Less effective, but individually less costly, prophylactic measures can reduce disease prevalence in a simple epidemic model accounting for human behavior

Hugo Martin

Joint work with François Castella and Frédéric Hamelin

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Epidemics dynamics depend crucially on human behavior

Figure: Confirmed new covid-19 cases in France from 05/20 to 06/23. Source: data.gouv.fr

A recent (19/04/2023) preprint:

Revealing the unseen: About half of the Americans relied on others' experience when deciding on taking the COVID-19 vaccine

Azadeh Aghaeeyan[1*], Pouria Ramazi[1*], Mark A. Lewis[2]

Some existing models in behavioral epidemiology

Infection term :

$$\beta si = M \times (s \times i) \times C$$

with M meeting rate and C probability of contamination when an $s - i$ encountering occurs

- Bauch 2005: perfect, single-dose vaccination at birth
- Poletti *et al.* 2009, Martcheva *et al.* 2021, Cascante-Vega *et al.* 2022 : social distancing or reducing encountering $\longrightarrow$ reduction of transmission occurs if **at least** one in the pair adopt the protective behavior
- Two textbooks: Manfredi & d'Onofrio 2013, Tanimoto 2021

A behavioral SIS model

- Assumptions and modelling
- Analysis of the dynamical system

Force of infection: the different types of encounter

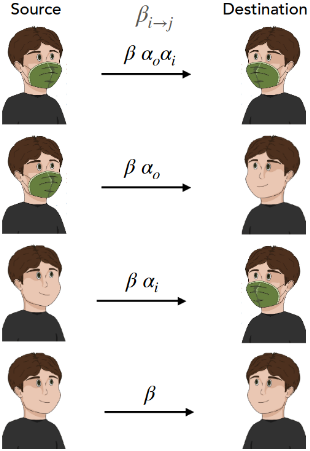


Figure: illustration from Pastor-Satorras' talk, Girona 06/2023

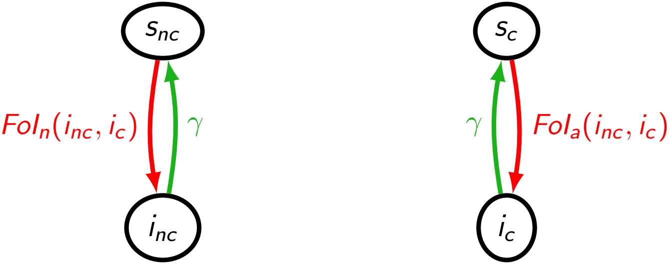
Force of infection: transmission rate associated with the types of encounter

e_T: efficacy on transmission, e_S: efficacy on susceptibility

Infection rate		Infected	
		Cooperator	Defector
Susceptible	Cooperator	$\beta(1-e_S)(1-e_T)$	$\beta(1-e_S)$
	Defector	$\beta(1-e_T)$	β

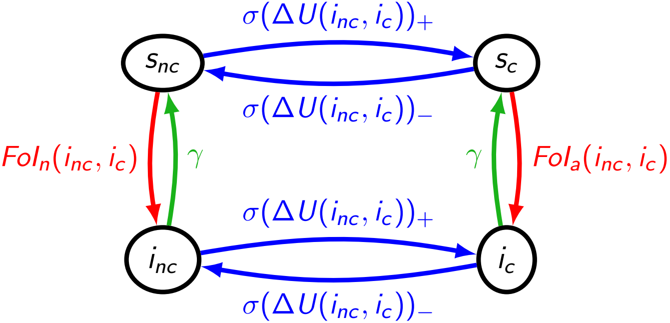
E.g.: face mask, $e_T \approx 95\%$, $e_S << e_T$.

Flux diagram for a fixed level of compliance



$$\begin{cases} \frac{\mathrm{d}i_{nc}}{\mathrm{d}t} = \beta(i_{nc} + (1 - e_T)i_c)s_{nc} - \gamma i_{nc} \\ \frac{\mathrm{d}i_c}{\mathrm{d}t} = \beta(i_{nc} + (1 - e_T)i_c)(1 - e_S)s_c - \gamma i_c \\ \frac{\mathrm{d}s_c}{\mathrm{d}t} = -\beta(i_{nc} + (1 - e_T)i_c)(1 - e_S)s_c + \gamma i_c \end{cases}$$

Flux diagram for a coupled behavior-epidemic SIS model



$$\begin{cases} \frac{\mathrm{d}i_{nc}}{\mathrm{d}t} = \beta(i_{nc} + (1-e_T)i_c)s_{nc} - \gamma i_{nc} - \sigma\left[(\Delta U(i_{nc}, i_c))_+ i_{nc} - (\Delta U(i_{nc}, i_c))_- i_c\right] \\ \frac{\mathrm{d}i_c}{\mathrm{d}t} = \beta(i_{nc} + (1-e_T)i_c)(1-e_S)s_c - \gamma i_c + \sigma\left[(\Delta U(i_{nc}, i_c))_+ i_{nc} - (\Delta U(i_{nc}, i_c))_- i_c\right] \\ \frac{\mathrm{d}s_c}{\mathrm{d}t} = -\beta(i_{nc} + (1-e_T)i_c)(1-e_S)s_c + \gamma i_c + \sigma\left[(\Delta U(i_{nc}, i_c))_+ s_{nc} - (\Delta U(i_{nc}, i_c))_- s_c\right] \end{cases}$$

A usefull change of variables

$$i := i_{nc} + i_c, \qquad c := s_c + i_c, \qquad x := \frac{s_c}{(1-i)\times c}, \qquad y := \frac{i_c}{i \times c}$$

$$\begin{cases} \frac{\mathrm{d}i}{\mathrm{d}t} = \beta(1 - e_S cx)(1 - e_T cy)i(1-i) - \gamma i \\ \frac{\mathrm{d}c}{\mathrm{d}t} = \sigma c(1-c)\Delta U(i,c) \\ \frac{\mathrm{d}y}{\mathrm{d}t} = \beta(1 - e_T cy)\left[(1 - e_S(1-cy))(1-iy) - (1-i)y\right] \\ \qquad\qquad +\sigma(1-y)(\Delta U(i,c))_+ \\ (1-i)x + iy = 1 \end{cases}$$

Behavior: game theory and payoffs

Main assumption: people are unaware of their sanitary status $\longrightarrow$ consistent with situation in which few tests are available.

- Payoff of Cooperators: $\pi_C = \pi_{C,C} \times C + \pi_{C,D} \times D$
- Payoff of Defectors: $\pi_D = \pi_{D,C} \times C + \pi_{D,D} \times D$

$\downarrow$ meeting $\rightarrow$	Cooperator	Defector
Cooperator	$\pi_{C,C} =$	$\pi_{C,D} =$
Defector	$\pi_{D,C} =$	$\pi_{D,D} =$

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$\downarrow$ meeting $\rightarrow$	Cooperator	Defector
Cooperator	$\pi_{C,C} =$	$\pi_{C,D} = -k$ $-r_s(1-e_S)i$ $-r_a(1-e_T)i$
Defector	$\pi_{D,C} =$ $-r_s(1-e_T)i$ $-r_a(1-e_S)i$	$\pi_{D,D} =$ $-r_s i$ $-r_a i$

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Defector	$\pi_{D,C} =$ $-r_s(1-e_T)i$ $-r_a(1-e_S)i$	$\pi_{D,D} =$ $-r_s i$ $-r_a i$

Nondimensionalized full model

Denoting

- $\tau := \frac{t}{\gamma}$ a new time-scale, $\mathcal{R}_0 := \frac{\beta}{\gamma}$ the basic reproduction number
- $\kappa := \frac{\sigma(r_a+r_s)}{\gamma}$ a renormalized opinion update rate, $p := \frac{r_a}{r_a+r_s}$ the mean level of altruism in the population, $\rho = \frac{k}{r_a+r_s}$ the renormalized perceived cost
- $\mathcal{A} := (1-p)e_S + pe_T$, $\mathcal{H} = \frac{1}{\frac{p}{e_S}+\frac{1-p}{e_T}}$

after some calculations, we obtain:

$$\begin{cases} \frac{\mathrm{d}i}{\mathrm{d}t} = (\mathcal{R}_0(1-e_S c - i(1-e_S cy))(1-e_T cy)-1)\, i \\ \frac{\mathrm{d}c}{\mathrm{d}t} = \kappa c(1-c)\left([\mathcal{A}(1-\mathcal{H}c)]\, i - \rho\right) \\ \frac{\mathrm{d}y}{\mathrm{d}t} = \mathcal{R}_0(1-e_T cy)(1-y-e_s(1-iy)(1-cy)) \\ \qquad + \kappa(1-y)\left(\mathcal{A}(1-\mathcal{H}c)i-\rho\right)_+ \end{cases}$$

Context and motivations

A behavioral SIS model

- Assumptions and modelling
- Analysis of the dynamical system

Take home messages

Which equilibrium is selected?

Quantity of interest:

$$\frac{\rho}{\mathcal{A}}$$

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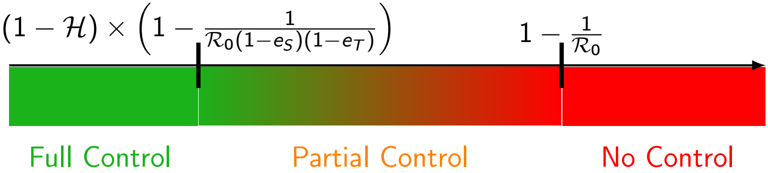
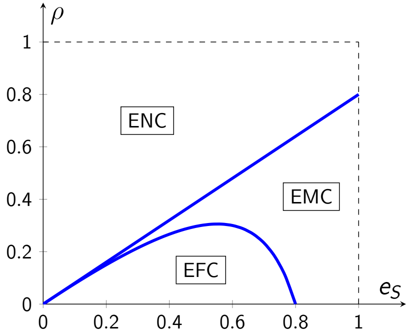
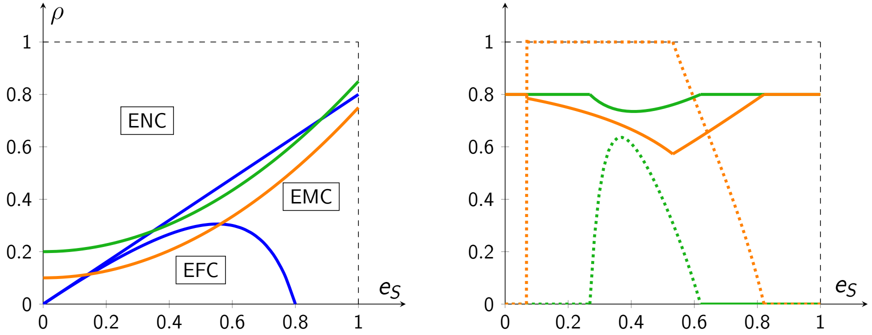


Graphical representation of the selected equilibrium: case fully selfish $p = 0$ and $e_T = 0$



Graphical representation of the selected equilibrium: case fully selfish $p = 0$ and $e_T = 0$ with a correlation between the cost and efficacy

$\rho(e_S) = \rho_0 + 0.65 \times e_S^2$ with $\rho_0 = 0.2$ and $\rho_0 = 0.1$



Take home messages

Achievements and work in progress

- Main results:
  - We produced a new model accounting for possible different behaviors of two agents involved in a pairwise encounter.
  - An intermediate efficacy for the control measure might be the best choice to minimize the prevalence. It is obtained as a balance between efficacy and large adoption of the measure in the population.
- Next tasks:
  - Study the effect of various levels of altruism and misperception of the efficacy.
  - Derive some extra 'rule of thumb' to reduce prevalence.
  - Finish writing the paper and submit it!

Perspectives

- Modelling and analysis:
  - Model a situation in which agents are perfectly aware of their health status $\longrightarrow$ different decision-making processes for s and i.
  - Model an intermediate situation in which agents have a priori on their health status, possibly with confirmation at some point $\longrightarrow$ hybrid model with a stochastic part.
- Validation:
  - Find accurate values for the parameters.
  - Compare to real data $\longrightarrow$ methods of image analysis?

Une courte page de publicité

Je cherche un postdoc à partir de septembre, autour de l'épidémiologie mathématique, idéalement comprenant une composante décision.