Extreme reaction times determine fluctuation scaling in human color vision

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H I G H L I G H T S

- Extreme reaction times obey a U-shaped pattern in the skewness–kurtosis plane.
- Fluctuation scaling describes the experimental data quite well.
- The scaling exponent depends on the cardinal directions in the color space.
- Very large reaction times are associated with dragon-kings events.

A R T I C L E   I N F O

A B S T R A C T

In modern mental chronometry, human reaction time defines the time elapsed from stimulus presentation until a response occurs and represents a reference paradigm for investigating stochastic latency mechanisms in color vision. Here we examine the statistical properties of extreme reaction times and whether they support fluctuation scaling in the skewness–kurtosis plane. Reaction times were measured for visual stimuli across the cardinal directions of the color space. For all subjects, the results show that very large reaction times deviate from the right tail of reaction time distributions suggesting the existence of dragon-kings events. The results also indicate that extreme reaction times are correlated and shape fluctuation scaling over a wide range of stimulus conditions. The scaling exponent was higher for achromatic than isoluminant stimuli, suggesting distinct generative mechanisms. Our findings open a new perspective for studying failure modes in sensory–motor communications and in complex networks.

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1. Introduction

Extreme events occurring in time series have attracted the attention of scientists because of their great impact in many complex systems. Extreme events seldom appear and their properties are difficult to predict. Examples of extreme events include natural disasters and catastrophes in a variety of fields such as financial crises and epidemics. Other examples of extreme events include wave phenomena such as "rogue" or "freak" waves in ocean surfaces and optical fibers [1]. In human visual reaction/response times (RT) [2–4], at least two major types of extreme events are usually discarded in data analysis: false alarms and misses [2,3,5,6]. False alarms are very short RTs indicating fast guesses or anticipatory responses before stimulus presentation. They are rejected below a lower cutoff in the left tail of RT distributions. Misses are very large RTs in which spontaneous eye blinks, fatigue, inattention, etc. can be important factors. They are rejected above an upper cutoff in the right tail of RT distributions. Although RT distributions have been extensively studied [2,3,5,6], the functional role

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of extreme RTs is still an open issue. In general, extreme RTs are treated as independent response errors and are assumed uncorrelated across stimulus conditions and unpredictable. However, extreme RTs affect eye-brain-motor coordination and modify the shape and moments of RT distributions [5,6] and therefore they affect human performance in everyday tasks.

In the present study, we address the question whether extreme RTs can be associated with large-scale failure modes of stochastic latency mechanisms and reflect non-trivial correlations within the visual-motor system at supra-threshold conditions. We focus on the statistical properties of extreme RTs by examining an important relation that appears between higher-order central moments in many physical systems, namely, between the sample skewness γ_1 and the sample kurtosis γ_2 of a probability density distribution (pdf) [2,7]. The skewness and the kurtosis are sensitive to the presence of very short and very large events in RT distributions [2,3,5,6]. Understanding the statistical properties of extreme RTs is of great importance for better elucidating the propagation of temporal instabilities in brain networks at a macroscopic scale, for modelling RT pdfs, and for better controlling visual RTs in an optimal way (e.g., sport performance, air and land navigation, etc.), as well as in other sensory modalities, etc.

By representing the sample skewness as a function of the sample kurtosis or the (γ_1, γ_2)-plane, a large body of experimental time series has followed a U-shaped pattern with two different regimes [8–11]. The first regime is characterized by low and moderate γ_1 and γ_2 values and can be described by a parabolic function. This parabolic function is an appropriate framework to evaluate the non-Gaussian structure of pdfs. Examples can be found in plasma physics, atmospheric science, etc. [8–11]. However, in the second regime extreme events can produce very large γ_1 and γ_2 values above the parabolic region. These large γ_1 and γ_2 values are better described by a power function with a scaling exponent, $\alpha = 4/3$. Examples of extreme events in the (γ_1, γ_2)-plane can be found in earthquake, financial data, etc. [11,12]. For a class of multiplicative growth processes [13], the power function in the (γ_1, γ_2)-plane represents a generalized version of fluctuation scaling observed in many different complex systems (also known as "Taylor's law" in ecology) [13–15]. The scaling exponent $\alpha = 4/3$ represents an asymptotic limit that is independent of a particular multiplicative generative process. However, multiplicative processes with a scaling exponent α different from 4/3 could implicate a signal-dependent mechanism that is modulated by temporal transitions in the external environment [13,14]. The main goal is to investigate the effects of RT false alarms and misses in the (γ_1, γ_2)-plane and whether temporal fluctuation scaling (i.e., the statistical properties are calculated over time) [15] holds for a wide range of stimulus conditions.

2. Experimental methods and procedure

2.1. Visual stimuli

We have performed a re-analysis of an extensive RT database for manual responses in color vision. Details have been reported elsewhere [16–21]. Visual stimuli were presented in a color calibrated display and were selected from the cardinal directions in the human color space. This affords us the possibility to examine whether extreme RTs are mediated by specialized subcortical mechanisms in the retina and lateral geniculate nucleus [22,23]. In current color vision models, L (long-), M (middle-) and S (short-) wavelength-sensitive cone photoreceptor signals are re-organized into three postreceptoral mechanisms or orthogonal cone axes [22,23]: a luminance axis (L + M); and two chromatic-opponent cone axis at a constant luminance level or isoluminance: a red–green (L − M) axis and a blue–yellow axis [S − (L + M)] as illustrated in Fig. 1(a). The chromaticity coordinates of representative red–green and blue–yellow stimuli used in the RT experiments are shown in the MacLeod–Boynton cone excitation diagram in Fig. 1(b) [24]. The same stimuli in Fig. 1(b) are also represented in the CIE-1931 (Commission Internationale de l'Éclairage) chromaticity diagram in Fig. 1(c) [25]. All stimuli were uniform circular patches as shown in Fig. 1(d).

2.2. Procedure

Isoluminant conditions were established by using heterochromatic flicker photometry. RTs at isoluminance were measured by using the hue-substitution method [16–21]. In all experimental conditions, subjects were allowed 3 min to adapt to darkness and 3 additional minutes to adapt to the reference stimulus. After a random delay (3–7 s, uniform sampling distribution), the reference stimulus was changed to the test stimulus. This remained on the screen until the subject responded by pressing the button on the mouse connected to a computer. Subjects did not know which stimulus was the next in the sequence and their task consisted only of responding as soon as possible. The computer clock timer was programmed to provide 1 ms accuracy [16–21]. RTs were measured separately for achromatic stimuli (L + M axis), for red–green (L − M axis) and blue–yellow [S − (L + M) axis] stimuli and for random chromatic stimuli containing a mixture of red–green and blue–yellow variations in the isoluminant plane as shown in Fig. 1(a). Stimuli were presented at fovea, in both binocular and monocular vision and by using natural and artificial pupils. Stimuli vary over a wide range of sizes as shown in Fig. 1(d), contrast values, and reference adapting levels as shown in Fig. 1(b), (c). 5 different subjects with normal color vision and visual acuity performed the RT experiments. Human RT experiments were in accordance with the Declaration of Helsinki. The total number of RTs was well over 135,000 and they were grouped in 1617 stimulus conditions [16–21].