Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Multilevel network interventions: Goals, actions, and outcomes

Garry Robins a,b,*, Dean Lusher a, Chiara Broccatelli d, David Bright e, Colin Gallagher b, Maedeh Aboutalebi Karkavandi a, Petr Matous c, James Coutinho a, Peng Wang a, Johan Koskinen b, Bopha Roden a, Giovanni Radhitio Putra Sadewo a

a Swinburne University of Technology, Australia
b University of Melbourne, Australia
c University of Sydney, Australia
d University of Queensland, Australia
e University of Melbourne, Australia
f Deakin University, Australia

ABSTRACT

COVID-19 has resulted in dramatic and widespread social network interventions across the globe, with public health measures such as distancing and isolation key epidemiological responses to minimize transmission. Because these measures affect social interactions between people, the networked structure of daily lives is changed. Such largescale changes to social structures, present simultaneously across many different societies and touching many different people, give renewed significance to the conceptualization of social network interventions. As social network researchers, we need a framework for understanding and describing network interventions consistent with the COVID-19 experience, one that builds on past work but able to cast interventions across a broad societal framework. In this theoretical paper, we extend the conceptualization of social network interventions in these directions. We follow Valente (2012) with a tripartite categorization of interventions but add a multilevel dimension to capture hierarchical aspects that are a key feature of any society and implicit in any network. This multilevel dimension distinguishes goals, actions, and outcomes at different levels, from individuals to the whole of the society. We illustrate this extended taxonomy with a range of COVID-19 public health measures of different types and at multiple levels, and then show how past network intervention research in other domains can also be framed in this way. We discuss what counts as an effective network, an effective intervention, plausible causality, and careful selection and evaluation, as central to a full theory of network interventions.

1. Introduction

Since early 2020, in response to COVID-19 the world has seen a range of public health measures that go beyond vaccination and hospital treatment. Public health policies have been directed at minimizing disease transmission through intervention in the social structures of daily life, with network ties disrupted or transformed. As vaccination programs change this landscape, we can look back at policy action in the form of lockdowns, social distancing, isolation, and quarantine, and recognize that these have constituted – for some of us at least – the most widespread social network intervention of our lifetimes.

Such dramatic, largescale alterations in social network structures, often ubiquitous and controversial, present an opportunity to refocus attention on social network interventions. To represent COVID-19 responses fully, network intervention theory needs to be cast across a broad society-wide framework, and yet still retain consistency down to smaller scale, local interventions restricted to given domains. Such different scales require a multilevel perspective, with interventions and outcomes having implications across and within different societal levels.

Many current public health network interventions focus on the utilization, rather than the change, of an existing social network, with the goal of diffusing individual behaviors or attitudes. Behavior change in a target population is seen as encouraged by leveraging individuals’ network ties (e.g., to friends, work colleagues, peers) to influence them to adopt, for instance, better health behaviors. The idea that attitudes, knowledge, and behaviors spread across individuals within a social system has a long history in social theory, back at least to Diffusion of Innovation Theory (Rogers, 1962) and the Katz and Lazarsfeld (1955) theory of mass communication. Indeed, it was already a feature of Moreno’s (1934) sociology, at the very beginnings of modern social network analysis.

Even though behavioral diffusion with a focus on individual outcomes is perhaps the most familiar network intervention strategy, as explained below other approaches have been identified in the literature, including changes to network structure. Because they are not as common, we have less insight into these types of network intervention.
is, neither its constituent relationships, nor its structure. The term is used
value but gives no precise detail about the elements of what the network
many COVID-19 public health measures. We follow this with some brief
responses. Recent arguments in the public health literature (e.g., Ski
societal focus have been prominent, with change in individual behavior
an ancillary response. In this article, we continue to emphasize the
importance of diffusion and individual behaviors, but a multilevel focus
also requires attention to interventions that go beyond actor-level re
sponses. Recent arguments in the public health literature (e.g., Ski
vington et al., 2021) have noted that collective outcomes, more than just
an aggregation of individual responses, may be crucial. The importance
of situating public health measures within a multilevel ecology (indi
vidual, interpersonal, community) is an important theoretical theme
(Pescosolido, 2011).
COVID-19 public health policies, seen as society-wide network in
terventions, have traversed multilevel features, structural change and
much more, with both individual and collective outcomes. In this
theoretical paper, we add a multilevel dimension to existing interven
tion typologies, creating a taxonomy that distinguishes goals, actions,
and outcomes at different levels, from individuals to the whole of the
society, from nodes to the whole social network. This taxonomy captures
the wide-range of network interventions implicit in COVID-19 policies
but remains consistent with previous categorizations of smaller scale
interventions in other domains.
Before we introduce our taxonomy, in the next section we present the
basic social network theory that we require (and that will be familiar to
many but not all readers), including the introduction of multilevel is
sues. We go on to review Valente’s seminal typology of network in
terventions; to discuss goals, actions, and outcomes in interventions; and
to consider structural intervention actions. With this groundwork in
place, we then present our multilevel taxonomy with illustrations from
many COVID-19 public health measures. We follow this with some brief
remarks about multilevel goals and outcomes, and then illustrate how
previous network intervention work from the domains of crime, edu
cation, organizations and other non-COVID health-related matters can
be framed in our extended taxonomy. We conclude by noting various
issues that need further work in developing a fuller social network
intervention theory.

2. Social network theory

This section presents the basic social network concepts that are used
in presenting our network intervention taxonomy.

We wish to be precise about what we mean by social network. In the
general literatures around social interventions, there are several
different usages of the term.

**Network as metaphor:** This conceptualization of social networks
recognizes that connections between people are important and carry
value but gives no precise detail about the elements of what the network
is, neither its constituent relationships, nor its structure. The term is used
as an explanatory and intuitive device that is often amorphous and
undefined.

**Network as group:** The term network is often used synonymously
with the term group, such that ‘I am part of the Southern Research
Network’. It implies a membership of a group, whose purpose is to
connect and allow people to ‘network’. The often-unspoken assumption
of such ‘networks’ is that by virtue of membership, everyone is con
nected to everyone else, an assumption that may not always be justified.
Like the previous definition, there is lack of specificity of the types of
social ties or the structures of ties that might be important.

**Network as social ties among actors:** This is our usage. A social
network is a set of individuals or social actors (nodes) and the social ties
among them. There will be individuals who are not connected by a social
tie and the absences of ties can be just as important as their presence
(White et al., 1976). Actors may have attributes, demographic, attitu
dinal or other properties that vary across individuals. Nodes can be of
fundamentally different types in a social network (e.g., individuals and
venues in a two-mode network), so that more complex network struc
tures can be included. The social network is then precisely defined, so
that a clear analysis of structure, social process and outcomes can be
undertaken.

**Network as a representation of a social system:** This usage goes
hand in hand with the previous definition and emphasizes the systemic-
multilevel aspect of a network perspective. Because a social network
comprises the social ties among individuals, and these ties pattern across
all individuals, the network is a representation of the social system of
those individuals. This baseline network description can be extended to
incorporate other aspects of a social system, including macro-level enti
ties (institutions and the like), network evolution over time, and
multiple types of tie.

We distinguish between network ties and interactions. A tie is a social
connection between individuals of indefinite duration across time. An
interaction is a specific time-limited meeting or social exchange between
individuals. So, two friends share the tie of friendship; they interact
when they meet. An interaction is sometimes referred to as a contact tie
(in the same sense that a public health contact tracer might ask with
whom you had contact over the last week, an interaction partner with
the potential for disease transmission.) For the most part in this paper,
we will skate over the distinction between ties and interactions, except
where it is important to emphasize that contact ties are the focus.
Because a tie carries particular social content, a contact tie is differen
t from, for instance, a friendship tie, in turn different from a work tie.
A dyadic social relationship then may comprise different types of tie (you
may be friends with a work colleague); and so may endure, albeit in a
different form, if its constituent ties change.

A network perspective automatically carries potential multilevel con
siderations (Lazega and Snijders, 2016; Monge and Contractor,
2003). The nodes and ties cumulate into the one social network (in
dividuals are within the one social system). Certain patterns across the
social network are not fully evident from just part of it: observation of
the whole network is required, for instance, to determine average path
length, diameter, or core-periphery structure. Such whole-network fea
tures, which we will term system level, are conceptually distinct from
aggregated actor-level properties, or other aggregations of local level
features. By local, we do not mean place-based as in “the local area” but
“local” in a network sense, including or in the network vicinity of in
dividual actors. Similarly, there are system level outcomes for an entire
social system that are distinct from aggregated local level outcomes,
including outcomes for the individuals within the system. So, our
network intervention taxonomy will incorporate the more individual,
local level as well as the wider, social system level. Furthermore, we will
introduce an intermediate level that goes beyond specific individuals
but falls short of the entire system.

The local level is often focused on the individuals in the system (the
nodes in the network) but we also consider localized network structures
centered around individuals. A dyad is a pair of individuals and the ties
between them, whereas an egonet comprises a given individual (ego), its
network partners (i.e., those other nodes connected to it by ties) and the
ties among the network partners. Other possible local structures could
be considered, but we focus on nodes, dyads and egonests as local level
structures of interest given they are fundamental social network con
cepts.

Our intermediate level is that of a social setting, discussed in a
network context by Pattison and Robins (2002). Their notion is deliber
ately skeletal and general, essentially a social space within which
social interaction may occur among many individuals. In concrete terms, a social setting could be place-based, a physical place such as a school or a town hall, or more abstract akin to Feld’s (1981) idea of a social focus, such as a society or club, or a less formal arrangement such as a group of friends. Social settings may also be seen as akin to what have been termed social situations (Funder, 2009), spaces that provide affordances for interaction. Settings interventions may, for instance, include the closing of a setting, or altering who can operate in that setting, and what they may do (e.g., Nishi et al., 2020). The structure of potential network ties can be altered, or within-settings ties utilized towards an intervention goal.

As an intermediate level, a setting is considered as relative to what is determined as the entire social system. In social network research, we are familiar with the network boundary issue (Laumann et al., 1983), where the boundary of the network needs to be defined or specified. That decision then identifies the entire social network under study. If we are thinking in terms of a network-based social system, then the boundary of the social system needs to be defined equivalently. At the system or network level, we may study for instance an entire school, in which case the classrooms within it may be identified as settings. But of course, there are many examples of network research into an individual classroom. If that is our focus, then the classroom rather than the school provides the boundary. Our study has narrowed to the social system of the classroom, within which of course there may well be settings (for instance, student workgroups or teams). In our COVID-19 examples below, we are choosing the social system of an identifiable government jurisdiction, such as state with a government capable of making public health orders that apply across that jurisdiction. Within the social system, relevant settings might include schools, hospitals, workplaces and the like. Especially with a contagious disease, that social system, there are levels within levels. The decision that a social system of the classroom, within which of course there may well be settings (for instance, student workgroups or teams). In our COVID-19 examples below, we are choosing the social system of an identifiable government jurisdiction, such as state with a government capable of making public health orders that apply across that jurisdiction. Within the social system, relevant settings might include schools, hospitals, workplaces and the like. Especially with a contagious disease, that social system can be represented as a social network, and so if the government or some other body intervenes, this takes the form of a social network intervention.

This is a familiar issue in multilevel research more generally: in any social system, there are levels within levels. The decision that a researcher/interventionist cannot avoid is where to set the boundary for the system to consider, or in other words how to lump the reality into discrete levels, and which levels to focus on.

It is worth briefly noting that here we are using the term “level” in the sense of “level of analysis”. A social network or social system can be studied from the point of view of its constituent nodes or actors, its dyads, its egonets and so on, up to the entire system. This is a different use of “multilevel” than that of a multilevel network, which is a hierarchical social network with distinct levels for different types of nodes (e.g., Lazega et al., 2008; Lazega and Snijders, 2016; Wang et al., 2013). We are not dealing with this type of more complex network structure, although our analysis could be extended in that direction. Pescosolido (2006) presents an early discussion of such multilevel network structures in a public health context.

A social network is not just a static structure but one that evolves and changes across time. The social network structure is the outcome of social processes, at the same time as it constrains those very same social processes. Important social network processes that occur at the local level include social selection and social influence. Selection occurs when an individual chooses a new network partner and establishes a tie (or, alternatively, relinquishes a tie to an existing network partner). Social influence occurs when one network partner convinces another to change their attitudes or behaviors. When influence processes lead to spread across the network with a cascade of nodal attribute changes, then we talk about network diffusion. We can see how these processes can change the network, either structurally (through changing ties by selection) or through diffused attribute change (by influence). At the same time, the processes are constrained by the network: social selection of a new network partner is not independent of other network partners, and social influence depends on the presence of a tie to even get started.

3. Typologies of social network interventions

Valente (2012) sets out a systematic and influential typology of network interventions that is the basis of our own taxonomy. He presents four categories of network interventions:

- **Individual identification**: Opinion leaders or key actors are identified from the social network. Identification may be based on network measures such as centrality or brokerage, to find those in prominent network positions; or on perceived popularity based on social status among peers. For instance, the police may identify a central criminal from links to other criminals.
- **Segmentation**: Rather than individuals, segmentation interventions identify groups of individuals to effect change amongst group members at the same time. Groups might be identified, for instance, through network group-detection algorithms. For instance, in the disruption from a major disaster, social network links may identify smaller groups relatively isolated from the major population and thereby missing recovery support.
- **Induction**: These interventions stimulate person-to-person interactions to induce cross-network cascades of behavior or information diffusion. For instance, people may be encouraged to pass on important public information to their friends.
- **Alteration**: These interventions alter the network to some purpose (“to improve efficiency”: Valente, 2012, p.51), either by adding or deleting nodes; adding or deleting ties; or rewiring existing links. For instance, organizations may restructure their formal reporting lines to achieve better results.

These four categories are now well recognized in the network intervention literature. In a social media context, with the aim of disrupting misinformation spread, Young et al. (2021) added a fifth category of redesigning digital platforms. They claim that as we shift focus to the study and treatment of online (mis)information, new perspectives and levels of analysis present themselves. As our concentration is on social networks rather than digital platforms, we base our work on the original Valente typology and do not include platform redesign.

The first two categories (Identification and Segmentation) utilize the existing network to identify key actors or groups. Network identification of individuals or groups can only be part of an intervention, for there is no intervention without further steps. For instance, the identification of a central criminal in an illicit network does not by itself count as an intervention, unless something is done with this new information (e.g., arrest, surveillance). A relatively isolated group after a disaster does not receive extra support just from being identified; obviously, steps have to be taken to deliver the support. A researcher may identify opinion leaders to spread new information, but those opinion leaders must be primed to do so, by provision of the information, instructions about what to do, possibly training and even payment. But as identification and segmentation are network-based mechanisms, they are actions that may be part of a broader intervention program and hence need to be included in any typology.

The identification process emphasizes the demand for adequate network data. To understand and mobilize the structure and processes of the network for an effective intervention – to go beyond constraining the
network as a metaphor or a group – requires an evidence-based empirical focus.

**Induction** also utilizes the existing network but, in this case, to activate local influence processes to diffuse nodal attribute change across the network. So, identification and induction often work together. **Alteration** is the category that includes action to change the structure of the network. Change to existing social connections, and thereby to entire social systems, has been one of the major – and sometimes controversial – public health responses to COVID-19.

We will extend Valente’s typology by reflecting on the COVID-19 experience and viewing the resulting public health interventions through a network and multilevel perspective. Beforehand, however, we discuss phases in a network intervention – goals, actions, and outcomes – and consider some issues relating to structural change.

4. Goals, actions, and outcomes in a network intervention

Valente (2012, p.49) defined “network interventions” as “purposeful efforts to use social networks or social network data to generate social influence, accelerate behavior change, improve performance, and/or achieve desirable outcomes.”

For an intervention to be purposeful there must be an intervenor – whether a government, an authority, an institution, or a researcher – with a goal. The intervenor acts in some way (i.e., intervenes). For it to be a network intervention, the intervention action of the intervenor must be directed towards a social network, utilizing or altering the social processes or structures operating in the network towards achieving the goal. So, an intervention action is itself a social process started by the intervenor, aimed at, but distinct from, the goal. Of course, the intervention need not be successful. The outcome, successful or otherwise, is then also conceptually different from both the goal and the action of the intervenor.

So, each network intervention can be analyzed within a goal-action-outcome framework, even if an intervention program includes multiple intervenors or multiple intervention actions. Just as Valente’s typology is of the intervenor’s action, not of goals or outcomes, our taxonomy focusses on the **intervention action**. We will make separate comments about goals and outcomes only after we introduce the taxonomy of actions.

The value of the goal-action-outcome analysis of network interventions is to differentiate the possibly different levels at which goals, actions and outcomes may apply. The goal of the intervention may be for the whole system, but the action may be at a lower level, or vice versa. A successful intervention implies the goals are achieved, but there may still be ancillary outcomes, perhaps unexpected and undesired, at other levels. Optimal outcomes need not occur at all levels and the highest individual returns do not necessarily cumulate to the best system level outcome. For outcomes, we may be operating in a world of complicated within- and cross-level trade-offs.

5. Structural change

Castillo et al. (2019) reviewed the different levels of non-network interventions in community mental health but noted that most occurred at a local level, seldom at system levels. Often the same occurs in network interventions, with many focused on dyadic influence-based interventions to create network diffusion of behavioral change. Action to change network structure to alter the workings of the system has received less attention (although see Siciliano and Whetsell, 2021). Such structural action intends to achieve outcomes by altering the social network structure, rather than just using the existing network to cumulate individual change. Structural action may be direct (e.g., by changing formal organizational structure in a business or by disrupting leadership in an illicit network) or indirect (e.g., changing the “rules” of social engagement within an organization to reshape social network interactions). Importantly, while diffusion interventions spread individual change, structural action can have collective goals, such as in typical organizational restructures, where the desired outcome (e.g., organizational efficiency) may be at the system rather than the local level. Nevertheless, as shown below in our taxonomy, structural action can occur at all levels in a multilevel framework.

Structural change is of course frequently planned and implemented; it is just not always viewed as a network intervention. Organizational restructuring, for instance, typically operates on the formal organizational structure, usually with a goal to change more informal organizational network processes (more efficient diffusion of information, strengthened lines of control, more effective workflow routines, greater ease of collaboration). Even though a change to the formal structure naturally invokes a change to social network structure and processes, organizational restructuring has not been given especially wide attention as a network intervention (McEvily et al., 2014). The social structural changes are often not a consideration themselves in the program evaluation which may focus instead on individual or group level outcomes, while avoiding the network-based social processes. This major gap in evaluating interventions limits understanding of these network strategies and the mechanisms that drive the intervention. We have more to say about evaluation below.

6. Network interventions in a time of COVID

Our own thinking on network interventions has been sharpened by observation and lived experience during attempts by governments and authorities to manage the COVID-19 pandemic. In this section we present a taxonomy of network interventions, illustrated by COVID-19 examples, by extending Valente’s typology to incorporate a multilevel focus. In following sections, we discuss multilevel goals and outcomes and then go on to illustrate how our taxonomy applies in non-COVID domains. We will conclude with comments on important areas that need further work in a fuller theorization of network interventions.

We present our taxonomy in the context of COVID because of the recent and dramatic interventions we have seen in relation to the disease. However, just as with Valente’s typology, our categorization of intervention actions into type by level is intended to generalize to other domains of network intervention, not just public health. We illustrate applications to other domains after presenting the COVID example. Of course, not all the actions are necessarily widely applicable, and as with any categorization, a particular intervention action will not apply to network interventions beyond its category. Nevertheless, because we can populate our entire taxonomy with examples at least from COVID, the entire framework is necessary to cover all types of intervention action that have occurred. It is also important that a given network intervention program may contain more than one type of intervention action, as we show below, and that these may be at different levels. In short, our taxonomy categorizes possible intervention actions even if in practice some have been more popular in a specific domain or for a particular program than others.

**Table 1** summarizes intervention actions by level. The rows refer to the three different levels of intervention action (local, setting, system) while the three columns are derived from Valente’s four categories. For the three columns, we have collapsed Valente’s Individual Identification and Segmentation into the one column labeled Identification. Both of Valente’s categories use the network structure to identify either key individuals or groups. The distinction between individuals and groups is accommodated by the different levels, local and setting. Valente’s Induction category, even though it is originally defined specifically in a dyadic context, roughly corresponds to our column for Diffusion. The third column, Structural change, is analogous to Valente’s Alteration. Our change in terminology for the second and third columns reflects the fact that diffusion and structural change are more commonly used network terms with less ambiguity than induction and alteration. Under Structural change, the network intervention action is directed at changing the network, whereas Identification and Diffusion are directed at using the
existing network structure.

A network intervention may combine several of the intervention actions in Table 1 into a wider program. For instance, influential figures may be identified from the network structure (Node identification), each of these may be primed to spread information (Node priming), and then they may diffuse that information either dyadically, through their egonets, or through social settings (Local or Setting level diffusion). The cells of the Table do not necessarily describe all possible intervention actions, but rather provide some general descriptors that are pertinent to the subsequent COVID-19 examples. The point is that the rows and columns of the Table provide a framework into which network interventions may be situated.

Our most obvious first point about COVID-19 – and about any contagious disease – is that it spreads through social networks. The nature of the disease determines the nature of the social tie relevant to that transmission, so our understanding of social tie needs to be broad in general, and precise for specific diseases. Some disease transmissions require direct physical contact with another person, whereas others such as COVID-19 may be transmitted simply by people present together in the same physical location at approximately the same time, perhaps through airborne or droplet transmission. When people do not know each other but occupy the same space the notion of social setting comes to the fore and, if need be, can be represented in a two-mode network.

This is not to say that all interventions are network interventions. But because COVID spread is a network phenomenon, any intervention, even if seemingly non-networked, may have implications across the social network and at different levels. Similarly, because COVID-related behaviors and attitudes may be spread across networks through the various processes of social influence, any intervention relating to behaviors and attitudes may have network implications.

We begin by describing in network terms the situation of disease spread without any medical or social intervention. COVID-19 is spread principally from infected individuals to their network close contacts (the precise definition of close contact has somewhat shifted as the pandemic has progressed and as more becomes known about transmission). In the most basic Susceptible-Infected-Recovered (SIR) epidemiological models, there are three categories of individuals: an Infected person transmits to a Susceptible person with some probability; after the period of infection (assuming recovery and no death), the Recovered person has immunity and can no longer be infected. People move through susceptible/infected/recovered categories depending on their disease status.

Of course, this description does not fit the COVID case exactly: for instance, re-infection is possible with COVID-19. In the basic SIR model, however, the disease is not just transmitted through social ties but across a particular dyad type that involves nodal attributes: it is a contact tie from infected to susceptible that is necessary, not just any network tie. We will call these social contagion ties.

All this is obvious enough, but this case illustrates how diffusion/contagion/influence and structural change may necessarily co-occur. The diffusion of COVID is not just a network contagion effect but changes the effective network structure of social contagion ties as it goes. In short, the disease status of the actors affects whether a contact tie is a social contagion tie or not, so the transmission of the disease in effect changes the structure of the social contagion network. Other co-variate networks (e.g., the friendship network) may be unchanged, but for the social contagion network, changes in attribute are necessarily accompanied by changes in structure. There are implications for network intervention outcomes that we discuss further below.

We now illustrate the intervention actions described in Table 1 by specific COVID-19 public health measures.

| Type of intervention action | Discovering from the network: Identification | Spreading through the network: Diffusion | Altering the network: Structural change |
|-----------------------------|---------------------------------------------|-----------------------------------------|----------------------------------------|
| Level of intervention action| Local                         | Node: Identification of target individuals. | Node: Priming of influencers. | Node: Change nodal attributes to affect ties. |
|                            | Setting                       | Dyad: Identification of key dyads that connect the network. | Dyad: Dyadic social influence to encourage nodal change. | Dyad: Change the nature of existing dyadic ties. |
|                            | System                        | Egonet: Identification of egonet partners. | Egonet: Social influence processes within egonet. | Egonet: Change the structure of the egonet. |

**Table 1.** Network intervention actions by Type and Level.
so this intervention action is often combined with node-level identification and diffusion. Of course, publicly well-known influencers may not be necessary. Vaccinated individuals might be called on to convince a family member or a friend, or doctors to encourage their individual patients, to undertake vaccination.

Egonet social influence: This is like dyadic social influence except that the influencer is to direct the message across their entire egonet. A social media influencer might be primed to alert all followers about a public health message, rather than just certain dyads.

Structural change:

Nodal attribute change: A fundamental individual-level intervention in a pandemic is vaccination of a person to prevent infection. In network terms, the attribute of the node changes from unvaccinated to vaccinated. The direct intention is to protect individual health, but network implications remain. As the virus can only be spread from infected to susceptible individuals, i.e., across social contagion ties, a vaccinated individual who ceases to be susceptible becomes an isolate in the social contagion network. As vaccination levels increase, that network becomes less dense, perhaps until the disease is unable to find sufficient paths through the network to spread widely (so-called herd immunity.) Of course, no vaccine has perfect efficacy in preventing infection, so a more nuanced description focusses on the strength of social contagion ties, and how these weaken with vaccination. Vaccination to prevent contagion changes the structure of social contagion ties, a kind of “de-networking” intervention that removes density, or at least the density of strong ties.

Dyadic tie change: Social distancing is an intervention designed to affect the nature of social ties, to minimize disease transmission. (“Social distancing” is perhaps better termed “physical distancing” but the term has now become ubiquitous in epidemiological contexts.) In social distancing, existing relationships are maintained but one element of the ties (physical distance of interaction) is changed. In that sense, this action is directed at changing the nature of a social tie, not the node, and so altering the network structure.

Egonet structural change: Social isolation has obvious similarities to social distancing but is more extensive in stripping away egonet structure. Isolation in COVID-19 contexts may be mandated in response to individual infection. All possible egonet contact ties are removed for the duration of the isolation, a dramatic change to egonet structure.

Social setting intervention actions:

Identification: Sometimes crucial social settings need to be identified. For COVID-19, public health officials may seek to identify public sites where exposure may or has occurred. This will enable further responses such as deep cleaning of the site, perhaps a restaurant or shopping facility, and alerting the general public so as to warn others who have attended the site but not yet been identified.

Diffusion: Settings may be used to deliver other forms of intervention. For instance, vaccination centers may be established for specific schools, where the school community, including parents and teachers, may be encouraged to attend and be vaccinated. The use of trusted, iconic, or culturally sensitive social settings in this way may diffuse behavior more successfully for certain communities by providing a well-recognized and safe place to participate.

Structural change: The setting structures themselves may be altered. Exposure sites of extreme risk may be closed for a period, so that the setting is essentially removed from the network. Mandating people to work from home removes the office as a social setting for disease spread; closing a school because of a high level of infection removes that school as a setting until the school-based outbreak has subsided.

System level intervention actions:

Identification: At the level of the entire system, identification relates to system level properties, including the average path length and diameter, both of which are relevant to the speed and extent of disease spread across a social network. Groups of individuals with high levels of contact ties may be identified from the network structure (c.f., Valente’s segmentation category). For a social system, system level properties also include exogenous factors such as geo-spatial and socio-economic structures within which the network is embedded. These exogenous factors may interact with or shape the system-level network structure in various ways and need to be accounted for in planning network interventions. For instance, the exogenous geography of a city can interact with the social structure and the network ties that constitute it, to affect network connectivity. In a COVID-19 context, “long range” social ties, encouraged perhaps by business or transport links, may reach across the entire geography of the city to present specific risks of virus spread from infected suburbs to previously uninfected areas.

Mandated aggregation of lower level interventions: Local or setting level diffusion and structural change interventions may be mandated across the entire system. For instance, whether or not an individual wishes to isolate, public health mandates might require that all infected people do so, with penalties for non-compliers. To close a single setting such as one school is to act at the level of that setting, a setting-level intervention action. But a government mandate to close all schools is an intervention action across the entire social system. So, even though one may entail the other, we distinguish action at the level of the system (the mandate) from closure of a particular school which is action at the setting level. In this intervention, we see two intervention actions, one at system and one at settings level, and multiple intervenors, the government issuing the public health order and the individual principals closing their schools in response to that order. This example demonstrates that a network intervention can involve more than one intervention action, and more than one intervenor, and that these can be at different levels.

Diffusion dependent on structural position: Burt (1987) observed that diffusion may occur not just through dyadic social ties but also through people occupying similar network positions derived from the global network structure. These positions may be based on structural equivalence as Burt argued, or other exogenous factors that decompose the network in various ways. For COVID-19, for instance, information diffusion interventions may need to be differentiated for distinct communities or for people in different strata of society.

Structural change: Social activity across the community may be varied according to system-wide exogenous factors. For instance, there may be mandated limitations on social access across the entire community for unvaccinated individuals (e.g., to events). In network terms, by dividing the community on the basis of vaccination status, the intervenor (in this case, government) creates an a priori blockmodel based on an attribute (vaccination) and then reduces density of contact ties in some of the blocks.

These examples show that COVID-19 public health interventions can be cast in a social network framework with multilevel considerations a central feature. We will go beyond COVID-19 to illustrate how this framework can also be applied to other domains. Before we do so, however, because Table 1 is explicit only about the action of an intervention, we make some comments about intervention goals and outcomes.

7. Multilevel goals and outcomes of network interventions

Our main aim is to explain the taxonomy of intervention actions in Table 1, leaving a systematic examination of intervention goals and outcomes to further work towards a fuller theorization. In this section, we provide some early thoughts, particularly on outcomes, towards that end.

Intervention outcomes at multiple levels simultaneously.

Intervention goals, actions and outcomes are often at different levels, with implications at multiple levels simultaneously. Intervention actions that target individuals may have system level consequences; actions aimed to optimize collective outcomes will produce individual outcomes.

Examples of system level consequences arising from the COVID-19 pandemic include:
Exclusive focus on individual outcomes can lead to suboptimal outcomes for collectives and, in turn, for the individuals that comprise them. Considerations about “the commons” are not always reflected in the theorization and design of network interventions, even though they have been extensively addressed beyond the network literature (Hardin, 1968). Network research has been traditionally dominated by the drivers and consequences of networks either at the individual or system level, while too often neglecting the link between these two levels. Fortunately, a multilevel perspective is now gaining more traction in network approaches (see, e.g., Bodin et al., 2019; Coutinho et al., 2020; Lazega and Snijders, 2016).

The social processes activated by network interventions may operate simultaneously on various levels, with potential for important cross-level effects, and intervention outcomes at one level may contribute to or diminish successful outcomes at another. In practice, such recognition should help in the design of more effective network interventions, with outcomes better matched to goals, as well as fewer unintended or unrecognized consequences of intervention programs at other levels.

To illustrate this somewhat abstract point, here we provide three examples of everyday (non-COVID) interventions with multilevel outcomes, especially contrasting local and system level outcomes. Sometimes these outcomes may be in line with the goals of the intervention, but sometimes not, leading to unintended consequences at another level. Each of these examples is a form of network intervention, although not always examined in that context:

- **Organizational restructuring is a common network intervention, although not always viewed as such, and is designed and implemented to produce system-wide improvement of firms or institutions. Local level actions may be taken with individuals shifted into different positions or made redundant, or new people recruited to fix perceived issues. At the system level, formal structures may be altered (e.g., departments may be merged or scrapped, or reporting lines changed). The goal is typically at the system level with the intent of producing improved organizational outcomes. Nevertheless, the restructuring inevitably has consequences, sometimes unintended, for the individuals subjected to them.**

- **Many organizations work on projects, and entire economies are becoming at least partially “projectified” (Lundin and Söderholm, 1998). Projects have been theorized as interventions in wider systems such as in the functioning of a city, its infrastructure, or the health of its natural environment (Whyte and Davies, 2021). As opposed to “business as usual”, projects have a beginning and an end and are designed to shift the targeted system from one state to another. This is achieved by a collaboration of teams of experts with a range of skills. The project outcome is a result of the combination of their individual competencies as well as their interactions with one another and with the project stakeholders. Nevertheless, outcomes (positive or negative) go far beyond any of the individual benefits each project team member receives for the work.**

Social network theory usually accepts that network social influence processes leading to a change in individual attributes, and social selection, a change in network ties, are conceptually separable, even if sometimes difficult empirically to pull apart. Table 1 maintains this distinction in treating columns 2 and 3 separately. The most sophisticated methodology to separate influence and selection empirically is the Stochastic Actor Oriented Model (for a summary, see Snijders et al., 2010). These models and related approaches, however, do not countenance situations where the two processes are necessarily intertwined and inseparable.

Our earlier discussion provides one example where this separability is not tenable in practice: simple disease spread under an SIR model, where the change in the infection attribute of the individual is necessarily linked to creation or destruction of social contagion ties. This raises the possibility of special types of ties where changes in nodal attributes is necessarily – or at least, almost inevitably – accompanied by changes in network ties. In these cases, the tie and the attribute are what we term co-constitutive (as opposed to co-evolutionary as in the stochastic actor-oriented framework): the attribute of the node is related to the structure of the ties about the node, so that tie-change and attribute-change shape each other. COVID-19 examples are easy to find: the disease status of an infected person may lead to contagion but once known it also can lead to a simultaneous change in network ties where network partners avoid the diseased person. We also see examples in non-disease contexts. If person a ceases to believe that person b is a friend, the change in the attribute, belief about person b, is necessarily accompanied by a change in the nature of the tie between a and b. This is dramatically so for romantic relationships where the romantic tie crucially depends on beliefs about the other person. If the beliefs change, the tie may simply cease to exist.

This is important for network intervention studies if the action of an intervention is directed at a co-constitutive tie-attribute. Here, the potential for unintended outcomes undermining the goal of an intervention is increased. We have already presented the familiar social influence intervention that primes influencers (nodal attribute change) to diffuse a desired behavior or information to their network partners (dyadic or egonet diffusion). But if the intervention is aimed at a co-constitutive tie-attribute, so that the attribute change in priming the influencer is associated with tie change to followers, it may be that the diffusion process is diminished or even halted before it starts. The goal of diffusion is then confounded by the process of structural change that accompanies the diffusion action. The intervention outcome has been stymied.

For instance, if the leader of a smoking group changes his or her smoking in order to diffuse non-smoking among the followers, but the effect is that the followers cease to see him or her as the leader because of the behavior change, the intervention may fail (de la Haye et al., 2019; Schaefer et al., 2013; Weihua, 2015; Shannon et al., 2020). In contrast, a clever intervention may also use co-constitutive tie-attributes to enhance the efficacy of a network intervention. If providing the influencer with certain skills or resources leads to an increase in popularity (increased ties) through greater fame or status, then the diffusion of those skills to the new followers and hence across the network may be accelerated (Matous and Wang, 2019).

Co-constitutive tie-attributes are not the only ways in which intervention actions can be undermined by ongoing network processes. For instance, a commonly described intervention in terrorist networks is the identification of leaders of terrorist or criminal cells (see below) to enable arrests or the fragmented nature of criminal and terrorist networks. The action of the underlying network, however, has the capacity to reconstitute itself, then a new cell with an unknown leader may simply come into being. The goal of lessening danger may be undermined to produce an opposite outcome.

8. Multilevel network interventions in non-COVID applications

Table 1 shows that to cover the network interventions utilized in COVID-19 public health responses, a multilevel dimension is necessary.
All the cells in the Table can be populated with COVID examples. The question then arises whether a multilevel framework is also applicable for network interventions in other domains. In this section, our goal is simply to provide illustrations from research in four other areas to show that the intervention actions studied encompass different levels, whether or not a multilevel focus has been overtly considered in the research. Of course, current research in a particular domain may favor a particular type of intervention, but our examples show that in each of the areas, once attention is given to the issue, a multilevel dimension is readily applicable.

### 8.1. Non-COVID-related public health

Over recent decades, the application of social network theories and methods in the field of public health has substantially increased. Originally—and before COVID-19—the concept of networks was used by epidemiologists to understand the propagation of infectious diseases such as cholera, Ebola, HIV/AIDS, and yellow fever; (Bell et al., 1999; see Keeling and Eames, 2005, for a review of early studies), and extended later to simulation studies of disease-spread across networks (e.g., Read et al., 2008). These arguments about network contagion were broadened beyond disease applications to include the diffusion of health behavior across networks, behaviors such as smoking (Alexander et al., 2001), alcohol (Kremer and Levy, 2008; Litt et al., 2007), even obesity (Christakis and Fowler, 2007) and loneliness (Cacioppo et al., 2009), although not without some controversy (e.g., Lyons, 2011). The public health applications are strongly rooted in the innovator approach derived from Diffusion of Innovation theory (Rogers, 1962; Valente, 1995; see also Valente and Davis, 1999). Through social ties and affiliations, people exert influence on one another in ways that induce changes in behaviors. These social influence arguments and related methodologies have long traditions in social network science extending well beyond public health behaviors (e.g., Dowen, 1982; Erbring and Young, 1979; Friedkin, 1998; Friedkin and Johnsen, 1990; see also Katz and Lazarsfeld, 1955).

So, the public health focus has often been on how to activate social influence mechanisms (Valente and Rogers, 1995), leading to applications with a social network design to induce behavior change to improve health (see Castillo et al., 2019, Hunter et al., 2019, and Latkin and Knowlton, 2015, for reviews). Typically, these follow the diffusion intervention strategy of Table 1, with nodal identification and local level diffusion actions (see Campbell et al., 2008 as an example).

However, there have been public health intervention examples that go beyond this diffusion framework and fit in with the other categories of Table 1.

- **Dyadic Identification**: A child abuse intervention program that targeted adolescents and (one of) their caregivers to improve social support, reduce violence, and improve mental health (Cluver et al., 2016).

- **Dyadic Structural change**: Interventions that aim at changing intimate partner violence by altering household dynamics (Buller et al., 2016).

- **Egonet Diffusion**: Interventions based on respondent-driven sampling strategies or that target specific cliques of respondents. Recruited individuals are asked to bring a few people from their egonet partners to be enrolled in the program (e.g., Hoffman et al., 2015; Buller et al., 1995).

- **Egonet Structural change**: Interventions that aim at changing personal social support networks to healthier social environments. For example, Litt et al. (2007) aimed to change personal support networks to foster alcohol abstinence.

- **Diffusion at social setting level**: Community-based interventions that involve the delivery of a service in a community setting (e.g., tobacco and alcohol prevention programs at school or workplaces).

### 8.2. Criminal networks

The use of social network research methodologies to study crime has expanded over the last twenty years to include the study of co-offending (e.g., Frank and Carrington, 2007; Grund and Morselli, 2017; Sarnecki, 1999), terrorism (e.g., Bright et al., 2020; Krebs, 2002), and organized crime (e.g., Coutinho et al., 2020; Morselli, 2009a).

In the context of crime networks, identification could involve identification of brokers, highly connected actors or leaders, in order to dismantle or disrupt criminal activity (see Bright, 2015). Diffusion-based interventions in crime networks include programs that co-opt influential community leaders in crime prevention strategies. Structural change includes attempts to fragment an illicit network (e.g., a drug trafficking network) or sever crime scripts by removing connections between actors who play key roles (see Malm and Bichler, 2011; Morselli and Roy, 2008; Bright, 2015), often by making strategic arrests of key actors.

Research on offending and crime networks provides the following examples.

- **Nodal identification**: network identification of brokers, highly active actors, and leaders (e.g., Morselli, 2009b; Bright et al., 2012; Calderoni and Superchi, 2019).

- **Nodal diffusion action**: Influential community leaders are primed to disseminate pro-social, non-extremist messages (e.g., Macnair and Frank, 2017).

- **Dyadic diffusion**: peer-based programs to prevent crime, extremism, and illicit drug use (e.g., MacArthur et al., 2016).

- **Egonet Diffusion**: mentoring programs (e.g., O’Dwyer, 2019); interventions to overwhelm the effect of negative ties by counteracting with positive ties (Boman and Mowen, 2017), following differential association theory (Sutherland, 1947).

- **Egonet Structural change**: programs to improve social supports and increase social activity for isolated actors at risk of engaging in crime (Hickert et al., 2019) or terrorism (Rousseau et al., 2019).

- **Identification at setting level**: detection of settings where criminals or terrorists meet, form ties and plan crime or terrorism (e.g., Argomaniz and Bermejo, 2019).

- **Diffusion at setting level**: interventions in prisons or juvenile justice facilities to reduce recidivism (Beaudry et al., 2021).

- **Diffusion and Structural change at system level**: broad-based interventions to build community resilience and efficacy to reduce crime (Ellis and Abdi, 2017).

### 8.3. Organizational networks

Our multilevel intervention framework aligns with two frontiers in management and organization studies. The first frontier is the increasing interest in the interplay between formal and informal organizational structures (McEvely et al., 2014). The levers available to leaders to affect organization change typically involve formal organizational design interventions; but the crucial role of informal networks in organizational change management is often overlooked (Stouten et al., 2018). The second frontier is the understanding of organizations as networked systems that produce outcomes at multiple levels of analysis. Much organizational network research has focused exclusively on a single level of analysis, for example, linking individual network position to...
is not a common method of intervention in educational contexts. When it is used, it is mainly intended to provide opportunities to build social connections with new and diverse peers (e.g. Boda et al., 2020; van Waes, 2017).

Examples of network intervention research in education, following the taxonomy of Table 1, include:

- **Nodal Identification**: identification of peer leaders to deliver health behavior change such as tobacco prevention (e.g., Valente et al., 2003) or promoting water consumption (Smit et al., 2021).
- **System level Identification**: use of network diagnostics of the social structure of the classroom to help teachers to recognize and reduce behavioral problems such as bullying and victimization (e.g., Kaufman et al., 2021).
- **Nodal Diffusion action**: training influential students to be peer supporters to encourage healthy behaviors (e.g., Buller et al., 1999; Campbell et al., 2008).
- **Egonet Structural change**: strengthening a teachers’ network through professional development programs (van Waes et al., 2018).
- **Structural change at system level**: inducing mixed-gender friendship through creating contact opportunities across gender boundaries (Boda et al., 2020).

9. Concluding comments: where next for a theory of network interventions?

We have focused in this paper on a taxonomy of network intervention actions, with the aim of widening the conceptualization of such interventions as they might unfold in the real world. These are explicitly social network interventions, intended to generate change and produce outcomes for social actors, social groups, or whole populations. We have followed Valente (2012) in proposing the tripartite categorization of Identification, Diffusion and Structural change, but have extended this with an orthogonal dimension to capture the multilevel aspects implicit in any network formulation. The use of a multilevel framework is necessary, we argue, if we are to consider seriously the possibility of parallel and sometimes unintended consequences at a different level from the original intervention action. By conceptually separating an intervention into its goals, actions, and outcomes, we can consider how these multilevel outcomes arising from a given intervention action may intersect to fulfill, enhance or in some cases even defeat the goals of that intervention.

Our focus has been on network interventions that are designed to implement change. Of course, there are interventions that are designed to mitigate against change, to preserve or sustain a productive network. These interventions can be described as aimed at network resilience. Simple examples abound: for instance, reunions of schools or organizations are designed to sustain or revive past social ties that might otherwise lapse. Academic conferences are a similar example. Little research attention has been paid to such forms of interventions, although given the major implication of, for instance, climate change or natural disaster, how best to sustain effective social systems are obvious questions (see, e.g., Barnes et al., 2017, for discussion of how social ecological networks might either adapt or transform in response to changing ecological conditions.).

Beyond these issues of network resilience, there is much still to be done in developing the theory and empirical application of network interventions. Methodological development will continue to be necessary. While there have been advances in recent times in modeling multilevel and hierarchical network structural and influence processes (e.g., Wang et al., 2013; Koskinen and Snijders, 2022), different outcomes at different levels, and possible dependencies between outcomes, presents new challenges. Modeling over time would add additional complexity. Yet, with recent advances in hand, these next steps are within reach.

Our categorization of network levels into local-settings-system
mirrors the micro-meso-macro framework of more general, well-established multilevel theory (see, for instance, House et al., 1995; Kozlowski and Klein, 2000). For the local level, we have focused on node, dyads and egonets because they are basic and familiar in social network research. In various contexts, however, other well-established local network structures may also be applicable, such as cliques, structural holes or even four-cycles (Barnes et al., 2017). In family studies, for instance, interventions might focus on specific family dyads, on just part of the egonet rather than the whole of it, or on the entire family social structure (Boettcher et al., 2020). So, a partial egonet may count as a local network structure of interest. Whether family members are treated as part of an egonet or whether the family is rather construed as a social setting in its own right will depend on the focus of the research and the intervention. Nevertheless, multilevel issues in family contexts are never far from the surface: for instance, Berger and Fowlkes (1980) provide an early example of interventions that contrast dyadic with family-system interventions. The general point is that whatever may be the local, settings, or system structures of interest, a multilevel perspective is required.

Theoretically, several concerns remain central to a fuller consideration of network interventions. We briefly comment on some major – somewhat overlapping – issues that we see as important to further progress: network effectiveness, causality, intervention selection and evaluation, and who benefits from network interventions.

9.1. Network effectiveness

In large part, social network research is not teleological but essentially descriptive. Empirical social networks are often considered as deprived of any overall, global purpose, although it is agreed that actors create and extinguish ties to suit their own individual goals. This conceptualization comes from the idea that a social network is essentially endogenous. It has its own internal dynamics and localized evolution deriving from no more than the social actions emerging from decisions and preferences of its individuals, shaped though these actions may be by the surrounding network environment of each actor. Major network methodologies are built on such a conceptualization (e.g., Stochastic actor oriented models, Snijders et al., 2010).

Yet, with network interventions, teleology comes to the forefront in ways that are not always easilyaccommodated with past social network theories. This is especially so for structural change interventions which are designed to alter the network structure in ways that make it more effective for some purpose. That purpose is exogenous, selected by the intervenor, and often global in applying to the whole network, collectively. Organizations, for instance, have purpose from the start: they have goals, priorities, outputs and so on. Organizational restructuring, typically involving change to organizational network structures, is intended to improve the operations of the organization in achieving these collective purposes.

So, what can be said about a social network that makes it more or less effective for a given purpose? While network scholars have insight whether a node is more or less advantaged given a network position, they are often reluctant and on much less certain ground when deciding whether a network, based on its internal structures and processes, is more or less effective in achieving a collective purpose.

Nevertheless, there are social network research traditions where the question of changing network effectiveness under various conditions is the central focus, stretching at least back to Leavitt (1951) who examined group performance under different group communication structures. Current work that directly confronts issues of effective network structure tends to be concentrated in specific domains (e.g., organizational networks, Brennecke et al., 2019, Kenis and Raab, 2020; environmental governance, Barnes et al., 2017, Berardo and Sholz, 2010; team performance, Müller et al., 2020). While questions of network effectiveness surely need to be contextualized, these different areas do not have consistent approaches to the types of network properties that are relevant. In a general theorization of network interventions, there needs to be a more overt and coordinated discussion of network effectiveness.

9.2. Causality

Once we determine what counts as an effective network, then we can consider designing an intervention to shift an existing social network towards “better” structures or processes. Within a multilevel world with actions and outcomes potentially at different levels, however, it is not always straightforward how to determine causality or how to measure the precise effect of the intervention. Intervention by necessity implies a causal framework. Causality in social networks is something of a vexed issue, as is the identification of treatment effects (see, e.g., Manski, 1993; Fafchamps, 2015). Identification of a causal effect, which may or may not be a treatment effect, is typically concerned with ruling out endogeneities in data. There are circumstances where this can be done, even with cross-sectional data (Bramoullée et al., 2009). These endogeneities are however arguably the main interest of network research and are referred to as network dependencies (Brandes et al., 2013). An early example of interventions that contrast dyadic with family-system interventions.

Nevertheless, network experiments (e.g., Aral, 2016) and randomized control trials (e.g., Campbell et al., 2008) offer ways forward. Such studies can afford to be agnostic as to the network mechanisms that affect change, with pre- and post- measures taken as measures of the treatment effect. If, however, we want to understand the mechanisms of network interventions, rather than just the results, we must deal with both the issue of how influence, selection, and context may be inherently confounded (Shalizi and Thomas, 2011), as well as indeterminacies in peer effects (Manski, 1993). Simulation studies can also provide insights into plausible causal mechanisms (e.g., Nishi et al., 2020; Schaef er et al., 2013). Rather than single studies, programs of research that can triangulate on plausible mechanisms in different ways may be required to give a good sense of causal direction (Robins, 2015).

One definition of the causal effect of an intervention is a counterfactual interpretation in terms of potential outcomes (Rubin, 1974, 2005). The effect of an intervention is then defined as the difference between the observed outcome after intervention and the potential outcome that we would have observed under the counterfactual scenario that there was no intervention. Naturally, we can never observe both outcomes but there are techniques for estimating this treatment effect based on random (and sometimes non-random) allocation of the intervention and comparison of treatment and non-treated units. If the units are networks, then any network level measure can be compared across treated and non-treated networks. The problem is of course that we do not know the role of the network in creating any measured differences – maybe the differences would have been observed for any arbitrary collection of non-connected individuals. If we want to investigate the causal effect on a network selection or influence process, assuming that this is specifically parameterized, then we could construe the effect of an intervention as the difference in this parameter between the treated and non-treated groups. However, this poses two problems. The first is that we need to compare magnitudes of effects across networks, something which is notoriously fraught. The second issue arises when the intervention is administered to some but not all individuals in a network – to what extent is the measured effect then contingent on specific individuals and to what extent has the intervention affected the entire network?

Although these can be difficult issues, there are currently methods that can be applied to assist. Stochastic actor oriented models parameterize both influence and selection (van der Weele, 2015, p.439) and multilevel longitudinal networks in addition account for system level effects (Koskinen and Snijders, 2022).

While these comments point to some of the ongoing issues for a rigorous causal interpretation, it is also worth noting that a network
intervention may nevertheless assist our understanding of causality in networks. In the study of network interventions, we can increase our understanding of social network processes in a way that is not readily available in observational studies without controlled exogenous alteration of some network elements.

So, there is a rich ground for further work on network causality within an intervention framework.

9.3. Network intervention selection and evaluation

A further pressing question is the choice of an appropriate intervention in a particular context, and how best to evaluate network interventions.

The variety of network-based interventions we have described above in the context of COVID-19 is remarkable. The degree to which these interventions are (or should be) supported by empirical evidence is a matter of some controversy. Nevertheless, what fundamentally enables the extent of interventions for COVID-19 is that we understand a great deal about the diffusion process of COVID-19 itself. As more and more becomes understood about how COVID-19 spreads person-to-person, it is possible to model the likelihood of infection across network structures, through either simulation or mathematical means. This allows us to identify the types of people, relationships, and settings that may be considered high-risk, and to suggest alterations to social structure that might interrupt the spread of contagion over the network. So, for example, the work of Rolls and colleagues, in the contagious spread of Hepatitis C over needle-sharing networks: Rolls et al., 2012, 2013a, 2013b).

In contrast to biological processes of contagion, we understand relatively less about how behaviors, attitudes, and beliefs spread on a micro-level. While one person may undoubtedly influence another on these psychological domains, understanding the precise dynamics of this influence requires much greater knowledge about the type of relationship they have, their respective personal attributes, the setting in which the influence takes place, and so forth. Even then, we must infer the operation of these influence processes, rather than observe them directly (as can be done with biological contagion). While considerable work has been done in psychology on social influence pressures on individuals, even on dyads (e.g., Cialdini and Goldstein, 2004), these micro-mechanisms have not been well integrated into social network formulations (e.g., Friedkin, 1998). Veenstra and Laninga-Wijnen (2022) point to the need for a better understanding of the various types of relationships and social mechanisms in network interventions using peer influence.

As a result, choosing an appropriate network intervention is more difficult. When we lack a detailed understanding of the person-to-person influence mechanisms for a given outcome, it becomes harder to postulate how that outcome spreads across a network, so the evaluation of the intervention is more difficult. We echo the call of Veenstra and Laninga-Wijnen for ongoing work on the basic micro-level processes by Argomaniz, J., Bermejo, R., 2019. Jihadism and crime in Spain: a convergence settings approach. Eur. J. Criminol. 16, 351–368.

Barnes, M., Bodin, O., Guerrero, A., McAllister, R., Alexander, S., Robins, G., 2017. The social structural foundations of adaptation and transformation in social-ecological systems. Ecol. Soc. 22, 16.

Beaudry, G., Yu, R., Perry, A.E., Fazel, S., 2021. Effectiveness of psychological interventions in prison to reduce recidivism: a systematic review and meta-analysis of randomised controlled trials. Lancet Psychiatry 8, 759–773.

Bell, D.C., Atkinson, J.S., Carlson, J.W., 1999. Centrality measures for disease transmission networks. Soc. Netw. 21, 1–21.

Berardo, R., Sholtz, J., 2010. Self-organizing policy networks: Risk, partner selection, and cooperation in estuaries. Am. J. Political Sci. 54, 632–649.

Bodin, O., Alexander, S.M., Baggio, J., Barnes, M.L., Berardo, R., Cumming, G.S., et al., 2019. Improving network approaches to the study of complex social-ecological interdependencies. Nat. Sustain. 2, 551–555.

Boettcher, J., Fritter, B., Denecke, J., Hot, A., Daubmann, A., Zapf, A., et al., 2020. Evaluation of two family-based intervention programs for children affected by rare disease and their families–research network (CARE-FAM-NET): study protocol for a randomised, randomized, controlled multicenter trial in a 2×2 factorial design. BMC Fam. Pract. 21, 1–11.

Boman IV, J.H., Mowen, T.J., 2017. Building the ties that bind, breaking the ties that don’t: Family support, criminal peers, and reentry success. Criminology & Public Policy 16, 753–774.

Borgatti, S.P., Molina, J.L., 2003. Ethical and strategic issues in organizational social network analysis. Journal of Applied Behav. Sci. 39, 337–349.

references

Albott, C.S., Wozniak, J.R., McGlinch, B.P., Wall, M.H., Gold, B.S., Vinogradov, S., 2020. Battle buddies: rapid deployment of a psychological resilience intervention for health care workers during the COVID-19 pandemic. Anesth. Analg. Alexander, C., Piazza, M., Mekos, D., Valente, T., 2001. Peers, schools, and adolescent cigarette smoking. J. Adolesc. Health 29, 22–30.

An, W., 2011. Models and methods to identify peer effects. In: Scott, J., Carrington, P. (Eds.), Handbook of Social Network Analysis. Sage, pp. 514–532.

Aral, S., 2016. Networked experiments. In: Bramoulle, Y., Galeotti, A., Rogers, B.W. (Eds.), The Oxford Handbook of the Economics of Networks. Oxford University Press, pp. 376–411.

Argomaniz, J., Bermejo, R., 2019. Jihadism and crime in Spain: a convergence settings approach. Eur. J. Criminol. 16, 351–368.

Barnes, M., Bodin, O., Guerrero, A., McAllister, R., Alexander, S., Robins, G., 2017. The social structural foundations of adaptation and transformation in social-ecological systems. Ecol. Soc. 22, 16.

Beaudry, G., Yu, R., Perry, A.E., Fazel, S., 2021. Effectiveness of psychological interventions in prison to reduce recidivism: a systematic review and meta-analysis of randomised controlled trials. Lancet Psychiatry 8, 759–773.

Bell, D.C., Atkinson, J.S., Carlson, J.W., 1999. Centrality measures for disease transmission networks. Soc. Netw. 21, 1–21.

Berardo, R., Sholtz, J., 2010. Self-organizing policy networks: Risk, partner selection, and cooperation in estuaries. Am. J. Political Sci. 54, 632–649.

Bodin, O., Alexander, S.M., Baggio, J., Barnes, M.L., Berardo, R., Cumming, G.S., et al., 2019. Improving network approaches to the study of complex social-ecological interdependencies. Nat. Sustain. 2, 551–555.

Boettcher, J., Fritter, B., Denecke, J., Hot, A., Daubmann, A., Zapf, A., et al., 2020. Evaluation of two family-based intervention programs for children affected by rare disease and their families–research network (CARE-FAM-NET): study protocol for a randomised, randomized, controlled multicenter trial in a 2×2 factorial design. BMC Fam. Pract. 21, 1–11.

Boman IV, J.H., Mowen, T.J., 2017. Building the ties that bind, breaking the ties that don’t: Family support, criminal peers, and reentry success. Criminology & Public Policy 16, 753–774.

Borgatti, S.P., Molina, J.L., 2003. Ethical and strategic issues in organizational social network analysis. Journal of Applied Behav. Sci. 39, 337–349.
Bramouille, Y., Djebbari, H., Fortin, B., 2009. Identification of peer effects through social networks. J. Econ. 150, 41–55.

Brandes, U., Robertson, P., McGranick, A., Wasserman, S., 2013. What is Network Science? Netw. Sci. 1, 1–15.

Breuncke, J., Cootinou, J., Borgatti, S.P., Gossner, T., Kleinbaum, A.M., Labianca, G., & Parker, A. (2019). Towards a Theory of Organizational Network Effectiveness: Challenges and Opportunities. Academy of Management Proceedings, 79th Annual Meeting of the Academy of Management, Boston, Massachusetts, United States, 9–13 August 2019.

Bright, D., Whelan, C., Harris-Hogan, S., 2020. On the durability of terrorist networks: Revealing the hidden connections between jihadist cells. Stud. Conf. Terror. 45, 638–656.

Bright, D.A., 2015. Disrupting and dismantling dark networks: Lessons from social network analysis and enforcement simulations. In: Gerdes, L.M. (Ed.), Illuminating Dark Networks: The Study of Clandestine Groups and Organizations. Cambridge University Press, pp. 39–51.

Bright, D.A., Hughes, C.E., Chalmers, J., 2012. Illuminating dark networks: A social network analysis of an Australian drug trafficking syndicate. Crime, Law & Soc. Change 57, 151–176.

Buller, A.M., Hidrobo, M., Peterman, A., Heine, L., 2016. To what a man’s heart is through his stomach?: a mixed methods study on causal mechanisms through which cash and in-kind food transfers decreased intimate partner violence. BMC Public Health 16, 1–13.

Buller, D.B., Morrill, C., Taren, D., Aickin, M., Sennott-Miller, L., Buller, M.K., et al., 1999. Randomized trial testing the effect of peer education at increasing fruit and vegetable intake. J. Natl Cancer Inst. 91, 1491–1500.

Burt, R., 1987. Social contagion and innovation: Cohesion and structural equivalence. Am. J. Sociol. 92, 1287–1335.

Burt, R.S., 2004. Structural holes and good ideas. Am. J. Sociol. 110, 349–399.

Cappella, J.T., Fowlkes, E., Christakis, N.A., 2009. Alone in the crowd: The structure and spread of loneliness in a large social network. J. Personality & Social Psychol. 97, 977–991.

Calderoni, F., Superti, E., 2019. The nature of organized crime leadership: Criminal Interlocks in wrought wire organizations. Soc. Netw. 52, 419–444.

Calloway, M., Morrissey, J.P., Paulson, R.I., 1993. Accuracy and reliability of self-reported data in interorganizational networks. Soc. Netw. 15, 377–398.

Campbell, R., Starkey, F., Holliday, J., Aubrey, S., Bloor, M., Parry-Langdon, N., et al., 2008. An informal school-based peer-led intervention for smoking prevention in adolescence (ASSIST): a cluster randomized trial. Lancet 371, 1595–1602.

Castillo, E.G., Ijadi-Maghsoodi, R., Shadravan, S., Moore, E., Mensah, M.O., et al., 2019. The way to a man

Cheung, L., Morselli, C., 2017. Overlapping crime: Stability and specialization of co-offending relationships. Soc. Netw. 51, 14.

Cilliers, J., Dube, O., Siddiqi, B., 2016. Reconciling after civil conflict increases social capital but decreases individual well-being. Science 352, 787–794.

Cilliers, J., Magubane, S., Mweetwa, D., 2019. Reconciliation and community resilience in areas affected by civil conflict. J. Health Soc. Behav. 60, 362–376.

Clarke, R.M., 1971. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Cleaver, M., 1993. The social organization of health. Soc. Sci. Med. 36, 1015–1035.

Clifford, N.E., 1998. The spread of obesity in a large social network over 32 years. N. Engl. J. Med. 337, 370–379.

Clodd, R.B., Goldstein, N.J., 2004. Social influence: Compliance and conformity. Annu. Rev. Psychol. 55, 591–621.

Cliffords, J., Dube, O., Siddiqi, B., 2016. Reconciling after civil conflict increases social capital but decreases individual well-being. Science 352, 787–794.

Cloward, D., Ohlin, K., 1960. Differential association and differential opportunity: A theory of delinquency. Rev. Soc. Change 72, 419–444.

Conway, T., 1971. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Cook, D. (2009). The spread of evidence-poor medicine via flawed social-network analysis. J. Behav. Health Serv. Res. 24, 4

Cooley, C.H., 1909. Human Nature and the Social Order. Macmillan.

Cottle, F., 2000. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Crowley, R., 1971. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Cullen, E.J., 1988. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Curte, L., Meinck, F., Yakubovich, A., Double, J., Redfern, A., Ward, C., et al., 2016. Reducing child abuse amongst adolescents in low and middle-income countries: A pre-post trial in South Africa. BMC Public Health 16, 1–11.

Curran, J.A., Devis, T., Bright, D., Koskinen, J., 2020. Multilevel determinants of collaboration between organised criminal groups. Soc. Netw. 63, 56–69.

Doreian, P., 1982. Maximum likelihood methods for linear models. Social. Methods Res. 10, 243–269.

Dittrich, N., 1992. Building community resilience to violent extremism through genuine partnerships. Am. Psychol. 72, 284.

Erbring, L., Young, A.A., 1979. Individuals and social structure: contextual effects as endogenous feedback. Social. Methods Res. 7, 369–430.

Falk, L., 1999. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feld, S., 1981. The focused organization of social ties. Am. J. Sociol. 86, 1015–1035.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.

Feldman, R., 2009. The communication of crime. J. R. Soc. Psychol. 3, 160–167.
Morselli, C., 2009b. Hells Angels in springtime. Trends Organ. Crime. 12, 145–158.
Morselli, C., Roy, J., 2008. Brokerage qualifications in ringing operations. Criminology
46, 71–98.
Müller, S., Ghawi, R., & Pfeffer, J. (2020). Using Communication Networks to Predict
Team Performance in Massively Multiplayer Online Games. In 2020 IEEE/ACM
International Conference on Advances in Social Networks Analysis and Mining
(ASONAM) (pp. 353–360). IEEE.
Nishi, A., Dewey, G., Endo, A., Neman, S., Iwamoto, S.K., Ni, M.Y., Young, S.D., 2020.
Network interventions for managing the COVID-19 pandemic and sustaining
economy. Proc. Natl. Acad. Sci. 117, 30285–30294.
O’Dwyer, K., 2019. Reducing Youth Crime: The Role of Mentoring. Irish Probat. J. 16.
Pattison, P., Robins, G.L., 2002. Neighbourhood based models for social networks.
Sociol. Methodol. 32, 301–337.
Pescosolido, B.A., 2006. Of Pride and Prejudice: The Role of Sociology and Social
Networks in Integrating the Health Sciences. J. Health Soc. Behav. 47, 189–208.
Pescosolido, B.A., 2011. Organizing the Sociological Landscape for the Next Decades of
Health and Health Care Research: The Network Episode Model III-R as Cartographic
Subfield Guide. In: Pescosolido, B., Martin, J., McLeod, J., Rogers, A. (Eds.),
Handbook of the Sociology of Health, Illness, and Healing. Handbooks of Sociology
and Social Research. Springer, New York, NY.
Read, J.M., Eames, K.T., Edmunds, W.J., 2008. Dynamic social networks and the
implications for the spread of infectious disease. J. R. Soc. Interface 5, 1001–1007.
Robins, G., 2015. Doing Social Network Research: Network-based Research Design for
Social Scientists. Sage.
Rogers, E.M., 1962. Diffusion of Innovations. Free Press, New York.
Shannon, C.M., Michael, D., Prachi, B., Angela, C., Frank, K., Ruth, F.H., 2020. Peer
social network processes and adolescent health behaviors: A systematic review. Prev.
Med. 130, 1–19.
Siciliano, M.D., & Whetsell, T.A. (2021). Strategies of network intervention: A pragmatic
approach to policy implementation and public problem resolution through network
science. arXiv:2109.08197.