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Original article

Interdependent effects of cohesion and concurrency for epidemic potential

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ABSTRACT

Purpose: Network diffusion depends on both the pattern and timing of relations, but the relative effects of timing and structure remain unclear. Here, we first show that concurrency (relations that overlap in time) increases epidemic potential by opening new routes in the network. Because this is substantively similar to adding contact paths, we next compare the effects of concurrency by observed levels of path redundancy (structural cohesion) to determine how the features interact.
Methods: We establish that concurrency increases exposure analytically and then use simulation methods to manipulate concurrency over observed networks that vary naturally on structural cohesion. This design allows us to compare networks across a wide concurrency range holding constant features that might otherwise conflate concurrency and cohesion. We summarize the simulation results with general linear models.
Results: Our results indicate interdependent effects of concurrency and structural cohesion: although both increase epidemic potential, concurrency matters most when the graph structure is sparse, because the exposure created by concurrency is redundant to observed paths within structurally cohesive networks.
Conclusions: Concurrency works by opening new paths in temporally ordered networks. Because this is substantively similar to having additional observed paths, concurrency in sparse networks has the same effect as adding relations and will have the greatest effect on epidemic potential in sparse networks.

Introduction

Social networks shape the extent and speed of disease diffusion, particularly for sexually transmitted infections like HIV [1,2]. For infection to spread, there must be an unbroken contact chain exposing those who are uninfected to those who are infected. Because such networks change over time, understanding epidemic potential requires understanding how relationship timing in general, [3] and concurrent relations in general, affect diffusion [4]. Here, we examine how concurrency affects epidemic potential and how it is moderated by network connectivity.

Concurrency refers to relationships that overlap in time and has been linked to epidemic potential ([4,5], for detailed reviews, see [6–8]), although debate continues as to the relative role of concurrency vis a vis other factors [9]. Given data collection complexities with modeling disease diffusion in real settings, much of the work on concurrency uses simulations and recent data-grounded simulations extend such work to explain prevalence disparities across populations [8,10].

We first show that concurrency affects epidemic potential by altering the constraints inherent in temporally ordered networks. We then examine how this effect is moderated by network structure. To do so, we distinguish observed "contact networks" from those that can carry infection given timing constraints, which we call the "exposure network." Because the set of relations that carry an infection is a stochastic subset of the exposure network, the number of people ultimately infected will correlate with the density of the exposure network. Concurrency increases the density of the exposure network by creating symmetry that would not exist in networks without concurrent relations. Because concurrency creates multiple pathways in the exposure network, we explore whether the contact network structure moderates the effects of

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concurrency. We find that concurrency has the strongest effects when the contact network is sparse, while returns to concurrency are lower when connectivity is high, mainly because the proportion of people directly exposed is much higher. In low-cohesion networks, concurrency is equivalent to adding new independent paths in the contact network.

Formalizing the problem

Diffusion potential in a network depends on relational timing, since pathogens cannot spread over relations that have ended: one can only pass infection to current or future partners, not past partners. To formalize this fundamental constraint, it helps to consider three related networks:

1. The contact network: Pairs of people linked by direct contact. Contact relations are timed by date of first and last contact.
2. The exposure network: A subset of the relations in the contact network where timing makes it possible for one person to infect another.
3. The transmission network: The subset of the exposure network where infection passes. This is a stochastic tree layered on the exposure network determined by the particular source individuals(s) and pairwise transmission probability.

The timing of relations in the contact network determines the exposure network which in turn limits the number of people infected in the transmission network. Figure 1 illustrates how timing affects exposure on three identical contact networks.

In Figure 1, the first column presents the contact network, with numbers over the relations indicating timing. For example, person A in panel A has a relation with person B at time 2. A “time-ordered path” is a sequence of adjacent relations where, for each pair of relations in the sequence, the start time *S*( ) of the first relation is less than or equal to the end time *E*( ) of the second: $S(R_1) \le E(R_2)$, and the set of all time-ordered paths defines the exposure network. The second column of Figure 1 provides a graphical representation of the exposure network, representing all pairs reachable by time-ordered paths, recorded as an adjacency matrix in column 3. Diffusion can only occur given exposure; for example, we see that in panel A person B can infect person D, but because the BC relation ends before the CD relation starts, person D cannot infect B.

Adjacent relations are concurrent if they overlap in time, which occurs if $S(R_1) \le E(R_2)$ and $S(R_2) \le E(R_1)$. In panels A and B of Figure 1, there are no concurrent relations, creating asymmetry in who can infect who. For example, in panel B, person B could infect person D but D cannot infect B, because the BC relation ended before the CD relation started. In panel C, the BC and CD relations are concurrent, which would allow D to infect B. In general, concurrency in the contact network creates symmetric exposure. The same contact structure with different timing can generate widely different sets of people at risk of infecting each other. A simple measure for the effect of timing on risk is the proportion of pairs in the population who could infect each other (column 3 in Fig. 1), which we call reachability. Here, reachability in the concurrent case (83%, panel C) is about 1.25 times higher than that in the first case (66%, panel A).

These examples illustrate several ways that concurrency necessarily shapes epidemic potential. First, concurrent relations create symmetry in the exposure network by removing the protective temporal ordering created by serial monogamy. In serially monogamous settings, indirect exposure always flows down one path or another around a coupled pair, because one relation must precede the other, and infection can only flow from preceding relations to later relations. Concurrency erases this constraint, opening exposure to a potentially much wider downstream population. Second, concurrency affects exposure to partners-of-partners by opening new exposure paths but does not necessarily affect people directly engaged in concurrent relations, since number of partners remains constant. This helps explain why associations between individual concurrency and infection risk is sometimes quite low [11]. Third, as these are path-level features, there can be large nonlinear effects: small changes in the path structure can potentially expose large portions of the network to new risk. As such, concurrency can increase the density of the exposure network even in cases where most people have nonconcurrent relations. Because transmission is a stochastic function operating over the exposure network, any increase in the density of the exposure network will generate larger transmission trees, all else constant (This is true for a fixed dyadic transmission

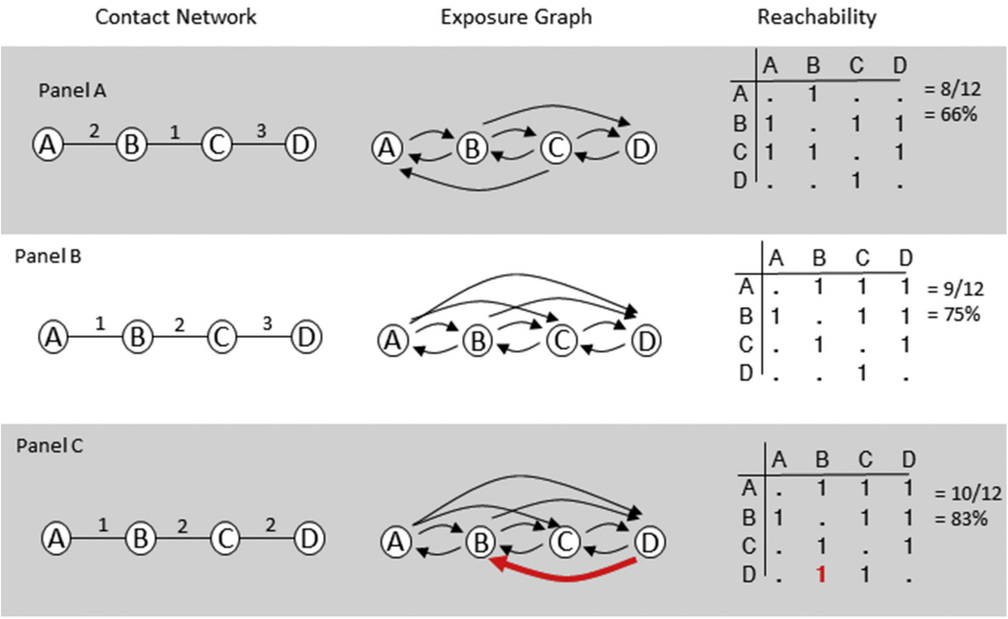

Fig. 1. Illustrating the effect of timing on exposure.