The MMR vaccine scare and human behavior: Why does measles persist in the United Kingdom?

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What are the consequences of voluntary vaccination on the spread of measles in the UK?
Reported Measles Cases in England & Wales 1940-2007
Building a model

Model of Measles Incidence

- Model with Age-Structure
- Model with Vaccination Behavior
- Model with Age-Structure and Learning Behavior

Social Learning
Environmental Learning
An SEIR model for disease dynamics

Susceptible, Exposed, Infected, Recovered

\[ \beta I = \text{contact rate} \times \text{level of infection} \]

\[ \delta = \text{latent transition rate} \]

\[ \rho = \text{recovery rate} \]
The transmission of measles is highly age-dependent

- Model of Measles Incidence
  - Model with Age-Structure
  - Model with Vaccination Behavior
  - Model with Age-Structure and Learning Behavior

- Social Learning
- Environmental Learning
Schenzle (1984): Age-Specific Contact Rates

Contact rates for adults < Contact rates for children
Schenzle (1984): Age-Specific Contact Rates

- **Age 0**
  - $S_0$ → $E_0$ with rate $\beta_0I$
  - $E_0$ → $I_0$ with rate $\delta$
  - $I_0$ → $R_0$ with rate $\rho$

- **Age 1**
  - $S_1$ → $E_1$ with rate $\beta_1I$
  - $E_1$ → $I_1$ with rate $\delta$
  - $I_1$ → $R_1$ with rate $\rho$

- **Ages 20+**
  - $S_{20+}$ → $E_{20+}$ with rate $\beta_{20+}I$
  - $E_{20+}$ → $I_{20+}$ with rate $\delta$
  - $I_{20+}$ → $R_{20+}$ with rate $\rho$

- Birth and death transitions are indicated with arrows.
Results of Schenzle (1984)

model yields a biennial measles cycle
Reported Measles Cases in England & Wales 1940-2007

The graph shows a significant decrease in the number of reported measles cases after the introduction of the measles vaccine and the MMR vaccine. The number of cases spiked in the 1940s and 1950s, reaching a peak in 1956, before dropping sharply after the introduction of the measles vaccine in the late 1960s and the MMR vaccine in the 1980s. The number of cases continued to decrease steadily until the late 1990s, when a resurgence occurred due to declining vaccination rates. Since then, the number of cases has remained low, with a slight increase in recent years.
Compulsory Vaccination

- Model of Measles Incidence
- Model with Age-Structure
- Model with Vaccination Behavior
- Model with Age-Structure and Learning Behavior
- Social Learning
- Environmental Learning
Incorporating Vaccination

fraction immunized with MMR vaccine ($x$)
Vaccination Programs

Model of Measles Incidence

Model with Age-Structure

Model with Vaccination Behavior

Model with Age-Structure and Learning Behavior

Social Learning

Environmental Learning
Vaccination is Voluntary in the UK

Model of Measles Incidence

Model with Age-Structure

Model with Vaccination Behavior

Social Learning

Model with Age-Structure and Learning Behavior

Environmental Learning
Social Learning


- Innovation spread by contact between individuals is characterized by an s-shaped curve
- Potential adopters of an idea initially resist change
- There is an exponential growth phase and a leveling off phase

Diffusion of hybrid corn seed in two Iowa farming communities
Social Learning

Bauch (2005): “Imitation Dynamics Predict Vaccination Behavior”

• Individuals adopt vaccination strategies according to an imitation dynamic

• Vaccination decision based on disease prevalence and perceived risk of vaccine and disease
Bauch’s Model

\[ \frac{dx}{dt} = \kappa x(1-x) [\omega I - 1] \]

\( \frac{dx}{dt} \) = change in proportion of vaccinators over time

\( x(1-x) \) = frequency at which vaccinators contact non-vaccinators and vice versa

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Model parameters

<table>
<thead>
<tr>
<th>( \kappa )</th>
<th>Rate at which individuals sample others and switch vaccination strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{\omega} )</td>
<td>Level of infection necessary before social learners can become convinced to vaccinate</td>
</tr>
</tbody>
</table>
Two Ways to Understand $\omega$

\[ \frac{dx}{dt} = \kappa \cdot x(1-x) \cdot [\omega \cdot I - 1] \]

\[ \frac{1}{\omega} = \text{Level of infection necessary before social learners can become convinced to vaccinate} \]

\[ \omega = \frac{\text{Perceived risk of infection}}{\text{Perceived risk of the vaccine}} \]
\[
\frac{1}{\omega} = \text{Level of infection necessary before social learners can become convinced to vaccinate}
\]

If \( \omega = 10,000 \) (a high value)
\[ \frac{1}{\omega} = \text{Level of infection necessary before social learners can become convinced to vaccinate} \]

If \( \omega = 3,000 \) (a low value)
Results of Bauch (2005)

- oscillations occur in vaccine uptake when individuals imitate each other more

Individuals react more quickly to disease prevalence
Environmental Learning


- Individual has complete knowledge of payoff gains of the innovation
- Individual chooses to adopt the innovation if it has a larger payoff

Actual and predicted curves for the diffusion of tetracycline prescriptions among Illinois doctors who receive many and few journals
Different Messages from Environmental Learning

ARE WE OVER-VACCINATING OUR KIDS?

Since 1982, the number of vaccines the Centers for Disease Control recommends for our kids has more than tripled. During this same time period, we've seen an explosion in neurological disorders like ADHD and autism, particularly with our boys, who represent 4 out of 5 cases.

Are these increases related? Can there be too much of a good thing? Until now, no one could know for sure, because no study had ever been done to compare the rate of neurological disorders between vaccinated and unvaccinated children.

A NEW SURVEY OF KIDS IN CALIFORNIA AND OREGON SAYS WE MAY WELL BE.

We commissioned a market research firm to survey more than 17,000 children in California and Oregon. We found that vaccinated boys had more than a 2.5-times greater rate of neurological disorders than unvaccinated boys. We believe a national study must be done to further explore these disturbing results.

Visit our site and read the results of our survey, as well as find helpful information on how to vaccinate your child more safely. Learn more at www.generationrescue.org

MEASLES
Don’t let your child catch it

The number of children catching measles is rising. To be protected they need to be immunised with the MMR vaccine.

It’s never too late to be vaccinated.

For more information contact your local GP surgery or visit:
www.immunisation.nhs.uk
How do we model voluntary vaccination?

- **Proportion of Vaccinators**: $x$
- **Proportion of Non-vaccinators**: $1-x$

- **Social Learning**
- **Environmental Learning**
Incorporating Environmental Learning into Vaccination Behavior

\[ \frac{dx}{dt} = L_s x(1-x) [\omega I - 1] + L_e (1 - x/c) \]

Social learning \hspace{1cm} \text{Environmental learning}

<table>
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<th>Learning parameters</th>
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<tbody>
<tr>
<td>( L_s )</td>
</tr>
<tr>
<td>( L_e )</td>
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<tr>
<td>( c )</td>
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</tbody>
</table>
Summary of Previous Work

• Schenzle (1984): accurately captured measles pre-vaccine incidence by incorporating age-structure but did not include voluntary vaccination

• Bauch (2005): modeled disease dynamics with vaccination behavior but did not include age-structure

• In our model we include both age-structure and voluntary vaccination
The Big Picture

Model of Measles Incidence

Model with Age-Structure
Model with Vaccination Behavior

Model with Age-Structure and Learning Behavior

Social Learning
Environmental Learning
Model with Age-Structure and Vaccination

- Age 0:
  - $S_0$ to $E_0$ with $\beta_0 I$
  - $E_0$ to $I_0$ with $\delta$
  - $I_0$ to $R_0$ with $\rho$

- Age 2:
  - $S_2$ to $E_2$ with $\beta_2 I$

- Ages 20+:
  - $S_{20+}$ to $E_{20+}$ with $\beta_{20+} I$
  - $E_{20+}$ to $I_{20+}$ with $\delta$
  - $I_{20+}$ to $R_{20+}$ with $\rho$

Vaccination path shown from $S_0$ to $E_0$.
Our Model

1. Age-Specific SEIR Equations

\[ N = 50 \text{ million}, \quad \nu = 666,666, \quad \mu = 1/55, \]
\[ \delta = 1/8, \quad \rho = 1/5, \quad \Sigma = \text{summation over } j = 1, 2, \ldots, 20 \]
\[ \beta = \text{matrix of age-specific contact rates.} \]

Age 0

\[
\frac{dS_0}{dt} = \nu - \Sigma \beta_{o_j}(\tau)S_0, \quad \frac{dE_0}{dt} = \Sigma \beta_{o_j}(\tau)S_0 - \delta E_0, \\
\frac{dI_0}{dt} = \delta E_0 - \rho I_0, \quad \frac{dR_0}{dt} = \rho I_0
\]

Age \( k \), where \( k = 1, 2, \ldots, 19 \)

\[
\frac{dS_k}{dt} = -\Sigma \beta_{k_j}(\tau)S_k, \quad \frac{dE_k}{dt} = \Sigma \beta_{k_j}(\tau)S_k - \delta E_k, \\
\frac{dI_k}{dt} = \delta E_k - \rho I_k, \quad \frac{dR_k}{dt} = \rho I_k
\]

Age \( n \), where \( n = 20^+ \)

\[
\frac{dS_n}{dt} = -\left[\Sigma \beta_{n_j}(\tau) + \mu\right]S_n, \quad \frac{dE_n}{dt} = \Sigma \beta_{n_j}(\tau)S_n - (\delta + \mu)E_n, \\
\frac{dI_n}{dt} = \delta E_n - (\rho + \mu)I_n, \quad \frac{dR_n}{dt} = \rho I_n - \mu R_n
\]

2. Vaccination Dynamics

\[
\frac{dx}{dt} = L_s x(1 - x)[\omega I - 1] + L_c [1 - x/c]
\]
Methods

• Fixed a population size of 50 million
• Chose constants for births, death rate, latent transition rate, recovery rate, and contact rate from measles data
• Ran simulations in the programming language MATLAB to examine both short and long term vaccination and disease dynamics
• Studied three scenarios
  – Social learning dominates
  – Mixture of social and environmental learning
  – Vaccine scare
An Example of a MATLAB Output of our Model
Results

• Studied three scenarios
  – Social learning dominates
  – Mixture of social and environmental learning
  – Vaccine scare
Only Social Learning

\[ \frac{dx}{dt} = L_s x(1-x) [\omega I - 1] \]

How do various parameter values influence vaccination and disease dynamics?
Effects of Social Learning on Vaccination

Average Vaccination

- Average vaccination increases with sensitivity to level of infection.
- Average vaccination is independent of the social learning rate.
Effects of Social Learning on Infection

Average Infection

- Average infection decreases with sensitivity to level of infection.
- Average infection is independent of the social learning rate.
An Example of a MATLAB Output of our Model

Measure average, maximum, and minimum
Max. and Min. Vaccination

Maximum Vaccination

Minimum Vaccination

L = 0.2, \omega = 4000

L = 0.5, \omega = 6000
Max. and Min. Infection
Max. and Min. Infection
Results

• Studied three scenarios
  – Social learning dominates
  – *Mixture of social and environmental learning*
  – Vaccine scare
Mixture of social and environmental learning effects on dynamics

- Higher vaccination decreases maximum infection
- The average vaccination is approximately the probability a person switching to a vaccinating strategy.
Mixture of social and environmental learning effects on dynamics

- Higher probability does not correspond to a high level of vaccinators
- Infection does not decrease as low levels.
Results

• Studied three scenarios
  – Social learning dominates
  – Mixture of social and environmental learning
  – *Vaccine scare*
Vaccine Scares

- Individuals are concerned over adverse side effects associated with the vaccine
- Low MMR vaccine uptake levels following the publication of Wakefield et al. 1998
Modeling a Response to a Vaccine Scare

- Model of Measles Incidence
  - Model with Age-Structure
  - Model with Vaccination Behavior
    - Model with Age-Structure and Learning Behavior

- Vaccine Scare
- Social Learning
- Environmental Learning

Vaccine Scare Response
Simulating a Vaccine Scare

Risk of vaccination increased $n$-fold for a duration of time

– People interact with each other and switch to non-vaccinating strategies due to the increased risk of the vaccine.
Responding to a Vaccine Scare

Counteract with environmental learning

– Public outreach campaigns encourage vaccination and the switching to vaccinating rate increases $m$-fold.
Before a scare

\[ L_s = 0.6, \quad \omega = 6000, \quad L_e = 0.2, \quad c = 0.5 \]
A Vaccine Scare

intensity = 4-fold, duration = 10 years

Recovery = 12 years
Responding to a Vaccine Scare

after 1 year, 2-fold response

Recovery = 10 years
Responding to a Vaccine Scare
after 1 year, 4-fold response

Recovery = 2 years
$L_s = 0.6$, $\omega = 6000$, $L_e = 0.2$, $c = 0.5$

intensity = 4-fold, duration = 10 years

after 1 year, 2-fold response

after 1 year, 4-fold response
Summary of Vaccine Scares

• Vaccine scares
  – A lag time between vaccination rates dropping and a rise in infection \(\rightarrow\) due to age-dependence
  – A quick, strong response can mitigate many of the effects
    • Non-linear increase in response: twice the response causes a recovery that is five times as fast
General Conclusions

• Voluntary vaccination causes oscillations in levels of vaccinators and disease prevalence
• Social learning does not affect the average but does has an effect on epidemic maxima and minima
• Social learning can greatly decrease vaccination levels (such as in a vaccine scare)
• Environmental learning has a strong effect on the level of vaccinators
• Environmental learning can counteract vaccine scares
Future Research

- Quantitative vs. qualitative results
- Parameter values
- The non-linear relationship between vaccine scare response and recovery
- Catch-up vaccine programs
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