The spreading of infectious diseases in modern socio-technical systems. Comment on "Pattern transitions in spatial epidemics: Mechanisms and emergent properties" by Gui-Quan Sun et al

Nicola Perra*

Centre for Business Network Analysis, Greenwich University, London, SE10 9LS, UK

We are all part of different, often interconnected, socio-technical systems [1]. These provide a set of unprecedented capabilities. The global air transportation network allows to travel between almost any two points on earth within one day. The network of roads and rails consent to reach different neighbourhoods, regions or even countries in matter of hours. A variety of platforms running over the Internet allows to communicate instantaneously across time zones with friends, family and strangers alike. The way we travel, commute, and communicate is drastically different and more efficient respect to any time in our history [2].

As Sun et al correctly note in their review [3], the recent outbreaks of SARS (2002), H1N1 (2009), H7N9 (2013), Ebola (2014), and MERS-CoV (2012 and 2015) show how such unprecedented global and local connectivity affects diseases' dynamics. The comparison between the spreading of the *black death* in the 14^{th} century and H1N1 in 2009 is particular revealing. The first took over Europe slowly moving from the south as a wave in a medium. The disease reached north Europe in about 2 years. The second instead, spread in 214 countries in matter of few months. Notably its spreading patterns have been seemly erratic and different respect to a wave propagation in space [4, 5]. In particular, the diffusion from one city to another was not simply driven by proximity but by their effective connectivity in the current transportation system [6]. Furthermore, the two diseases induced the proliferation of panic, fear, and behavioural changes. However, in the

*n.perra@greenwich.ac.uk

case of H1N1 people and governments, even those in a particular moment still unaffected by the spreading, were able to follow in near real time the unfolding of the disease and take, often irrational, actions. As this example shows, the complexity of modern mobility and communication introduces non trivial effects on the spatial unfolding of infectious diseases [7]. Consequently, the development of frameworks able to account and anticipate them has become a fundamental aspect of epidemiology.

From this intuition, the review provides an interesting summary of results and approaches that can be employed to characterise and understand the spreading patterns of infectious diseases in modern times. Interestingly, the authors identify three main forces driving current spatial diffusion of epidemics and thus the transition between different spatio-temporal patterns.

The first is *spatial heterogeneity.* This is one of the main feature of socio-technical systems; one of the hall marks of their *complexity* [1, 8]. From the number and intensity of contacts between individuals, to the flow of people connecting two cities, the statistical observables of such systems are characterised by heterogeneities encoded in heavy-tailed distributions [1]. The effects of these features on spreading processes unfolding on their fabric, are now well understood [7]. On one side they make systems more fragile. Indeed, the presence of heterogenous connectivity patterns among sub-populations in a meta-population system or among individuals in a contact network lowers the epidemic threshold necessary for an outbreak [9, 10]. On the other, they offer very efficient ways to halt spreading processes. Indeed, heterogeneous connectivity patterns imply heterogenous contributions to the diffusion by the nodes (i.e. sub-populations or individuals) involved. By protecting (immunising) few of them is possible to protect the entire system [11, 12].

The second is constituted by *seasonality and noise.* The review does a good job providing a summary of the causes behind these two phenomena namely variation in contacts rates, environment (temperature, humidity etc..), and demographics. More importantly, it points out how the fluctuations they entail interact with the complexity of socio-technical systems affecting diseases' dynamics even further.

The third is *human behaviour.* In tackling this crucial aspect, the review correctly focuses on *adaption.* As mentioned above, the spreading of infectious diseases might induce behavioural changes. These could be either imposed by authorities (ban of public gathering, traveling etc..) and or spontaneously emerge as result of concern (precaution) of the population (reduction of contacts, vaccination etc..) [13]. The effects of adaptation on the spatio-temporal patterns of diseases are highly non trivial and result in a rich phenomenology characterised by multiple peaks in the incidence as well as first order phase transitions [13, 14, 15]. The current communication capabilities have not parallel in history and have great influence on adaptation processes. On one side, these allow people to gather crucial information to protect themselves and their families from risks associated to transmittable diseases [16, 17]. One the other, these allow the spreading of unfounded and unscientific ideas, as for example the link between autism and vaccination, which can have dramatic consequences facilitating the (re)emergence of diseases [18, 19, 20]. As the review note, the role adaptation on the spreading of infectious diseases is a multifaceted subject that, mostly due to lack of real data, is still poorly understood.

The review clearly shows how characterising the transitions between different spatial or spatio-temporal patterns can be used to define unknown features of diseases, develop early detection systems, and make actual forecasts [21, 22, 23, 24]. To this end, the digital traces we leave while interacting with and via socio-technical systems are becoming extremely important [25]. For example, search engine queries, tweets, page views on wikipedia, and different activities on mobile phones can be used to gather unprecedented data proxies to estimate, model and predict the spreading of a range of infectious diseases. As the recent *Influenza Season Challenge* organised by the centers for disease control and prevention (CDC) in USA shows, these data can inform epidemic models enabling them to make forecasts at different spatio-temporal granularities [26].

In conclusion, the review highlights the importance of studying spatio-temporal diffusion patterns of infectious diseases. To this end, spatial heterogeneities, seasonality, noise, and human adaptation are crucial and responsible for a rich phenomenology. The unprecedented amount of digital traces we leave interacting via or with socio-technical systems has started a new era in epidemiology that is now becoming digital [25]. The potential of such new data streams to inform and develop spatially resolved epidemic models is largely unexplored and is likely to be an intense area of research in the years to come.

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