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Dynamic response and transfer function of social systems: A neuro-inspired model of collective human activity patterns

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HIGHLIGHTS

- We estimate the impulse response and transfer function of social systems.
- We model the relationship between social collective activity and time-varying influences.
- We show that human collective activity is analogous to the activity of a neuronal population.
- The model precisely reproduces online collective activity patterns.
- Human activity in various socio-economic contexts can be potentially predicted.

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ABSTRACT

The interaction of social networks with the external environment gives rise to non-stationary activity patterns reflecting the temporal structure and strength of exogenous influences that drive social dynamical processes far from an equilibrium state. Following a neuro-inspired approach, based on the dynamics of a passive neuronal membrane, and the firing rate dynamics of single neurons and neuronal populations, we build a state-of-the-art model of the collective social response to exogenous interventions. In this regard, we analyze online activity patterns with a view to determining the transfer function of social systems, that is, the dynamic relationship between external influences and the resulting activity. To this end, first we estimate the impulse response (Green's function) of collective activity, and then we show that the convolution of the impulse response with a time-varying external influence field accurately reproduces empirical activity patterns. To capture the dynamics of collective activity when the generating process is in a state of statistical equilibrium, we incorporate into the model a noisy input convolved with the impulse response function, thus precisely reproducing the fluctuations of stationary collective activity around a resting value. The outstanding goodness-of-fit of the model results to empirical observations, indicates that the model explains human activity patterns generated by time-dependent external influences in various socio-economic contexts. The proposed model can be used for inferring the temporal structure and strength of external influences, as well as the inertia of collective social activity. Furthermore, it can potentially predict social activity patterns.

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1. Introduction

Social networks constitute complex, high-dimensional, open systems generating dynamic activity patterns encoding the impact of exogenous forces that drive social systems far from an equilibrium state. Current affairs, emergencies, commercial promotion campaigns, business, economic, and political developments covered by mass media and news portals give rise to intense and time-dependent information streams whose temporal structure and strength are imprinted into the individuals' activity. Modeling the dynamic response of social systems to external perturbations is particularly important to explaining and predicting the evolution of human activity patterns in time-varying influence fields pertaining to diverse socio-economic contexts.

Using a mathematical model to describe a dynamical process is well established in physical systems, where observation and experimentation provide the information required for deriving the underlying physical laws. In recent years, the availability of data relevant to the individuals' activity in online social networks also enables the mechanistic description of partially observable, and less repeatable dynamical processes occurring on social systems. To derive a macroscopic mathematical description of human activity patterns, we analyze and model the transient and the steady-state behavior of collective activity in social media. While the

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transient behavior reveals the immediate population response to a perturbation, thereby permitting the estimation of the transfer function of a social system; the steady-state behavior reflects the dynamics of human activity patterns in a state of statistical equilibrium. Combining the dynamics of both activity modes in a single equation, we provide a state-of-the-art model capable of reproducing real, collective activity patterns with unprecedented accuracy, thus breaking new ground in the investigation of the dynamic response of social systems to various kinds of external interventions, such as socio-cultural, economic, political, and commercial. The proposed model rests on three theoretical pillars: (a) Neuroscience, and particularly the dynamics of passive neuronal membranes (Richardson, 2007; Rieke, 1999; Vogels, Rajan, & Abbott, 2005), as well as the dynamics of firing rate coding schemes (Abbott & van Vreeswijk, 1993; Fusi & Mattia, 1999; Gerstner, 2000; Gerstner & Kistler, 2002; Knight, 1972; Wilson & Cowan, 1972) describing the collective response of a population of neurons in the brain to a time-varying input. (b) Ornstein–Uhlenbeck processes (Uhlenbeck & Ornstein, 1930). (c) The fluctuation–dissipation theorem (Kubo, 1966), whereby the linear relaxation of a system from a non-equilibrium state, is considered analogous to the statistical characteristics of the wavering of the system in an equilibrium state.

To date, substantial progress has been made regarding the understanding and modeling of human activity patterns. Research on the underlying causes of the bursty dynamics of human activity attributed their formation to priority-based queuing processes in the individuals' decision making mechanisms (Barabasi, 2005). Bursts of human activity were modeled through queue-based decision models reproducing the heavy-tailed distributions observed in the individuals' waiting times between the arrival of tasks and their execution (Vázquez et al., 2006). Non-stationary periods in human activity patterns generated by the individuals' response to emergencies were quantitatively analyzed and varying spatio-temporal characteristics were discovered in bursts of activity (Bagrow, Wang, & Barabasi, 2011). The correlation of collective online activity with external events has also been utilized in detecting the spreading pattern of epidemics by analyzing the evolution of Google searches relevant to contagious diseases (Ginsberg et al., 2009). Also, Google trends patterns were used as indicators and predictors of economic activity (Choi & Varian, 2012). An early study on the characteristics of the collective response of social systems to endogenous and exogenous influences proposed four dynamical classes, which were modeled through a self-exciting Hawkes process (Crane & Sornette, 2008). Further research on the temporal variation of the online activity classified the emerging patterns into six elementary shapes (Yang & Leskovec, 2011), modeled as a function of the online content contagiousness, external events, and periodic activity (Matsubara, Sakurai, Prakash, Li, & Faloutsos, 2012). Bursty patterns generated by exogenous influences were detected and analyzed in the context of the evolution of the Twitter network structure (Myers & Leskovec, 2014). Other studies focused on investigating how the bursty propagation of online content affects the evolution of the number of links and the number of visits to web pages (Ratkiewicz, Fortunato, Flammini, Menczer, & Vespignani, 2010; Ratkiewicz, Menczer, Fortunato, Flammini, & Vespignani, 2010). Also, bursty patterns of online information streams were used in the identification of hierarchical structures in the meaning of online content (Kleinberg, 2003). Patterns of collective attention to online stories were analyzed, and it was shown that the evolution of the novelty of online information decays exponentially (Wu & Huberman, 2007). The investigation of the temporal correlation of the individuals' actions during activity bursts in various contexts, indicated that bursty human activity patterns are characterized by a fat-tailed inter-event interval distribution (Dezsö et al., 2006; Karsai, Kaski, Barabási, & Kertész, 2012).

The progress achieved so far has brought us closer to the explanation of human activity patterns. However, the development of models which can realistically reproduce such patterns is necessary for their deeper understanding and prediction. Recently, online activity patterns were modeled through a neuroscience modeling approach (Lymperopoulos & Ioannou, 2015, 2016a) approximating the online users' behavioral mechanics through the dynamics of leaky integrate-and-fire neurons excited by endogenous and exogenous, deterministic and stochastic stimuli. Using heterogeneous activation thresholds, refractory periods, and self-generated influence among interconnected agents, who were affected by time-varying external influences, real online activity patterns were precisely reproduced. In this study we shift our focus to the macroscopic description of social activity patterns. Instead of modeling the microscopic mechanism underlying the individuals' activity as in Lymperopoulos and Ioannou (2015, 2016a), we model the dynamics of collective activity and its response to external interventions. The proposed model accurately describes collective activity patterns using only a single, non-autonomous, linear stochastic differential equation consisting of a time-dependent variable and four parameters. This approach leads to a drastic reduction of the dimensionality of social systems, thereby enabling the study of social collective phenomena in a highly simplified and precise way. In particular, the proposed model can be used for:

i. Inferring the temporal structure and strength of the external influence that affects the collective activity of a social system.
ii. Estimating the inertia of a social system. In the proposed model the inertia is expressed through the time constant of a linear, non-autonomous, stochastic differential equation describing the rate of change of the collective social activity in the presence of a time-varying external influence field.
iii. Potentially predicting collective social activity patterns, provided that the model is trained through the reconstruction of external influence profiles in various contexts.

The proposed model shows that social activity patterns can be modeled without incorporating the characteristics of the connectivity structure and interaction among individuals, thus drastically reducing the high dimensionality of social systems. This modeling approach greatly facilitates the study of the collective dynamics of social systems. Also, it shows that complicated non-stationary activity patterns constitute the response of a social system to time-varying external influences which are effectively incorporated into the model, thereby resulting in the precise replication of real activity patterns. According to the proposed approach, the external influence is a time-varying stimulation signal generated by information streams relevant to factors which are exogenous to a social network. A stimulation signal of significant signal-to-noise ratio drives social activity out of an equilibrium state, as individuals function as encoders of the temporal structure and strength of the external simulation. It is demonstrated that the model can infer a unique external signal profile pertaining to the exogenous influence affecting a collective activity pattern. Since this signal profile gives rise to a simulated activity pattern accurately matching the real one, the proposed approach provides reliable evidence of correctly estimating the temporal structure and strength of the external influence generated by exogenous information streams entering a social system.

Also, the model provides a description of the transfer function of social systems, thus contributing to a mechanistic formulation of the response of a social system to external input by treating the internal structure of a network as a black box. Such a model can be used in developing input–output combinations, where the input would pertain to different kinds of external influences, and

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