Mathematical Analysis of the Behavioral Immune System

: Behavioral Ecological Approach

Myungjin Kim[1] kmj081722@snu.ac.kr , Hanson Park, MD, PhD[2] hansonpark@snu.ac.kr

Department of Economics, Seoul National University[1], Department of Anthropology, Seoul National University[2]

Abstract

This study proposes a behavioral ecology model to examine changes in the level of interpersonal contact during the spread of disease. We designed a fitness-maximizing model based on the Behavioral Immune System to predict the optimal level of interpersonal contact under infection risk. Reducing contact with infectious agents is a well-known adaptive behavioral strategy during disease spread. However, in the case of highly contagious diseases, reducing contact levels may not yield substantial benefits in terms of transmission avoidance. Thereby maintaining or slightly decreasing the original contact level may be advantageous. This could explain the lower adherence to social distancing policies during outbreaks of highly contagious diseases. It should be noted that this model is a simplified mathematical model, which does not consider the coevolution of pathogens and hosts.

Introduction

Behavioral Immune System, BIS

- Proactive avoidance against pathogen threat
- Inhibit contact to minimize infection risk
- The universal behavioral mechanism in infection risk situations(e.g., Pandemic)
- **Determine the level of interpersonal contact**

Behavioral Ecology

- Examine optimized behavioral strategies varying in different environmental contexts
- Fitness-maximizing mathematical model

Objectives

- Describe Behavioral Immune System (BIS) from the behavioral ecological perspective
- Provide theoretical evidence of the existence of the '*Maladaptive-appearing*' contact level as an adaptive behavioral strategy

Modeling Behavioral Immune System

1. **Model setup:** maximize Fitness=Benefit-Cost

$x = \arg\max F(x), \quad F(x) = B(x) - C(x)$

(1) x : contact rate (number of contacts per unit time)

(2) $F(x)$: Fitness, net fitness gain from interpersonal contact under infection risk

(3) $B(x)$: Benefit, benefit from interpersonal contact

(4) $C(x)$: Cost, expected fitness loss from infection

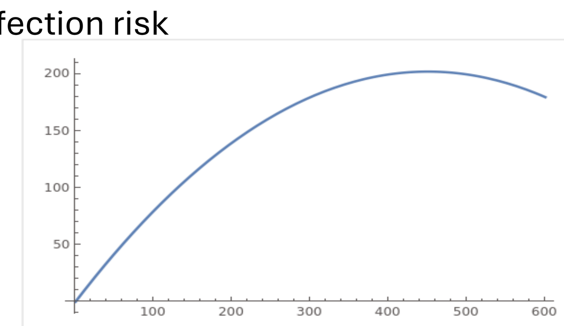
Fig. 1 $B(x)$, $u = 0.9, d = 0.002$

1) $B(x)$: net benefit from interpersonal contact

(1) quadratic form(diminishing marginal net benefit)

(2) u:(utility) the increment in the fitness

(3) d: (disutility) the decrement rate in the fitness

$\boldsymbol{B(x) = u \cdot x - \frac{1}{2} \cdot d \cdot x^2}, x \geq 0$ (Fig. 1)

$\boldsymbol{B'(x) = u - d \cdot x}, x \geq 0$ (Fig. 2)

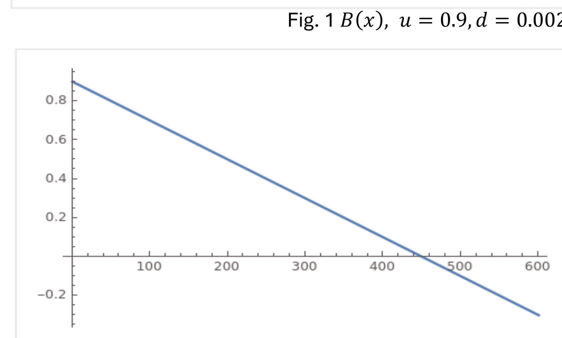
Fig. 2 $B'(x)$, $u = 0.9, d = 0.002$

2) $C(x)$: expected fitness loss from infection

(1) c: the conditional expected fitness loss

(2) i : the proportion of the infected in the population

(3) δ: the infection rate per unit contact

$\boldsymbol{C(x) = c \cdot i \cdot \{1 - (1 - \delta)^x\}}, x \geq 0$ (Fig. 3)

$\boldsymbol{C'(x) = c \cdot i \cdot \ln\frac{1}{(1-\delta)} \cdot (1 - \delta)^x}, x \geq 0$ (Fig. 4)

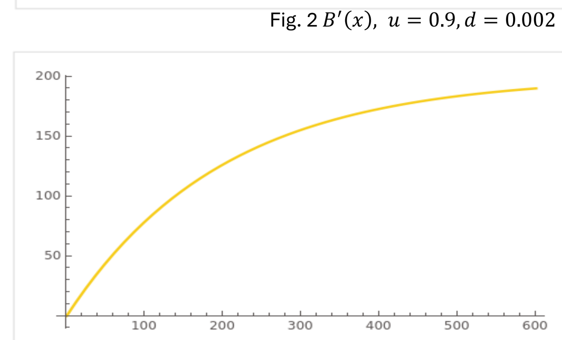
Fig. 3 $C(x)$, $c \cdot i = 200, \delta = 0.5\%$

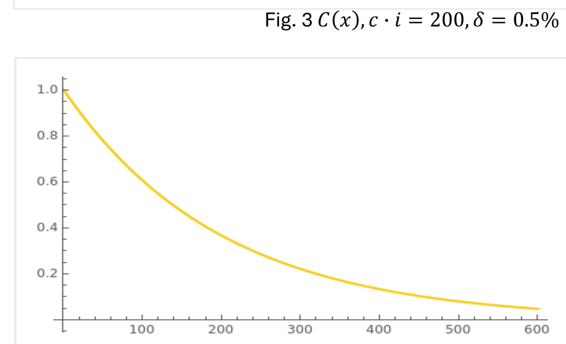
Fig. 4 $C'(x)$, $c \cdot i = 200, \delta = 0.5\%$

2. Conditions for the fitness maximization

The fitness-maximizing optimal contact rate(x^*) should match the first-order condition and the second-order condition: $x^* = x(u, d, c, i, \delta)$. Otherwise, there exists a corner solution($x^* = 0$)

1) First-order necessary condition (Fig. 5)

: the marginal benefit equals the marginal loss

: $F'(x) = 0$ or $B'(x) = C'(x)$

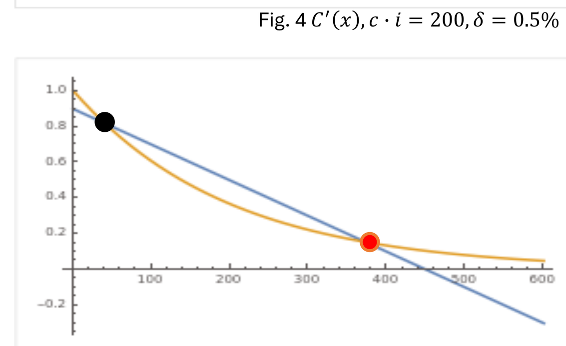
Fig. 5 First-order condition: $B'(x) = C'(x)$

2) Second-order sufficient condition (Fig. 6)

: the marginal benefit diminishes faster than the marginal loss

: $F''(x) < 0$ or $B''(x) < C''(x)$

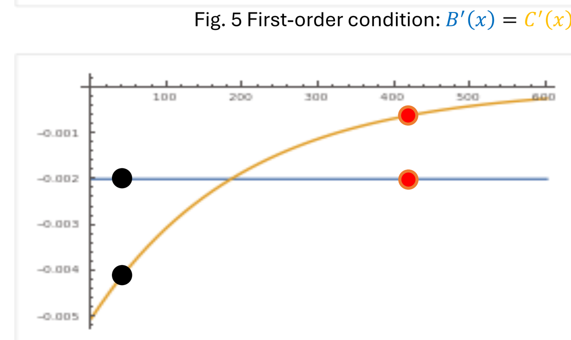
Fig. 6 Second-order condition: $B''(x) < C''(x)$

3) Fitness-maximizing optimal contact rate (Fig. 7)

Point black does not match the second-order condition

Point Red matches both First-order and Second-order condition

; Point Red is the fitness-maximizing optimal contact rate

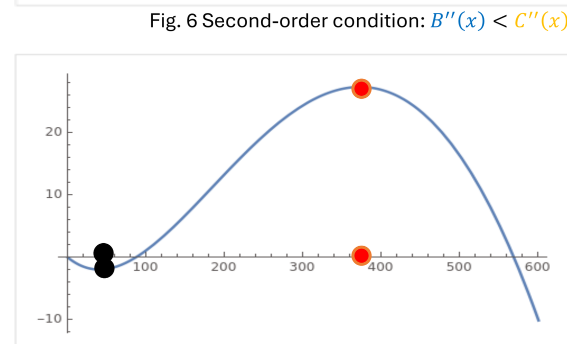
Fig. 7 $F(x) = B(x) - C(x)$

Comparative Statics

How do contact levels vary with changes in parameters or environment?

1. Higher benefit from interpersonal contact (Fig. 8)

- Higher contact level
- $\frac{\partial x^*}{\partial u} > 0$ and $\frac{\partial x^*}{\partial d} < 0$ for all u and d

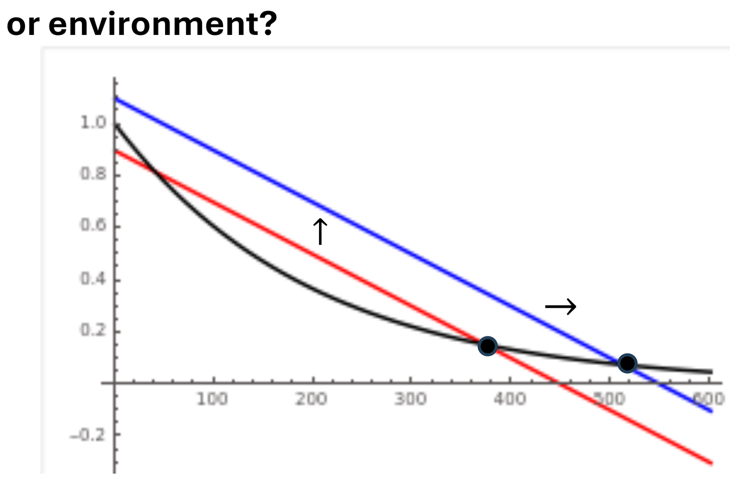
Fig. 8 Higher benefit from interpersonal contact yields higher contact level, Red ($u = 0.9$), Blue ($u = 1.1$)

2. Higher Perceived Vulnerability to Disease (PVD)

; higher fatality rate or the old (Fig. 9)

- Lower contact level
- $\frac{\partial x^*}{\partial c} < 0$ for all c

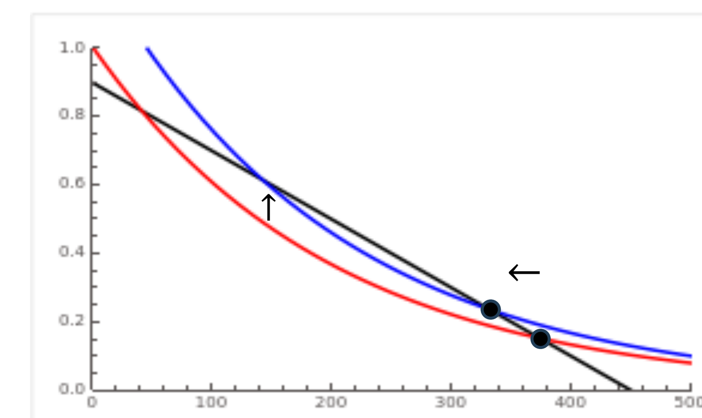
Fig. 9 Higher PVD yields lower contact level, Red ($c = 200$), Blue ($c = 250$)

3. More contagious disease

1) Infection rate lower than the threshold (Fig. 10)

- Lower contact level
- $\frac{\partial x^*}{\partial \delta} < 0$, for $\delta < \delta_0$ ($\cong 10\%$ for Fig. 10)

2) Infection rate higher than the threshold (Fig. 11)

- Higher contact level
- $\frac{\partial x^*}{\partial \delta} > 0$, for $\delta > \delta_0$ ($\cong 10\%$ for Fig. 11)

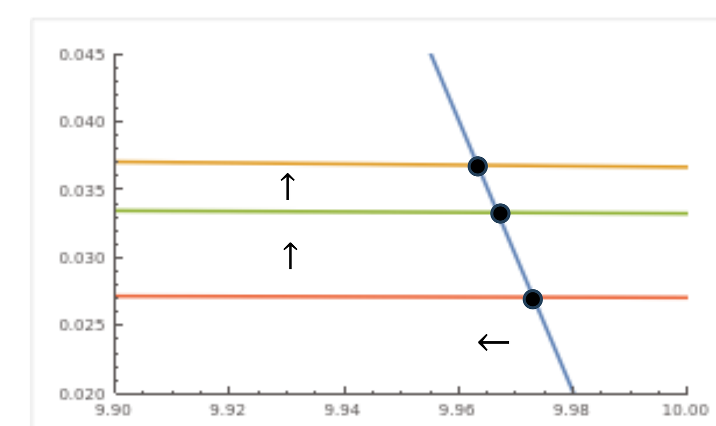
Fig. 10 $u = 10, d = 1, c \cdot i = 1$, Red ($\delta = 6\%$), Green ($\delta = 8\%$), Yellow ($\delta = 10\%$)

4. Infection rate threshold (δ_0)

Given $\bar{u}, \bar{d}, \bar{c}, \bar{i}$, $\left\{ \delta_0 = \delta \,\middle|\, \begin{array}{l} B'(x^*, \delta) = C'(x^*, \delta) \\ B''(x^*, \delta) < C''(x^*, \delta) \\ x^*(u, d, c, i, \delta) = \frac{1}{\ln\frac{1}{(1-\delta)}} \end{array} \right\}$

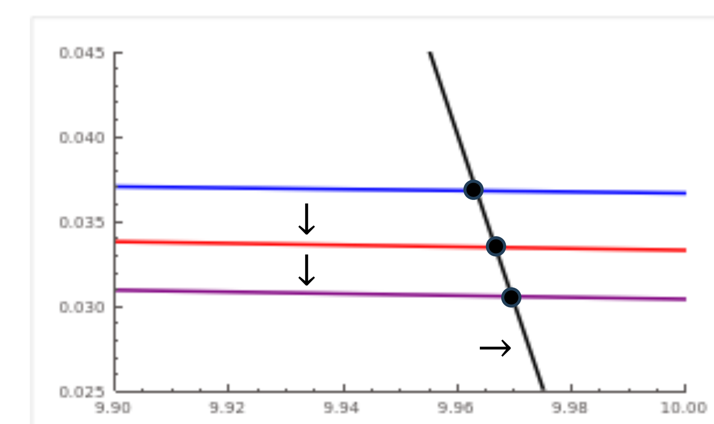
Fig. 11 $u = 10, d = 1, c \cdot i = 1$, Blue ($\delta = 10\%$), Red ($\delta = 14\%$), Purple ($\delta = 16\%$)

5. Applications of the Infection rate threshold (δ_0)

1) Individuals with **higher contact level**, **higher benefit from interpersonal contact**, or **lower PVD**:

- Lower Infection rate threshold
- More frequent 'Maldaptive-appearing' behavior
  - (1) to increase the contact level under increasing infection rate
  - (2) maintain contact level high under highly contagious diseases
- Low adherence to social distancing policies

2) Population consisted of **heterogeneous Infection rate thresholds**:

- Individuals react differently on the changes in environmental conditions regarding infection rate
  - (1) Individuals with low threshold: increase contact level under increasing infection rate
  - (2) Individuals with high threshold: decrease contact under increasing infection rate
- Polarization in the contact level

Conclusions

1. This model provides a technical description of the Behavioral Immune System (BIS).
2. The levels of Perceived Vulnerability to Disease (PVD) or benefits from interpersonal contact vary among individuals, resulting in diverse contact levels (or behavioral immune responses) in the context of disease spread.
3. In situations where the infection rate exceeds the Infection Rate Threshold and continues to rise, increasing the level of contact can be adaptive for individuals.
4. During the spread of a highly contagious disease, lowering contact levels may not yield substantial benefits in transmission avoidance. Therefore, a 'Maladaptive-appearing' behavioral strategy: maintaining high contact levels during the disease spread, can be adaptive.
5. From the perspective of managing disease spread, information regarding the severity of the infection rate, unlike fatality rates, can lead to increased social contact, low adherence to social distancing policies, and aberrant behavior from super spreaders, thereby facilitating further spread of the disease.

References

1. Schaller, Mark. (2011). The Behavioural Immune System and the Psychology of Human Sociality. Philosophical Transactions of the Royal Society of London. Series B. Biological Sciences 366.1583: 3418-426.

|Acknowledgement|

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