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Fractal scaling in bottlenose dolphin (*Tursiops truncatus*) echolocation: A case study

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HIGHLIGHTS

- We investigate fractal scaling behavior in two aspects of dolphin echolocation.
- We employ two widely used fractal analysis methods and compare their results.
- Results indicate persistent fractal scaling in both echolocation measures.
- Possible explanations for observed between-subject differences are discussed.

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ABSTRACT

Fractal scaling patterns, which entail a power-law relationship between magnitude of fluctuations in a variable and the scale at which the variable is measured, have been found in many aspects of human behavior. These findings have led to advances in behavioral models (e.g. providing empirical support for cascade-driven theories of cognition) and have had practical medical applications (e.g. providing new methods for early diagnosis of medical conditions). In the present paper, fractal analysis is used to investigate whether similar fractal scaling patterns exist in inter-click interval and peak–peak amplitude measurements of bottlenose dolphin click trains. Several echolocation recordings taken from two male bottlenose dolphins were analyzed using Detrended Fluctuation Analysis and Higuchi's (1988) method for determination of fractal dimension. Both animals were found to exhibit fractal scaling patterns near what is consistent with persistent long range correlations. These findings suggest that recent advances in human cognition and medicine may have important parallel applications to echolocation as well.

1. Introduction

Research on bottlenose dolphin echolocation has focused primarily on the physical properties of echolocation clicks such as frequency distribution, bandwidth, amplitude, beam width, directionality, and inter-click interval (ICI) [1–7]. While this approach has led to a greater understanding of many aspects of echolocation, collapsing click trains to average values overlooks the organization and structure of the click train as a whole. Because perception is a continuous process requiring

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organisms to interpret and react to new information about their environment in real time, it cannot be assumed that an animal's awareness of its surroundings and perceptual strategies remain constant throughout the periods in which we observe them. Continuous perceptual feedback, occurring over multiple time scales, likely results in changes in the click train as it is being produced, making echolocation a dynamic process [8]. The temporal structure of click trains, and the way in which that structure evolves, must be taken into account if we are to better understand the dynamics of echolocation.

Although echolocation is a product of internal cognitive processes, it is simultaneously a reflection of the animal's external environment. The physical characteristics of click trains are influenced by interactions on scales ranging from microscopic (e.g., neural firing) to macroscopic (e.g., the animal's position in its habitat) [5,9,10]. In this sense, animal and environment form a single cohesive system from which the measurable properties of click trains emerge. We propose an approach that views echolocation as the emergent result of interactions unfolding within a dynamic, complex system. We first introduce an important class of methods known as fractal analysis and review previous research regarding fractality in biological systems. With this foundation in place, we apply fractal analytical methods to measures of dolphin echolocation and explore ways in which our findings might be applied to future cognitive, behavioral and veterinary research.

1.1. Fractal methods for describing fluctuations

A fractal is a pattern, either spatial or temporal, that exhibits self-similarity on all scales [11]. In the case of a fractal time series, fluctuations in values over long periods (e.g., hours or days) resemble fluctuations over smaller periods (e.g., minutes or seconds). This self-similarity between different scales is referred to as fractal scaling. In mathematically ideal fractals, fractal scaling is exact and extends across an infinite range of scales. In the real world however, fractal analysis must deal with noise in the environment and a finite range of scales due to limiting factors such as sampling rate and length of observation. As a result, empirical fractals are said to exhibit statistical (as opposed to exact) self-similarity [12]. Because this statistical self-similarity is not always readily apparent through qualitative inspection, it is typically described via the following quantitative relationship:

$$m_n = pn^{\alpha} \tag{1}$$

where m_n is some property measured at scale n, p is a factor of proportionality, and α is an exponent used to characterize the scaling properties of the data set [12]. Values of α near 0.5 indicate random uncorrelated noise, values closer to 1.0 suggest the presence of persistent fractal scaling, and values approaching 1.5 are indicative of uncorrelated non-stationary random-walk processes [13].

Spatial and temporal measures of biological systems have often been found to exhibit fractal scaling. Examples include stride interval in human gait [14], displacement of center-of-pressure during upright stance [15], human eye-movement [16–18], wielding behaviors underlying haptic perception [19,20], tree growth [21], vascular structure [22], albatross search patterns [23,24], marine predator foraging patterns [25], human heartbeat [13], human respiration [26], wolf search paths [27], mammalian social hierarchies [28], copepod movement patterns [29], and *Tursiops aduncus* dive durations [30]. The prevalence of fractal scaling in biological systems raises the question of what process or processes might be driving the formation of these complex patterns.

1.2. Fractal scaling as the product of underlying cascade processes

In cascade-driven processes, energy is dispersed and transmitted by interactions that unfold across multiple temporal and spatial scales [31–33]. A common example involves a sand pile that is formed by an experimenter dropping a single grain of sand at a time on the floor [31]. As the pile grows and ultimately becomes unstable, it reaches a critical state in which the addition of a one more grain will trigger an avalanche. Depending on the conditions, this avalanche may die out quickly or it may increase in size multiplicatively, triggering larger and larger avalanches as it rolls down the side of the pile. Either way, the sand quickly settles into a more stable configuration and the experimenter resumes dropping grains one at a time (which continues to drive further cascading avalanches). Both the magnitude of these avalanches, and the time interval between consecutive avalanches exhibit strong fractal scaling over time [31].

The sand pile model is limited in that it only accounts for interactions between two distinct time scales (the slow local addition of individual grains versus the fast global cascades of avalanche activity) when processes in the real world unfold at a nearly infinite range of spatiotemporal scales. However, it clearly illustrates an important characteristic of cascade processes that we will revisit later—they are composed of a large number of strongly interconnected components. Through physical contact with their neighbors, the behavior of individual grains of sand can potentially affect the behavior of every other grain in the pile. Conversely, the behavior of every grain in the pile can potentially affect the behavior of each individual piece of sand. This strong interconnectivity between components is crucial to the emergence of fractal patterns in the behavior of the system as a whole. If interconnectivity were to break down (e.g., if partitions were inserted to separate distinct regions of the sand pile) the transfer of energy would be halted and the fractal characteristics of the avalanches would diminish or disappear [31,34].

Although they were initially developed for purely mathematical and physical applications [35,11], cascade models offer a useful theoretical framework for explaining how the complex, flexible behaviors that are characteristic of living organisms