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Modeling triple-diffusions of infectious diseases, information, and preventive behaviors through a metropolitan social network—An agent-based simulation

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ABSTRACT

A typical epidemic often involves the transmission of a disease, the flow of information regarding the disease, and the spread of human preventive behaviors against the disease. These three processes diffuse simultaneously through human social networks, and interact with one another, forming negative and positive feedback loops in the complex human-disease systems. Few studies, however, have been devoted to coupling all the three diffusions together and representing their interactions. To fill the knowledge gap, this article proposes a spatially explicit agent-based model to simulate a triple-diffusion process in a metropolitan area of 1 million people. The individual-based approach, network model, behavioral theories, and stochastic processes are used to formulate the three diffusions and integrate them together. Compared to the observed facts, the model results reasonably replicate the trends of influenza spread and information propagation. The model thus could be a valid and effective tool to evaluate information/behavior-based intervention strategies. Besides its implications to the public health, the research findings also contribute to network modeling, systems science, and medical geography.

Introduction

Recent outbreaks of infectious diseases, such as the H1N1 flu, bird flu, and severe acute respiratory syndrome (SARS), have brought images of empty streets and people wearing face masks to television screens and web pages, as fear of unknown diseases swept around the globe (Funk, Salathé, & Jansen, 2010). These images depict three basic components of epidemics, namely infectious diseases, information about diseases, and human preventive behavior against diseases. From a perspective of diffusion theory, each of the three components can be viewed as a spreading process throughout a population. The disease could be transmitted through person-to-person contact, the information is circulated by communication channels, and the preventive behavior can spread via the 'social contagion' process, such as the observational learning. The interactions among these three diffusion processes shape the scale and dynamics of epidemics (Funk & Jansen, 2013; Lau et al., 2005; Mao & Yang, 2011).

Mathematical and computational models have been extensively used by health policy makers to predict and control disease epidemics. A majority of existing models have been focused on the diffusion of diseases alone, assuming a 'passive' population that would not respond to diseases (Bian et al., 2012; Eubank et al., 2004; Longini, Halloran, Nizam, & Yang, 2004). This is rarely the case because it is natural for people to protect themselves when realizing disease risks (Eames, Tilston, Brooks-Pollock, & Edmunds, 2012; Ferguson, 2007). To improve, there has been much recent interest in modeling two diffusion processes in an epidemic, either a behavior-disease diffusion (House, 2011; Mao & Bian, 2011; Vardavas, Breban, & Blower, 2007), or an information (awareness)-disease diffusion (Funk, Gilad, Watkins, & Jansen, 2009; Kiss, Cassell, Recker, & Simon, 2010). These 'dual-diffusion' models have made a remarkable progress toward the reality, but none of them consider all the three diffusion processes together. The third diffusion process has often been neglected or simplified.

In the current literature, few modeling efforts have been devoted to explicitly representing all the three components, their spreading processes, and interactions. The lack of such models prevents researchers from unveiling a full picture of an epidemic, and inevitably introduces biases into the deep understanding on

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human-disease systems. For epidemiologists, it is of difficulty to explore how one diffusion process influences the other two, and what key factors govern the three diffusion processes. Without a complete model, health policy makers would not be able to systematically evaluate social-network interventions for disease control, such as mass-media campaigns and behavior promotion strategies. As in the age of information, the fusion of disease-behavior-information in epidemic modeling becomes a pressing task in public health.

To fill the knowledge deficit, this research proposes a conceptual framework to integrate the three diffusion processes, and develops a triple-diffusion model in a realistic urban area. Following sections discuss the conceptualization, formulation, and implementation of the model, and evaluate the simulation results.

Methods and materials

Conceptual framework

The proposed model conceptualizes a typical epidemic as one network structure, three paralleling diffusion processes, and three external factors (Fig. 1). First, the contacts among individuals form a network structure as a basis for diffusion and interaction. Second, infectious diseases are transmitted through direct contacts among individuals (the middle layer). Disease control strategies, such as vaccination program, case treatment and isolation, pose external effects on the disease diffusion. Third, the diffusion of diseases prompts the "word-of-mouth" discussion among individuals, which disseminates the information concerning diseases and prevention (the upper layer). The outbreak of diseases may also stimulate various mass media, such as TV, newspapers, and radio, to propagate relevant information, thus accelerating the diffusion of information. Fourth, people being informed start to consider and make a decision toward the adoption of preventive behaviors. The adoptive behavior of individuals also influences their network neighbors to adopt, widely known as the "social contagion" effects (the lower layer). The diffusion of preventive behaviors, in turn, limits the dispersion of diseases and speeds the diffusion of information. Behavioral interventions, as an external factor, can be implemented by health agencies to promote preventive behaviors, such as educational, incentive and role-model strategies. During an epidemic, these three diffusion processes interact with one another and form negative/positive feedbacks loops in the human-disease system, shown as arrows between layers in Fig. 1. Manipulated by the three external factors, these three diffusion processes, hereinafter named as the triple-diffusion process, determine the spatial and temporal dynamics of an epidemic.

Model formulation

Social network

The conceptual model is formulated by an agent-based approach, which has gained its momentum in epidemic modeling during the last decade (Burke et al., 2006; Huang, Sun, Hsieh, & Lin, 2004). Different from classic population-based models, each individual in a population is a basic modeling unit, associated with a number of attributes and events that change the attributes. To represent the contact network, individuals are modeled as nodes and are linked to one another through their daily contacts (as network ties). The individualized contacts are assumed to take place during three time periods in a day at four types of locations (Mao & Bian, 2010), namely the daytime at workplaces, the nighttime at homes, and the pastime at service places or neighbor households (Fig. 2). Individuals travel between the three time periods and the four types of locations to carry out their daily activities, thus having contact with different groups of individuals and exposing themselves to disease infection. These contacts link all individuals into a population-wide network.

Two types of individual contacts are modeled in terms of the contact duration and closeness. One type is the close contacts

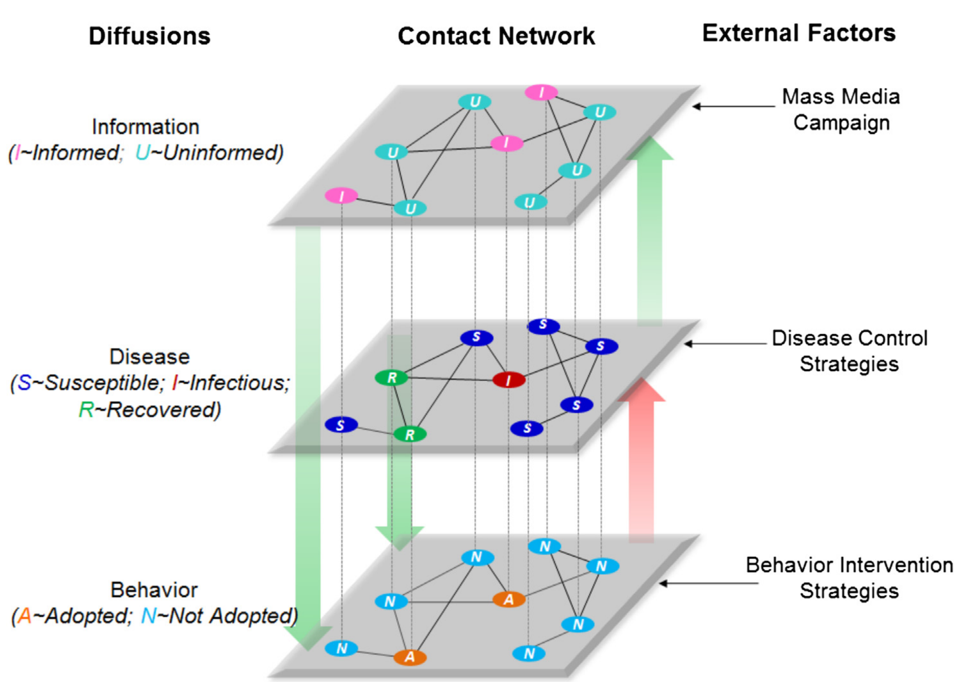

Fig. 1. Conceptual framework of the triple-diffusion model as a representation to an epidemic. Three layers illustrate three diffusion processes upon a contact network, where nodes represent individuals and links represent their relationships. Colors of nodes indicate the states of individuals in each diffusion process. Arrows between layers show the interactions between the three diffusions. Red arrow shows a negative effect, while the green arrow denotes a positive effect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)