused on classical techniques and behavioral tests including reaction times or speed, and for cognitive outcomes such as text comprehension across different alphabetic and logographic systems, such as English, Chinese, Arabic, Japanese, French or German [2,3]. Studies using nonlinear analysis to capture information from eye movements during reading are rare, and most studies focus on reading a single word or a single sentence that their findings are not readily applicable to reading of naturalistic, connected texts [1,4]. Therefore, an alternative can be studying connected text reading as a coordinative problem that explores how reader idiosyncrasies and cognitive components coordinate with each other to yield an observed level of performance [1].

However, reading involves intrinsic and extrinsic factors. Extrinsic factors include textual and typographical variables such as font complexity and difficulty of the text, while intrinsic factors are general across stimulus and the context originating from processes and structures that change only on longer timescales of reading skills, learning, and development. Therefore, typographical features such as font and text difficulty can manipulate the cognitive dynamics involved during reading. Also, two observable behaviors of the underlying control mechanism are fixation duration and saccade length. Fixation duration is an eye movement characteristic that indicates the periods of the times that eyes remain still during reading a text, and reflect the cognitive processing during a visual task [2], and saccade length refer to the distance between two quick eye movements in the same direction. Studies show that familiarity with the text determines both fixation duration and saccade size [5].

Moreover, eye movements during reading are generated by complex self-regulating systems that process inputs from different regions of the brain that mainly involves cognitive and visual processing [6]. In addition, like many natural signals such as heart rate [7], and response times [4], eye movements are extremely heterogeneous and non-stationary; two properties that may arise from complex underlying dynamics of the task. The complexity of reading may be expressed in terms of fractal patterns generated by eye movement characteristics such as fixation duration. Cognitive tasks like visual search [8], scene perception [9], and visual foraging [6] have revealed evidence for heavy-tailed distributions [6,10], and it was shown that spatial clustering of eye movements follow a power law distribution [11], saccade length distributions are log-normally distributed, and the speeds of slow, small amplitude movements occurring during fixations follow a $1/f$, spectral power law relation [11,12]; suggesting a fractal pattern for eye fixation duration dynamics during a reading task.

In [13], Feng introduced a stochastic model of eye movement control during reading task to illustrate the statistical regularities in the data; considering the inherently probabilistic feature of eye movements. The model is called SHARE framework; standings for Stochastic, Hierarchical Architecture for Reading Eye-movements, which suggests a 3-component Lognormal mixture model fit to the marginal distribution function of fixation durations. Wallot et al., [14] studied self-paced reading data to predict the text comprehension during connected text reading; assuming that distributions can be captured by a single scaling exponent. Furthermore, in a remarkable study that investigates the connected text reading performance in adults [4] – using both mono-fractal and multifractal analysis, response times were collected and analyzed from participants pressing the space bar on a standard computer keyboard in order to move to the next page of the text – it became clear that classical metrics do not capture text reading very well. Referring to the folk expression that ‘‘the eyes are the windows to the soul" Van Orden et al., [15] employed fractal and multifractal methods to find whether eye-movements detected by an eye-tracker generates intrinsic random variation and how features of the data recording procedure affected the structure measurement variability. Their results revealed that the structure of variation from a fake eye was random and uncorrelated in contrast to the fractal structure from a fixated real human eye. In a classical study, Rumelhart et al., [16] argued that perception required the simultaneous use of multiple sources of information, allowing perceivers to optimally interpret sensory information at many levels of representation in real time as information arrives. Building on Rumelhart’s arguments, McClelland et al., [17] present the Interactive Activation hypothesis-the idea that the mechanism used in perception and comprehension to achieve these feats exploits an interactive activation process implemented through the bidirectional propagation of activation among simple processing units. They also show interactive processing is a characteristic of the perceptual processing machinery in the brain.

Regarding reading strategies such as aloud reading, in an fMRI study [18], it was shown that reading aloud engages multiple brain regions during reading – such as left supramarginal, posterior middle temporal, and fusiform gyri, besides semantic processing, including left middle temporal gyrus/inferior-temporal sulcus, bilateral angular gyrus, and precuneus/posterior cingulate – which implies multiplicity of the reading tasks. In [19], authors explored to determine the accurate conditions that reading comprehension should be evaluated. Using maze assessment probe, a significant difference in comprehension under silent and aloud reading condition was found. However, to the best of our knowledge, no study has reported the fractal analysis of eye movements during different reading strategies such as aloud or silent, and goal-oriented vs. non-goal oriented reading.

Herein, we focus on analysis of fixation duration time series to discover the information regarding the cognitive coordination from fractal scaling in the series. Due to the heterogeneity of the eye movements during reading, this cognitive task relies on independent cognitive components and their interactions across multiple scales of behavior [17]. Evidence of interactions across scales in cognitive systems by examining perceptual–motor fluctuations is discussed in [20–23].

Furthermore, we presumed that there are significant differences between characteristics of eye movements during reading different languages, and generalization from one language to the others may not be applicable. Persian texts are