Behavioral consequences of ineffective vaccines
Theoretical and experimental evidence using an interactive vaccination decision making framework

Robert Böhm
Assistant Professor of Decision Analysis
School of Business and Economics
RWTH Aachen University

Joint work with: Cornelia Betsch (University of Erfurt), Marina Groß (RWTH Aachen University), Lars Korn (University of Erfurt), and Nicolas W. Meier (RWTH Aachen University)
Vaccination is one of the most successful preventive health measures

Vaccine hesitancy (i.e., desire to refuse or delay vaccination) poses a serious threat to individual and societal health.

<table>
<thead>
<tr>
<th>Infectious disease</th>
<th>Reported infections per year before/after national immunization program (USA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>before</td>
</tr>
<tr>
<td>Pertussis</td>
<td>147,271</td>
</tr>
<tr>
<td>Smallpox</td>
<td>48,164</td>
</tr>
</tbody>
</table>

Note: CDC data from 2003-2012 comes from its Summary of Notifiable Diseases, which publishes yearly rather than weekly and counts confirmed cases as opposed to provisional ones.
Outline

1. Strategic vaccination decisions: direct and indirect effects
   a. Theoretical analysis
   b. (Some) Empirical evidence

2. Vaccination in case of ineffective vaccines
   a. Theoretical analysis
   b. Empirical evidence
Determinants of vaccination decisions

Vaccination decision is typically treated as an individual decision making task, i.e., an individual’s costs/benefits of own vaccination decision (e.g., Weinstein, 1993 Health Psychol.)

Accordingly, the vaccination decision is influenced by:

- Subjectively expected risk of the disease:
  \[ E[r_D] = \text{severity} \times \text{probability of occurrence} \]

- Subjectively expected risk of vaccination (effort, time, vaccine adverse events):
  \[ E[r_V] = \text{severity} \times \text{probability of occurrence} \]

From this perspective, vaccination poses a rational decision when the expected value of vaccination exceeds the expected value of non-vaccination.
An individual’s vaccination yields positive externalities by reducing others’ probability of infection: **herd immunity** (e.g., Fine et al., 2011 *Vaccines*).

At a certain vaccination rate, the disease’s basic reproduction number $R_0$ becomes effectively smaller than 1 (i.e., each infected individual contracts the disease to less than one other individual on average) and the pathogen cannot spread anymore within the population (given a homogenous and randomly mixed population).

<table>
<thead>
<tr>
<th>Disease</th>
<th>Basic reproduction number $R_0$</th>
<th>Herd immunity threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal Influenza</td>
<td>2-3</td>
<td>50-70%</td>
</tr>
<tr>
<td>Smallpox</td>
<td>7</td>
<td>85%</td>
</tr>
<tr>
<td>Measles</td>
<td>15-18</td>
<td>95%</td>
</tr>
</tbody>
</table>
Network effect of vaccination
Indirect effect of vaccination

- Population with $n$ players, each endowed with $e$ tokens representing their health status.

- Players can simultaneously and independently choose between two behavioral strategies $a_i \in \{0,1\}$, representing non-vaccination and vaccination, respectively.

- Both non-vaccination and vaccination may impose costs $c_i$ to the player, i.e., $e - c_0$ in case of non-vaccination and $e - c_1$ in case of vaccination.

- Assumption: relative risk $r = c_1/c_0 < 1$. 
Indirect effect of vaccination

- Infection probability \( p \) of non-vaccinated \((a_0)\) players as a function of the infectiousness of the disease (basic reproduction number, \( R_0 \)) and the number of players vaccinated (vaccination rate, \( u, u \in [0, 1] \)):

\[
p(R_0, v) = \begin{cases} 
1 - \frac{1}{R_0(1 - v)}, & \text{if } R_0(1 - v) \geq 1 \\
0, & \text{if } R_0(1 - v) < 1
\end{cases}
\]

- \( p(u) \) is strictly decreasing with \( u \) and there is a critical herd immunity level \( u_c = 1 - (1/R_0) \) at which the infection probability becomes zero.

- \( u_c \) represents the vaccination rate that maximizes the expected utility of the entire population: social welfare optimum.
Indirect effect of vaccination

Infection probability $p(\nu)$

Vaccination rate $R_0$

$R_0 = 2$  $R_0 = 5$  $R_0 = 10$  $R_0 = 20$
There must exist a vaccination rate $v^*$ at which $c_0 = c_1$, which constitutes a Nash equilibrium in mixed strategies, at which no player has an incentive to change her strategy unilaterally:

$$v^*(R_0, r) = 1 - \frac{1}{R_0(1 - r)}$$

As long as $0 < c_1/c_0 < 1$, then $u^* < u_c$
since $u^* < u_c$, vaccination represents a $N$-person volunteer’s dilemma

$u^* = 1 - 1/(R_0(1 - r))$

$u_c = 1 - 1/R_0$
The Interactive Vaccination (I-Vax) Game

Endowment: 100 “fitness points”

Non-vaccination

- No fixed costs: 100 – 0 = 100
  - Healthy: 100 – 0 = 100
  - Infection: 100 – 50 = 50

Vaccination

- Fixed costs: 100 – 10 = 90
  - Healthy: 90 – 0 = 90
  - Side effects: 90 – 30 = 60

\[ p = \frac{1}{R_0 \cdot S} \]

\[ p = 1 - \frac{1}{R_0 \cdot S} \]

\[ p = .5 \]

\[ p = .5 \]

R₀: basic reproduction number, S: number of susceptible (i.e., non-vaccinated) individuals in the population
An economic game of interactive vaccination

- Laboratory experiment with $N = 180$ participants (students, 69% female)

- Repeated I-Vax Game
  - Group size: $n = 12$ players
  - Epidemiological parameterization: $R_0 = 3$
  - 20 rounds (partner matching) with feedback about payoff and vaccination rate after each round
  - Three levels of severity of disease and side effects
An economic game of interactive vaccination

- Additional measure:
  - Social preferences: 6-item (primary) Social Value Orientation Slider measure (Murphy, Ackermann & Handgraaf, 2011 *Judgm. Dec. Mak.*).
An economic game of interactive vaccination

- Prosocials
- Proselfs

Vaccination rate in previous rate below/above $u^*$ predicts vaccination decision in the subsequent round

Critical herd immunity level ($u_c$)

Nash equilibrium ($u^*$)

Decision round

Vaccination rate $[0,1]$
An economic game of interactive vaccination

Further (selected) findings:

- Omission bias: costs from vaccination (side effects) loom larger than costs from non-vaccination (infection) (Böhm, Betsch & Korn, 2016 *J. Econ. Behav. Organ.*)

- Feedback on effectively eliminated diseases (“small wins”) increases vaccine uptake (Korn, Betsch, Böhm & Meier, 2018 *Health Psych.*)

- Non-binding and non-restrictive vaccination recommendations affect vaccination behavior (Böhm, Meier, Korn & Betsch, 2017 *Health Econ.*)

- Individuals prefer a voluntary over a mandatory vaccination policy (Meier, Böhm, Korn & Betsch, submitted), and mandatory vaccination increases reactance (Betsch & Böhm, 2016 *Europ. J. Pub. Health.*)


- If non-vaccinators are not able (vs. not willing) to vaccinate, others’ vaccine uptake increases (Böhm, Meier, Groß, Korn & Betsch, in press *J. Behav. Medic.*)

- Communicating vaccination rate of incoming refugees may affect the host citizens’ vaccine uptake (Korn, Betsch, Böhm & Meier, 2017 *Lancet Infect. Dis.*)

Behavioral consequences of ineffective vaccines

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“If the vaccine is not effective, free-riding becomes the obvious choice and vaccination will be less likely.”

Physician after one of my presentations

<table>
<thead>
<tr>
<th>Vaccine</th>
<th>Effectiveness</th>
</tr>
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<tbody>
<tr>
<td>Rubella</td>
<td>97%</td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>82-95%</td>
</tr>
<tr>
<td>Mumps</td>
<td>78%</td>
</tr>
<tr>
<td>Seasonal influenza</td>
<td>10-60%</td>
</tr>
</tbody>
</table>

We define the effectiveness of a vaccine by introducing parameter $E \in [0, 1]$

$E$ affects the critical herd immunity threshold $u_c = 1 - (1/R_0)/E$ because ineffectively vaccinated players may contract and transmit the disease.

Both non-vaccination and vaccination may impose costs $c_i$ to the player, i.e., $e - c_0$ in case of non-vaccination and $e - c_1$ in case of vaccination.

Assumption: relative risk $r = c_1/c_0 < 1$
Consequences of ineffective vaccines?

Critical vaccination level ($V_c$) vs. Basic reproduction number ($R_0$)

- $E = 1$
- $E = .9$
- $E = .75$
- $E = .5$

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In a similar vein, the computation of the Nash equilibrium \( v^* \) changes to:

\[
v^*(R_0, E, r) = \begin{cases} 
1, & \text{if } p(0) > r/E \text{ and } 1/E - 1/(R_0(E - r)) \geq 1 \\
\frac{1}{E} - \frac{1}{R_0(E - r)}, & \text{if } p(0) > r/E \text{ and } 1/E - 1/(R_0(E - r)) < 1 \\
0, & \text{if } p(0) \leq r/E.
\end{cases}
\]
Consequences of ineffective vaccines?

\[ R_0 = 2 \]

\[ R_0 = 5 \]

\[ R_0 = 10 \]

\[ R_0 = 20 \]

Relative risk (r)

\[ r = .4 \]
\[ r = .3 \]
\[ r = .2 \]
\[ r = .15 \]
\[ r = .1 \]
\[ r = .05 \]
Consequences of ineffective vaccines?

Example calculation:

\[ R_0 = 2, \text{ effectiveness: } 55\% \text{ (e.g., seasonal influenza) } \]
Do decision makers understand the dynamics of indirect effects in case of ineffective vaccines and decide accordingly, i.e., are more likely to get vaccinated?
Vaccine effectiveness fallacy

Behavioral consequences of ineffective vaccines

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Online experiment:
N = 358 US American online participants
Vaccine effectiveness fallacy

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Online experiment:

$N = 138$ US American health care workers (physicians, nurses etc.)
Vaccine effectiveness fallacy under full incentive information?

- Laboratory experiment with $N = 288$ participants (students, 35% female)

- Repeated I-Vax Game
  - Group size: $n = 12$ players
  - Epidemiological parameterization: $R_0 = 2$
  - 20 rounds (partner matching) with feedback about payoff and vaccination rate after each round
  - Three levels of severity of disease and side effects (mild, medium, and severe)
Vaccine effectiveness fallacy under full incentive information?

Between-subjects treatments:

- 100% (n = 96)
  - Nash equilibrium $u^* = 0.41$

- 55% (n = 96)
  - Nash equilibrium $u^* = 0.57$

- 55% + Reciprocity information (n = 96)
  - Nash equilibrium $u^* = 0.57$
  - Additional reciprocity information: “When you get effectively vaccinated, you also protect other individuals who have been vaccinated but whose vaccination was ineffective. Also, when you get vaccinated but your vaccination is ineffective, you will be protected by other vaccinated individuals.”
Vaccine effectiveness fallacy under full incentive information?

- Additional post-experimental measures:
  - Social preferences (SVO; Murphy et al., 2011 *Judm. Dec. Mak.*)
  - Vaccination attitude (Askelson et al., 2010, *J. School Nurs.*)
  - Conditional vaccination based on other player’s vaccination decision, applying the strategy method (adapted from Fischbacher et al., 2001 *Econ. Lett.*)
Vaccine effectiveness fallacy under full incentive information?

- Higher vaccine uptake in 55% treatments than in 100% treatment (MWU, \(p < .001\) and \(p = .002\), respectively)
- 55% treatments do not differ

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Vaccine effectiveness fallacy under full incentive information?

Some evidence from additional mixed-effects regression analyses that prosocial individuals react positively to additional reciprocity information, whereas selfish individuals do not (interaction effect Treatment*SVO, p < .05)
Vaccine effectiveness fallacy under full incentive information?

**Behavioral consequences of ineffective vaccines**

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Theoretical analyses suggest that vaccination should increase if vaccination effectiveness decreases.

However, survey data suggests that lay persons as well as health care workers seem to be fooled by a vaccine effectiveness fallacy, i.e., their willingness to vaccinate decreases if vaccination effectiveness decreases.

Data from a laboratory experiment suggest that providing full information about incentives under ineffective (vs. effective) increases vaccine uptake (in line with game-theoretical prediction).

Some evidence that this might be due to increased reciprocity concerns in case of ineffective vaccines.
Outlook

- Replication, replication, replication

- Development of a (simple) behavioral intervention to buffer the decreased willingness in case of ineffective vaccines
Thank you for your interest!

Robert Böhm
Assistant Professor of Decision Analysis
School of Business and Economics
RWTH Aachen University

robert.boehm@rwth-aachen.de
http://www.robertboehm.info
@robert_bohm

Main collaborator: Cornelia Betsch (Chair of Health Communication, University of Erfurt)
Doctoral students: Cindy Holtmann, Lars Korn, Nicolas W. Meier

German Research Foundation (Grant No. BE 3970/8-1, BO 4466/2-1):
“An interdisciplinary approach towards understanding and overcoming vaccine hesitancy”