Individual Vaccination Decision under Uncertainty and Information Asymmetry

By

LEE, Wonseog

THESIS

Submitted to

KDI School of Public Policy and Management

In Partial Fulfillment of the Requirements

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Committee in charge:

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Finally, I would like to thank my wife Insun Jang, love of my life, for trusting and supporting me in everything unconditionally.

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Abstract

Two models for individual decisions on vaccination under incomplete information, which poses uncertainty and information asymmetry, have been presented in this thesis. In the state-preference model, the vaccine plays a role of insurance against the disease. It suggests that the interaction between actuarial fairness of the vaccine and risk aversion of the agent commands her vaccination decision. The more actuarially advantageous the vaccine is and the more risk-averse the agent's personality is, the more likely the agent will purchase the vaccine. The signaling game model shows that an individual buyer of the vaccine builds up her belief of the vaccine's quality by observing the signal sent by the producer, in this case, the type of technology. The producer's pooling and separating strategies may result in perfect Bayesian equilibria with conditions that bound the buyer's belief and the producer's incentive to deviate from the initial strategy.

I. Introduction

Vaccination has been considered one of the best measures to mitigate adverse effects of many contagious diseases. According to the World Health Organization (WHO), vaccination is “the best method for prevention and control of influenza” (Houser & Subbarao, 2015). The Centers for Disease Control and Prevention of the United States also acknowledges vaccination as the very means to have freed the U.S. from the polio epidemic (Centers for Disease Control and Prevention, 2018). As of 2021, vaccines “prevent more than 20 life-threatening diseases”, and 2-3 million lives are saved every year due to immunization in consequence of vaccination (World Health Organization, 2021).

Despite the evidenced efficacy, however, public sentiments doubting the effectiveness and safety of vaccines are widespread, especially as far as vaccination against a novel contagious disease is concerned, primarily due to the shortage of information on the disease and pathogen (Kennedy, 2019). The disease has too many unknown properties that have yet to be found. They take many different forms, such as an outbreak of variation in the disease, undiscovered symptoms, fatality, etc. In addition to these unknown properties, fundamentally, it is impossible to predict with certainty whether a particulr individual would be infected and must vaccinate herself even if the probability distribution of the risk of infection is well-known. Thus, it is not entirely irrational that an individual hesitates to get vaccinated.

These difficulties can be aggravated by an uneven distribution of the information crucial on making a decision on the purchase of vaccines between buyers and producers. A vaccine producer may have information which is unknown to potential buyers even though knowing that information can significantly affect their decision. For example, the quality of a vaccine is private information held by the producer before her products are rolled out unless the disclosure of the information is required. Without the quality assured, buyers may make suboptimal decisions such as delayed decisions, the purchase of subprime products, no purchase at all, etc. The problem of 'lemons' illustrated by Akerlof (1970) can exist in the vaccine market.

This thesis investigates the difficulties in individual vaccination decision through the lens of the state preference approach and signaling game models. Section II provides a review of the existing literature on uncertainty and information asymmetry and definitions of main terms used through this thesis. Section III is divided into two parts. In Part A, mainly, the state preference approach is applied to demonstrate the behaviour of vaccine buyers when uncertainty arises from the shortage of information on the disease. In Part B, a signaling game model is constructed to show how the buyer and the producer would interact in the setting of information asymmetry in favour of the producer. Section IV addresses problems identified in Section III. Section V provides concluding remarks.

II. Literature Review

This thesis is extended from studies on optimal choice under uncertainty and information asymmetry. Analytical frameworks are based on the expected utility hypothesis and Bayesian games approach. Those studies show how 'rational' economic agents respond to uncertainty and information asymmetry and what consequences would be led by their responses.

Uncertainty in this thesis is defined as the "subjective probability distribution" of 'risk' (Kohn, Uncertainty in Economics, 2017, p. 4). In other words, uncertainty arises because an individual economic agent lacks precise information on the underlying event that would potentially harm her utility while she has a faith to some degree that this event would or would not take place (Smith, Benson, & Curley, 1991). Thus, her utility takes a form of a random variable whose values are assigned by the probability distribution constructed based on her incomplete knowledge of the event bearing the potential harm, i.e., 'risk'.

A risk-bearing event is often compared to an investment opportunity that would make returns, i.e., profit or loss, depending on the outcomes of the investment following the agent's subjective probability distribution (Friedman & Savage, 1948). The agent would pursue to maximize the expected utility, which is defined as the probability-weighted sum of utilities from her wealth. The expected utility is equal to or more or less than the utility from the certainty equivalent of wealth, depending on her preference for risk. A risk-neutral agent will surely yield the expected utility from the expected wealth; a risk-loving agent will need more than the expected wealth to obtain the expected utility; and a risk-averse agent will require less than the expected wealth to yield the expected utility (Hirshleifer, 1965).

Thanks to this setting, the optimal allocation of an individual's wealth between the different states can be analyzed as conventional utility maximization problems (Arrow, 1964). The value of her wealth is altered depending on states, and the probability assigned to one state's occurring is equivalent to the price of wealth in this state. Probabilities are assigned to different states, and these probabilities also serve as prices of her wealth in different states. Expected wealth, which is nothing but a probability-weighted sum of wealth at different states, is equivalent to the budget constraint. An optimal allocation of one's wealth between the states is found by solving the expected utility maximization subject to the expected wealth (Nicholson & Snyder, 2008, pp. 216-221).

Uncertainty described above is assumed to be caused by a lack of information which evenly occurs to all the parties involved in the economic transaction in question. However, uncertainty may also arise from 'information asymmetry', which occurs when one party has information that other parties do not know and attempts to benefit from its advantage in the information. Two kinds of problems caused by information asymmetry are mainly discussed in economic accounts (Mishkin & Serletis, 2011, pp. 32-33). First, the problem known as moral hazard occurs when one party takes advantage of the other party by hiding its behaviour after the economic transaction in question. Second, the problem known as adverse selection occurs when one party benefits from the other party's expense by hiding its type before the economic transaction in question. Especially, this thesis focuses on adverse selection, the problem of the information asymmetry caused by hidden type.

The behavioural patterns of economic agents in the presence and mitigation of adverse selection are well addressed in 'signaling games' (Spence, 1973). A worker's productivity is usually unknown unless she is employed to prove her performance at work. There are both productive workers and unproductive workers in the labour market, but the employer cannot observe their productivity unless they are already hired. Once they are hired, the employer must pay the amount as promised in the employment contract regardless of their productivity. The worker may turn out to be productive or may not, but the employer's return on hiring may not be satisfactory unless she has randomly hired productive workers. To avoid this conundrum, the employer offers higher than what productive workers are supposed to receive but instead requires candidates to show a certificate of qualification or education relevant to the job as a signal that she is qualified for the job. Since it is costly for workers to have such a qualification, only those who believe it is worth obtaining the qualification will get the qualification and apply for the job. As a result, the employer will be able to maintain reasonable returns on hiring.

To make a rigorous analysis in signaling games, economists heavily owe to the Bayesian statistics (Tadelis, 2013). The employer's belief in the job candidate's hidden type (θ), i.e., productivity, is presented as the probability of θ conditional on her observing the signal sent from the other (S) such as $Pr(\theta|S)$. It is constructed from the Bayesian theorem: $Pr(\theta|S) = \frac{Pr(\theta)\Pr(S|\theta)}{Pr(S)}$. Then, the employer's belief that the candidate does not fall under θ when S is observed is $1 - Pr(\theta|S)$. By calculating the employer's expected payoffs using these beliefs, the employer's best responses are found. Finally, the outcome of the signal sent by the candidate needs to be consistent with her best interest given the employer's best responses. With all those conditions met, a perfect Bayesian equilibrium is reached.

III. Theoretical Framework

A. Vaccine Purchase Decision under Uncertainty

1) Basic Settings

Let's assume that a rational economic agent who generates utilities by consuming her wealth w. The agent falls under either of two genetic types referred to as $t \in \{b, g\}$, where b

means ‘infected’ and g means ‘not infected’. It is assumed that and that the genetic type determines whether one gets infected with the disease. In other words, without any preventive measure, type b would certainly be infected and type g would surely not be infected. However, the agent does not know her type unless she actually gets infected. These assumptions allow the agent’s type to follow a binomial probability distribution:

$$Pr(t) = \begin{cases} Pr(b) = p; \\ Pr(g) = 1 - p. \end{cases} \tag{1}$$

There is no viable cure for the disease, but a vaccine is introduced to prevent infection. The role of the vaccine is similar to an insurance in that it will secure one’s wealth against an unfortunate event, in this case, infection of the disease[1]. To see whether vaccination would make any difference in the agent's welfare, a superscript $i \in \{0,1\}$ is added when necessary: 0 if the agent is not vaccinated and 1 if the agent is vaccinated.

The agent’s wealth takes a form of a ‘contingent commodity’ because its value depends on states of the world, in this case, the agent’s type. The agent is initially endowed with w_0, but her wealth soon depends on her type: w_b if she is type b and w_g if she is type g. Without the vaccine, her wealth for each type is:

$$w_t^0 = \begin{cases} w_b^0 = w_0 - L \\ w_g^0 = w_0 \end{cases} \tag{2}$$

where L refers to the loss due to the disease, such as hospitalization costs or the decrease in income owing to workday loss. With vaccination, the agent’s wealth for each type is calculated:

[1] Of course, there should be some crucial differences between an insurance and a vaccine. First, an insurance usually covers the damage that has already occurred while a vaccine protects one from a contagious disease before she gets infected. Second, the insured amount is determined on the contract before the damage is realized while the effectiveness of the vaccine is identified after the subjects are inoculated.

$$w_t^1 = \begin{cases} w_b^1 = w_0 - L - qA + A \\ w_g^1 = w_0 - qA \end{cases} \quad \text{for } A \leq L, \tag{3}$$

where A refers to the dollar value of the vaccine effectiveness and q refers to the premium on the one-dollar value of the vaccine effectiveness. The effectiveness or the benefit of the vaccine A is not greater than the loss of infection L because the role of the vaccine is not to improve one's health but to prevent infection. Thus, the agent's wealth corresponding to each type, if she is vaccinated, must be $w_b^1 \in [w_0 - L, w_0 - qL]$ and $w_g^1 \in [w_0 - qL, w_0]$.

2) Expected Utility Improvement by Vaccination

It is obvious that the agent would be vaccinated only because it would improve her welfare, which is measured in her utility. The utility function is given by $u(w) = w^\alpha$ for $\alpha > 0$. As uncertainty arises from infection of the disease, it is reasonable to assume that the agent would maximize the expected utility, which takes a form of the probability-weighted sum of utilities of w_b and w_g, respectively:

$$v(w_b, w_g) = pu(w_b) + (1-p)u(w_g) = pw_b^\alpha + (1-p)w_g^\alpha \tag{4}$$

Its marginal rate of substitution of w_b for w_g is computed as follows:

$$MRS_{b,g} = -\frac{dw_g}{dw_b} = \frac{\frac{\partial v}{\partial w_b}}{\frac{\partial v}{\partial w_g}} = \frac{p}{1-p} \cdot \frac{u'(w_b)}{u'(w_g)} = \frac{p}{1-p} \cdot \left(\frac{w_g}{w_b}\right)^{1-\alpha}, \tag{5}$$

It is clear that the expected utility is generated by consuming within her budget constraint (BC), which is derived from (3) as follows:

$$\begin{cases} w_b - w_0 + L = (1-q)A \Rightarrow A = \dfrac{w_b - w_0 + L}{1-q} \\ w_g - w_0 = -qA \qquad \Rightarrow A = -\dfrac{w_g - w_0}{q} \end{cases} \Rightarrow -\frac{w_g - w_0}{q} = \frac{w_b - w_0 + L}{1-q}$$

$$\Rightarrow w_g - w_0 = -\frac{q}{1-q}(w_b - w_0 + L), \tag{6}$$

which can be re-arranged as:

$$qw_b + (1-q)w_g = w_0 - qL. \tag{7}$$

Equation (6) and (7) suggests that any pair of $w_b \in [w_0 - L, w_0 - qL]$ and $w_g \in [w_0 - qL, w_0]$ is attainable as long as the agent consumes within $w_0 - qL$.

Typically, the expected utility would be maximized if $MRS_{b,g} = \frac{q}{1-q}$, and then $(w_b^1, w_g^1) = (w_0 - qL, w_0 - qL)$, i.e., vaccination, would be her choice. However, it can be falsified if (w_b^0, w_g^0) yields greater expected utility than (w_b^1, w_g^1). To find whether vaccination actually leads to improvement in the expected utility, in application of Taylor expansion, the expected utility function valuated at (w_b^0, w_g^0) and (w_b^1, w_g^1) is examined as follows:

$$\begin{aligned} v(w_b^0, w_g^0) &= p(w_0 - L)^\alpha + (1-p)w_0^\alpha \\ &\approx p\left[w_0^\alpha + \alpha w_0^{\alpha-1}(-L) + \frac{\alpha(\alpha-1)}{2}w_0^{\alpha-2}(-L)^2 + R(-L)\right] + (1-p)w_0^\alpha \\ &= w_0^\alpha - p\alpha L w_0^{\alpha-1} - \frac{p\alpha(1-\alpha)L^2}{2}w_0^{\alpha-2} + pR(-L). \\ v(w_b^1, w_g^1) &= p(w_0 - qL)^\alpha + (1-p)(w_0 - qL)^\alpha = (w_0 - qL)^\alpha \\ &\approx w_0^\alpha + \alpha w_0^{\alpha-1}(-qL) + \frac{\alpha(\alpha-1)}{2}w_0^{\alpha-2}(-qL)^2 + R(-qL) \\ &= w_0^\alpha - q\alpha L w_0^{\alpha-1} - \frac{q^2\alpha(1-\alpha)L^2}{2}w_0^{\alpha-2} + R(-qL), \end{aligned} \tag{8}$$

where R refers to higher order terms, which are assumed to be negligible. This comparison reveals that vaccination would be determined by combination of the expected net benefit (whether $p = q$, $p < q$, or $p > q$) and preference for risk (whether $\alpha = 1$, $\alpha < 1$, or $\alpha > 1$). It requires consideration of actuarial fairness of the vaccine and risk aversion of the agent.

Actuarial fairness concerns whether the agent's decision would yield the expected benefit greater than the cost of the decision. The expected benefit (pA) must equal the cost of the vaccine (qA), more simply put, $p = q$ if the vaccine is actuarially fair; $p > q$ if the vaccine is actuarially advantageous; and $p < q$ if the vaccine is actuarially disadvantageous. Allowing for this property, a relationship between w_b and w_g, which is referred to as the 'fair odds line' (FOL), is derived from the expected value of wealth as follows:

$$E(w^0) = pw_b^0 + (1-p)w_g^0 = p(w_0 - L) + (1-p)w_0 = w_0 - pL + (p-q)A.$$

$$\Rightarrow w_g^0 - w_0 = -\frac{p}{1-p}(w_b^0 - w_0 + L)$$

$$E(w^1) = pw_b^1 + (1-p)w_g^1 = p(w_0 - L - qA + A) + (1-p)(w_0 - qA)$$

$$= w_0 - pL + (p-q)A.$$

$$\Rightarrow w_g^1 - w_0 = -\frac{p}{1-p}(w_b^1 - w_0 + L) + \frac{p-q}{1-p}A. \qquad (9)$$

where $E(w^0)$ refers to the expected wealth if the agent decides to remain vaccinated and $E(w^1)$ refers to the expected wealth if the agent decides to be vaccinated. Especially, $E(w^1)$ implies that the slope of the FOL is identical to that of the BC if the vaccine is actuarially fair, i.e., $p = q$; the FOL runs steeper than the BC if the vaccine is actuarially advantageous while the BC runs steeper than the FOL if the vaccine is actuarially disadvantageous. The FOL lies along

$(w_b, w_g) = ([w_0 - L, \}, \{, w_0])$ because it is unimaginable that even the type b agent is unable to consume at least $w_0 - L$ and that even a type g agent is able to consume at most w_0.

The exponent α represents the degree of the agent's risk aversion. Generally, the smaller α, the more risk-averse is the agent; for simplicity, $\alpha = 1$, $0 < \alpha < 1$ and $\alpha > 1$ correspond to risk-neutral, risk-averse and risk-loving personality, respectively. It determines the curvature of the indifference curve. If the agent is risk-neutral, the indifference curve is linear; if the agent is risk-averse, the indifference curve is convex to the origin; and if the agent is risk-loving, the indifference curve is concave to the origin.

More importantly, risk aversion relates her preference for certainty. Assuming that the vaccine holds one's expected wealth constant, i.e., $w_b = w_g$, a risk-neutral individual will feel indifferent between buying the vaccine and not buying the vaccine; a risk-averse individual will prefer buying the vaccine; a risk-loving individual will prefer not buying the vaccine. The relation $w_b = w_g$ appears as a 45-degree line on the indifference map called the risk-free line (RFL). The closer to the RFL, the more risk averse is the agent, holding other conditions fixed. The RFL also represents the property that the loss due to the disease equals the benefit of the vaccine, which is derived from Equation (3):

$$\begin{cases} w_b = w_0 - L - qA + A \\ w_g = w_0 - qA \end{cases} \Rightarrow w_0 - L - qA + A = w_0 - qA \qquad (10)$$

$$\therefore A = L$$

In other words, the agent will obtain a certain amount of wealth over the RFL because the vaccine will eliminate uncertainty caused by the disease.

a) ‘Actuarially Fair’ Vaccine $(\boldsymbol{p} = \boldsymbol{q})$

Figure 1 to Figure 3 demonstrates how the agent behaves when the vaccine is actuarially fair. The BC and FOL overlaps with the slope of $-\frac{q}{1-p} = -\frac{p}{1-p}$ along $\left(w_b, w_g\right) = ([w_0 - L, w_0 - pL], [w_0 - qL, w_0])$. The fully effective vaccine, which allows $A = L$, will fix the agent’s wealth at $w_0 - pL$, regardless of her genetic type. In other words, the agent must give up pL to be assured of a certain amount of wealth $w_0 - pL$.

Figure 1 indicates that a risk-neutral individual will be indifferent between buying the vaccine and not buying the vaccine as long as her *expected* wealth is maintained at $w_0 - qL$. Her actual wealth may rise over or fall below $w_0 - pL$, but she does not find it more or less attractive to choose any $\left(w_b, w_g\right)$ between E^0 and E^1. The agent may pay nothing to purchase any vaccine (E^0); She may pay pL to purchase a fully effective vaccine (E^1); or she may pay more than zero and less than pL to purchase a mediocre vaccine whose effectiveness is less than A (E^2). However, all these different choices will result in the same expected utility.

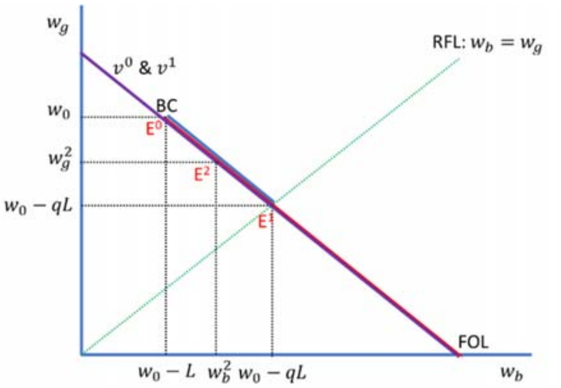
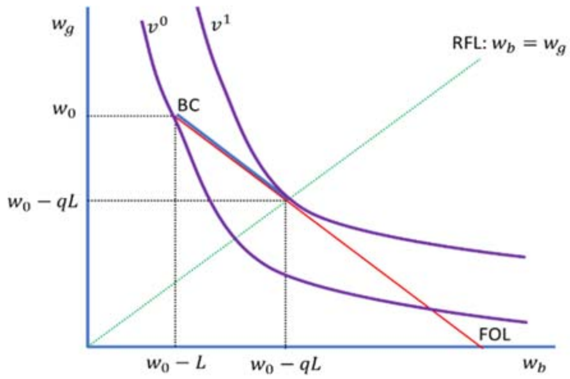


Figure 1. The risk-neutral agent with actuarially fair vaccine.



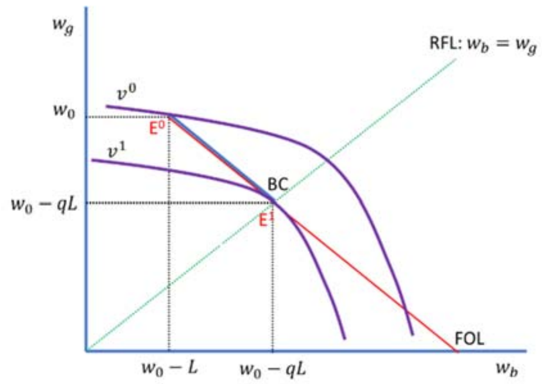


Figure 2. The risk-averse agent with actuarially fair vaccine. **Figure 3. The risk-loving agent with actuarially fair vaccine.**

Figure 2 shows that a risk-averse individual will purchase a fully effective vaccine. Even though her expected wealth remains the same anywhere between E^0 and E^1, she will pursue a *certain* amount of wealth, $w_0 - pL$, which requires her to purchase a fully effective vaccine (E^1). Since she prefers certainty to uncertainty, moving from E^0 to E^1 will improve her expected utility. She is willing to pay pL to purchase a fully effective vaccine; any other choice than E^1 that would result in lower welfare will be ruled out.

Figure 3 demonstrates why a risk-loving individual will not purchase the vaccine at all when the vaccine is actuarially fair. Even though the agent's expected wealth remains the same anywhere between E^0 and E^1, she will bet on herself being type g, which may actually earn her w_0, greater wealth than $w_0 - pL$. Thus, not buying a vaccine (E^0) will yield greater expected utility than buying the vaccine (E^1).

b) 'Actuarially Advantageous' Vaccine $(\boldsymbol{p} > \boldsymbol{q})$

Figure 4 to Figure 7 represents the agent's behaviour when the vaccine is actuarially advantageous. The FOL runs steeper than the BC, meaning $\frac{q}{1-q} < \frac{p}{1-p}$. Especially, the FOL runs over the BC beyond $(w_b, w_g) = (w_0 - qL, w_0 - qL)$, which suggests that the vaccine will raise the agent's expected wealth over the budget because its expected benefit is greater than its cost. If the vaccine is fully effective, her wealth will be kept at $w_0 - qL$, regardless of her genetic type. In other words, the agent must give up qL to make sure her wealth at $w_0 - qL$.

Figure 4 and Figure 5 show that a risk-averse individual as well as a risk-neutral individual will purchase a fully effective vaccine. It is obvious that the risk-neutral agent will choose the fully effective vaccine because the wealth in E^1 is greater than in E^0. It is also welfare-improving for a risk-averse individual to consume at E^1 because her wealth at E^1 is not only greater than in E^0 but also certain. Thus, both the risk-neutral agent and the risk-averse agent are willing to pay qL to obtain a certain amount of wealth $w_0 - qL$.

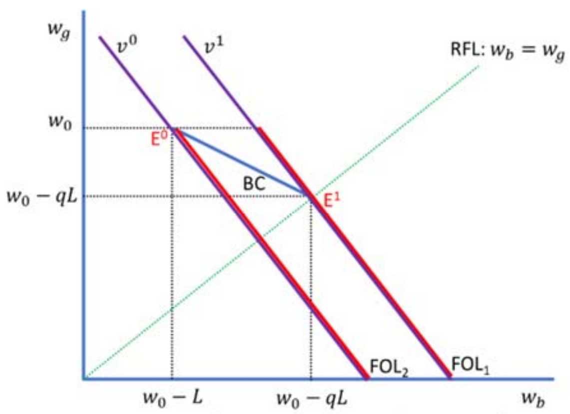


Figure 4. Risk-neutral agent with actuarially advantageous vaccine

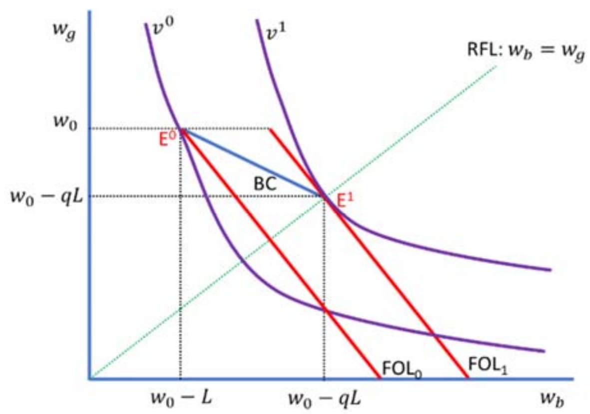


Figure 5. Risk-averse agent with actuarially advantageous vaccine

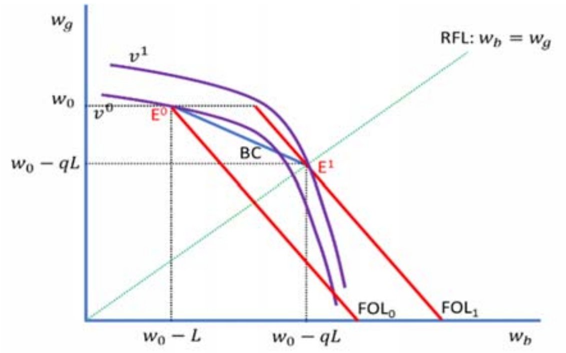


Figure 6. Weakly risk-loving agent with actuarially advantageous vaccine

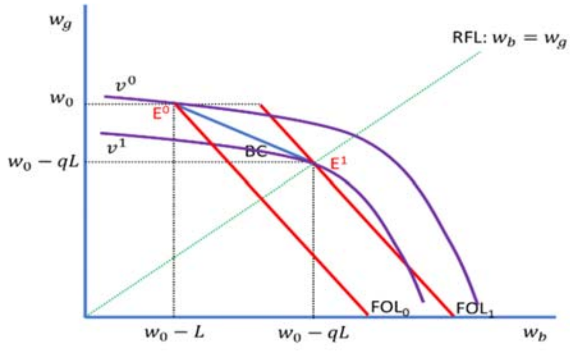


Figure 7. Strongly risk-loving agent with actuarially advantageous vaccine

Figure 6 and Figure 7 show that the agent is led to different consequences depending on the degree of her preference for risk. Figure 6 demonstrates that a risk-loving individual with the relatively weak preference for risk may purchase the fully effective vaccine. Even though the agent prefers risk to certainty compared to risk-neutral or risk-averse individuals, her preference for risk may not be great enough to induce her to take risk instead of a certain amount of wealth. Then, she may find the vaccine attractive and be willing to pay qL to purchase the vaccine. On the other hand, a risk-loving individual with the relatively strong preference for risk will not purchase the vaccine at all as illustrated in Figure 7. For her, it is worth taking risk betting on herself being type g, expecting w_0 to be earned and yielding greater expected utility than otherwise.

c) 'Actuarially Disadvantageous' Vaccine $(p < q)$

Figure 8 to Figure 11 illustrates the agent's choice when the vaccine is 'actuarially disadvantageous.' The BC runs steeper than the FOL, i.e., $\frac{q}{1-q} > \frac{p}{1-p}$. Especially, the FOL runs below the BC beyond $(w_b, w_g) = (w_0 - qL, w_0 - qL)$, which implies that the vaccine will lower

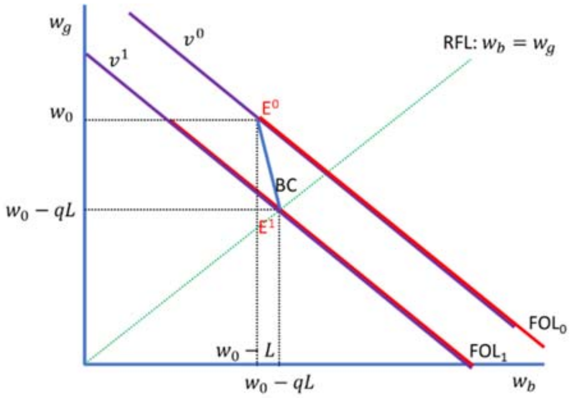


Figure 8. A risk-neutral agent with actuarially disadvantageous vaccine.

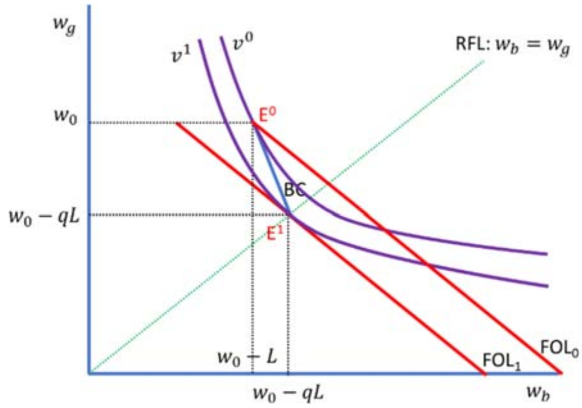


Figure 9. A weakly risk-averse agent with actuarially disadvantageous vaccine.

the agent's expected wealth below the budget because its expected benefit is outweighed by its cost. If the vaccine is fully effective, her wealth will be fixed at $w_0 - qL$, regardless of her genetic type. In other words, the agent must give up qL to make sure her wealth at $w_0 - qL$.

Figure 8 shows that a risk-neutral individual will not buy the vaccine when it is actuarially disadvantageous. Simply, she expects her wealth to be smaller if she purchases the vaccine than otherwise. The smaller the expected wealth, the lower the expected utility will be. Thus, it is reasonable for her to rather risk getting infected. Then, the expected wealth will be $w_0 - pL > w_0 - qL$, yielding greater expected utility than buying the vaccine (Note: $p < q$).

Figure 9 and Figure 10 show that a risk-averse individual's choice differs by the degree of her risk aversion. Figure 9 is the case where the agent has the relatively strong preference for certainty. She is so risk-averse that she will still purchase the vaccine even if she could make greater wealth by not purchasing the vaccine. She would rather choose a certain amount of wealth than what could be bigger but might not be realized. In Figure 10, the agent has relatively weak preference for certainty. She may find it worth risking getting infected.

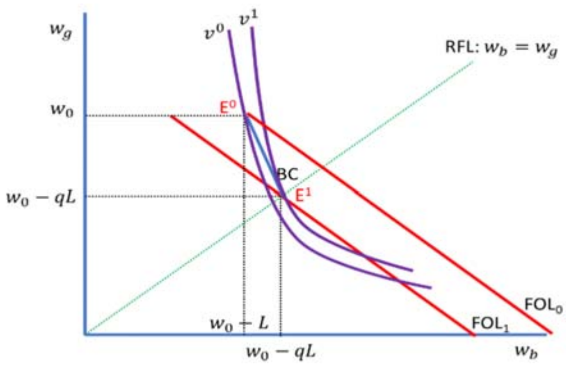


Figure 10. A strongly risk-averse agent with actuarially disadvantageous vaccine

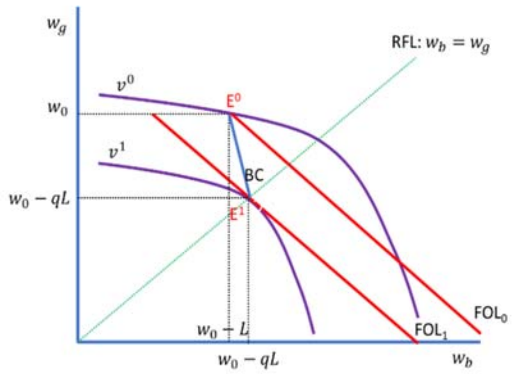


Figure 11. A risk-loving agent with actuarially disadvantageous vaccine

Finally, Figure 11 is the case where the agent has the risk-loving personality. To her, a certain amount of wealth earned by vaccination is too small to maintain. Expecting her wealth to be greater, she would rather risk getting infected than vaccinated.

B. The Choice of the Vaccine under Information Asymmetry

In the previous section, it is assumed that the quality of the vaccine is guaranteed: the vaccine is good enough to mitigate all the loss due to the disease. However, it is too optimistic to assume that a vaccine is always of good quality. The producer is typically well aware of the quality of her product while the buyer usually does not know what she buys before she buys and uses it. This imbalance of information between the producer and the buyer may lead the buyer to be so skeptical about the vaccine that she may not purchase it at all, which is very undesirable in the sense of disease control. In this section, whether such concerns are grounded will be analyzed in the framework of signaling games.

1) Basic Settings

Let's assume that there are two players: player 1 (denoted P1 hereinafter) is the producer of the vaccine and player 2 (denoted P2 hereinafter) is the buyer of the vaccine. P1 sends a signal hinting the quality of the vaccine, and P2 responds to the signal in accordance with her subjective belief in the quality of the vaccine, which is not necessarily identical to the actual quality of the vaccine, built upon the information obtained from the signal and other sources.

The quality of the vaccine is determined by P1's type, the level of skillfulness in this case. P1's type is expressed as $\theta \in \{H, L\}$, where H means that P1 is a high-skilled type while L means that P1 is a low-skilled type. P1's type θ has the following probability distribution determined by Nature:

$$Pr(\theta) = \begin{cases} Pr(H) = r \\ Pr(L) = 1 - r \end{cases} \text{for } 0 \leq r \leq 1, \tag{11}$$

which is a common knowledge, but P2 is not sure whether P1 belongs to H or L. It is assumed that only the vaccine produced by a high-skilled producer can prevent variants in the virus.

P2 guesses P1's type by observing the signal sent by P1, which takes a form of announcement or publication. P1's signal belongs to a form of set: $s_1 \in \{M, V\}$. M refers to "mRNA" technology, which is generally considered an advanced technology, and V refers to, "viral vector" technology, which is generally considered a traditional technology. Adopting M is costly but the low-skilled producer should bear higher cost because it is hard for the low-skilled producer to manage the advanced technology; and using the traditional technology will not incur any cost. Therefore, the cost function of P1's type conditional on the technology adopted by P1 is constructed as follows:

$$c(\theta; s_1) = \begin{cases} c(H;M) = c_H \\ c(L;M) = c_L \\ c(H;V) = 0 \\ c(L;V) = 0 \end{cases} \text{ for } C_H < C_L. \tag{12}$$

It is assumed which technology P1 uses would not change the effectiveness of the vaccine. The technology purely serves only signaling purposes.

P2 responds after observing P1's signal. P2's action belongs to a set: $s_2 \in \{h, l\}$. The action h suggests that P2 offers a high price believing that the vaccine is effective for both variant and non-variant virus; and the action l suggests that P2 offers low price believing that the vaccine is effective only for non-variant virus. The price offered by P2 is one of $\{\pi_h, \pi_l\}$ for $\pi_h > \pi_l$. P1's payoffs are derived as follows:

$$R_1\big((s_1;\theta); s_2\big) = \begin{cases} R_1\big(h, (H;M)\big) = \pi_h - c_H \\ R_1\big(h, (L;M)\big) = \pi_h - c_L \\ R_1\big(l, (H;M)\big) = \pi_l - c_H \\ R_1\big(l, (L;M)\big) = \pi_l - c_L \\ R_1\big(h, (H;V)\big) = \pi_h \\ R_1\big(h, (L;V)\big) = \pi_h \\ R_1\big(l, (H;V)\big) = \pi_l \\ R_1\big(l, (L;V)\big) = \pi_l \end{cases}. \tag{13}$$

P2's payoff depends on P1's type revealed after P2's price offer based on her belief in the proper use of the vaccine. It is described as in the following table:

		P2's Offer	
		h	l
P1's Type	H	a_H^h	a_H^l
	L	a_L^h	a_L^l

It is also expressed as the following equation:

$$R_2(\theta; s_2) = \begin{cases} R_2(H;h) = a_H^h \\ R_2(H;l) = a_H^l \\ R_2(L;h) = a_L^h \\ R_2(L;l) = a_L^l \end{cases} \text{for } a_L^h < a_L^l < a_H^l < a_H^h \tag{14}$$

If P2 offers h and P1's type turns out H, P2's payoff is the greatest because the purpose of the vaccine is matched with the quality; if P2 offers h and P1's type turns out L, P2's payoff is the smallest because P2 is paying too much for the vaccine only effective for non-variant virus. It is assumed that the vaccine produced by type H producer is more effective for the non-variant virus, which implies $a_L^l < a_H^l$.

P1 is assumed to take a mixed strategy that the same choice is made in different probabilities depending on her type. σ^H is the probability that P1 chooses M when her type is H; and σ^L is the probability that P1 chooses M when her type is L. P2 also builds her belief upon P1's type based on her observation of P1's action. μ_M is P2's belief that P1's type is H conditional on P1 choosing M; and μ_V is P2's belief that P1's type is H conditional on P1 choosing V. μ_M and μ_V are computed as follows:

$$\mu_M = \frac{r\sigma^H}{r\sigma^H + (1-r)\sigma^L}; \text{ and} \tag{15}$$

$$\mu_V = \frac{r(1-\sigma^H)}{r(1-\sigma^H) + (1-r)(1-\sigma^L)}. \tag{16}$$

Figure 12 is the signaling game tree that demonstrates the consequence of each course of actions sequentially taken by P1 and P2. This tree presents two different information sets, I_M and I_V, upon which players make their decisions: I_M includes all the information made when P1 chooses M; and I_V includes all the information made when P1 chooses V. The tree is also divided by Nature, which determines the underlying probability distribution of P1's type.

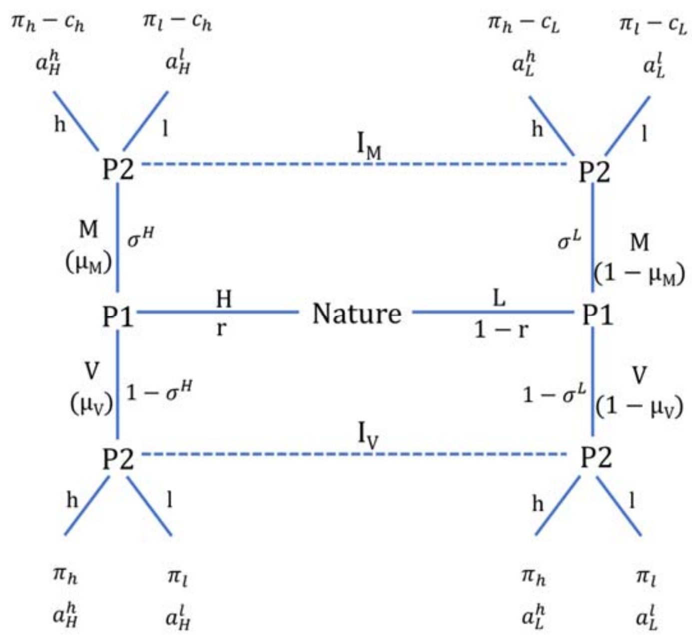


Figure 12. A signaling game tree of vaccine choice

2) Perfect Bayesian Equilibria

Using all the information laid out in Figure 12, perfect Bayesian equilibria (PBE), in which neither P1 nor P2 has incentive to deviate, will have to be found. A PBE is the state that meets both sequential rationality and consistency. Sequential rationality refers to the condition that each player plays a best response with respect to her belief in every information set. Consistency refers to the condition that each player's belief needs to be updated from every player's strategy using the Bayes' Rule. Each player's strategy, probability distribution determined by Nature and prior and posterior beliefs should be examined to find PBE.

P1's strategy is defined as a combination of P1's actions corresponding to her types. P1's action set s_1 is subdivided by her type: $\theta \in \{H, L\}$. There exist two action sets corresponding to her types: $s_1^\theta = \begin{cases} s_1^H \in \{M, V\} \\ s_1^L \in \{M, V\} \end{cases}$. P1's strategy is defined as $s_1^H s_1^L \in \{MM, MV, VM, VV\}$. A strategy xy in this strategy profile means that P1 chooses x if her type is H while choosing y if she is L. In case P1 adopts the same technology regardless of her type, i.e., MM or VV, such a strategy is referred to as a pooling strategy while in case P1 adopts different strategy depending on her type, i.e., MV or VM, she is taking a separating strategy.

P2's strategy is defined as a combination of P2's reactions corresponding to P1's signal. P2's action set is subdivided by P1's signal: $\{M, V\}$. There are two action sets corresponding to P1's signal: $\begin{cases} s_2^M \in \{h. l\} \\ s_2^V \in \{h. l\} \end{cases}$. P2's strategy is defined as $s_2^M s_2^V = \{hh, hl, lh, ll\}$. In other words, $x'y'$ means that P2 offers x' if she observes M and that P2 offers y' if she observes V.

A PBE derived from a pooling strategy taken by P1 is referred to as a pooling equilibrium while a PBE derived from a separating strategy taken by P1 is called a separating equilibrium.

a) $\boldsymbol{s_1^H s_1^L = MM}$

Suppose that P1 chooses M regardless of her type, i.e., $s_1^H s_1^L = MM$. Given that P2 observes only M from the signal sent by P1, $\sigma^H = \sigma^L = 1$ must be true. Thus, P2 has belief from I_M calculated as:

$$\mu_M = \frac{r\sigma^H}{r\sigma^H + (1-r)\sigma^L} = \frac{r \times 1}{r \times 1 + (1-r) \times 1} = r \tag{17}$$

In other words, P2 believes that P1's type is H with probability of r if she observes that P1 chooses M. On the other hand, P2 does not have well-defined belief from I_V because the probability that P1 chooses V is zero, regardless of her type.

Let us consider P2's responses in I_M. If P2 chooses h, i.e., offers a high price, with belief that the vaccine is effective for both variant and non-variant virus, the expected payoff will be the probability-weighted sum of her payoffs conditional on choosing h:

$$E\left(R_2^M(\theta;h)\right) = rR_2^M(H;h) + (1-r)R_2^M(L;h) = ra_H^h + (1-r)a_L^h. \tag{18}$$

If P2 chooses l, i.e., offers a low price for the vaccine against only non-variant virus, the expected payoff conditional on choosing l will be:

$$E\left(R_2^M(\theta;l)\right) = rR_2^M(H;l) + (1-r)R_2^M(L;l) = ra_H^l + (1-r)a_L^l. \tag{19}$$

If h is P2's best response to $s_1^H s_1^L = MM$ in I_M, $E\left(R_2^M(\theta;h)\right) > E\left(R_2^M(\theta;h)\right)$ msut be satisfied. It is also equivalent to the following relation:

$$ra_H^h + (1-r)a_L^h > ra_H^l + (1-r)a_L^l \Leftrightarrow \frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}. \tag{20}$$

Let us consider P2's response in I_V. Since $1-\sigma^H = 0$ and $1-\sigma^L = 0$, the belief that the vaccine is effective for both variant and non-variant virus when V is observed is not well-defined and an arbitrary probability should be assigned to μ_V in this case. If P2 chooses h, i.e., offers a high price, with the belief that the vaccine is effective for both variant and non-variant virus, the expected payoff will be the probability-weighted sum of her payoffs from P1 being H and L conditional on P2 choosing h:

$$E\left(R_2^V(\theta;h)\right) = \mu_V R_2^V(H;h) + (1-\mu_V)R_2^V(L;h) = \mu_V a_H^h + (1-\mu_V)a_L^h \tag{21}$$

If P2 chooses l, i.e., offers a low price for the vaccine against only non-variant virus, the expected payoff conditional on choosing h:

$$E\left(R_2^V(\theta;l)\right) = \mu_V R_2^V(H;l) + (1-\mu_V)R_2^V(L;l) = \mu_V a_H^l + (1-\mu_V)a_L^l. \tag{22}$$

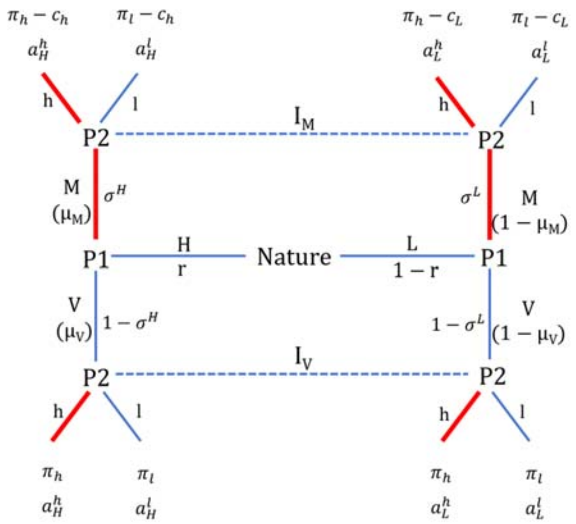


Figure 13. P1's pooling strategy (MM) and P2's response (hh)

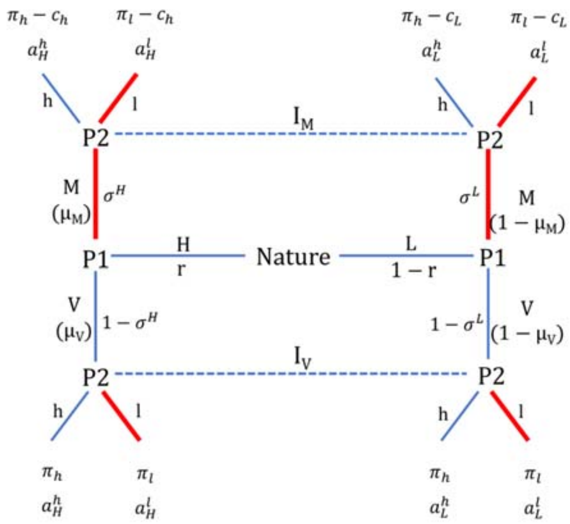


Figure 14. P1's pooling strategy (MM) and P2's response (ll)

If h is P2's best response to $s_1^H s_1^L = VV$ in I_V, $E\left(R_2^V(\theta; h)\right) > E\left(R_2^V(\theta; h)\right)$ msut be satisfied. It is also equivalent to the following relation:

$$\mu_V a_H^h + (1-\mu_V)a_L^h > \mu_V a_H^l + (1-\mu_V)a_L^l \Leftrightarrow \frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_V}{1-\mu_V}. \tag{23}$$

Figure 13 describes the case of (MM, hh). If Equation (20) and (23) are true, then h should be P2's best response in both I_M and I_V ($s_2^M s_2^V = hh$). P1, whose type is H, has incentive to deviate from M to V because she will earn greater payoff from choosing $V(\pi_h)$ than from choosing M $(\pi_h - c_H)$; P1, whose type is L, also has incentive to deviate from M to V because the payoff from choosing V (π_h) is greater than the payoff from choosing M $(\pi_h - c_L)$. Thus, (MM, hh) will not be a pooling equilibrium if $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_V}{1-\mu_V}$.

Figure 14 shows the case of (MM, ll). If neither Equation (20) nor (23) is true, then l should be P2's best response in both I_M and I_V ($s_2^M s_2^V = ll$). P1, whose type is H, has incentive to deviate from M to V because she will earn greater payoff from choosing $V(\pi_l)$ than from choosing M $(\pi_l - c_H)$; P1, whose type is L, also has incentive to deviate from M to V because

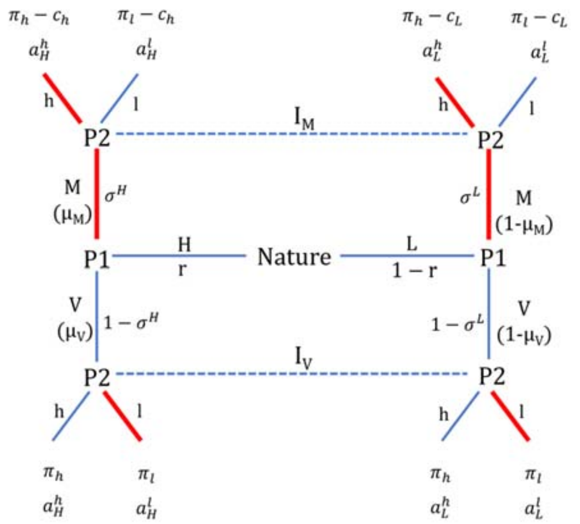


Figure 15. P1's pooling strategy (MM) and P2's response (hl)

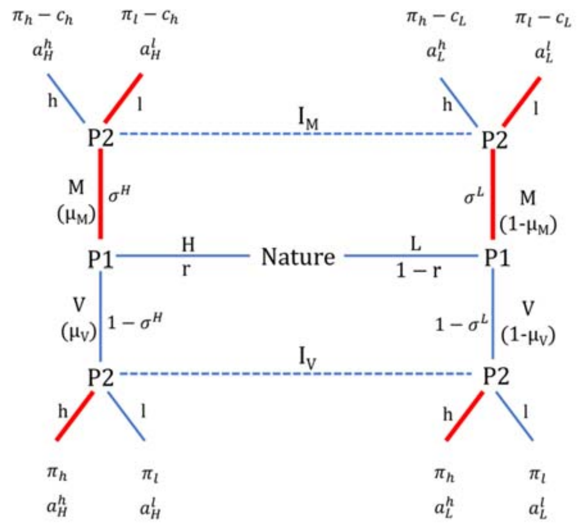


Figure 16. P1's pooling strategy (MM) and P2's response (lh)

the payoff from choosing V (π_l) is greater than the payoff from choosing M $(\pi_l - c_H)$. Thus, (MM, ll) will not be a pooling equilibrium if $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_V}{1-\mu_V}$.

Figure 15 demonstrates the case of (MM, hl). If Equation (20) is true and Equation (23) is untrue, then P2's best response is h in I_M and l in I_V $(s_2^M s_2^V = hl)$. P1, whose type is H, has no incentive to switch from to M to V if the payoff from choosing M $(\pi_h - c_H)$ is greater than the payoff from choosing $V(\pi_l)$; P1, whose type is L, has no incentive to switch from M to V if she earns greater payoff from choosing M $(\pi_h - c_L)$ than from choosing $V(\pi_l)$. Thus, (MM, lh) will be a pooling equilibrium if $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$, $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_V}{1-\mu_V}$ and $\pi_h - \pi_l > c_L$ are met.

Figure 16 illustrates the case of (MM, lh). If Equation (20) is untrue and Equation (23) is true, then P2's best response is l in I_M and h in I_V $(s_2^M s_2^V = lh)$. P1, whose type is H, has incentive to switch from to M to V because the payoff from choosing $V(\pi_h)$ is greater than the payoff from choosing M $(\pi_l - c_H)$; P1, whose type is L, also has incentive to switch from M to

V because she will earn greater payoff from choosing $V(\pi_h)$ than from choosing M $(\pi_h - c_L)$.

Thus, (MM, lh) will not be a pooling equilibrium if $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_V}{1-\mu_V}$.

Overall, with the following condition being met, P1's pooling strategy $s_1^H s_1^L = MM$ will lead to a PBE:

i) $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}, \frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_V}{1-\mu_V}$ and $\pi_h - \pi_l > c_L \Longrightarrow (MM, lh)$.

b) $s_1^H s_1^L = VV$

Suppose that P1 chooses V regardless of her type, i.e., $s_1^H s_1^L = VV$. Given that P2 observes only V from the signal sent by P1, $\sigma^H = \sigma^L = 0$ must be true. Thus, P2 does not have well-defined belief from I_M because the probability that P1 chooses M is zero, regardless of her type. On the other hand, P2 has belief from I_V calculated as:

$$\mu_v = \frac{r(1-\sigma^H)}{r(1-\sigma^H) + (1-r)(1-\sigma^L)} = \frac{r \times 1}{r \times 1 + (1-r) \times 1} = r \tag{24}$$

In other words, P2 believes that P1's type is H with the probability of r if she observes that P1 chooses V.

Let us consider P2's responses in I_M. Since $\sigma^H = 0$ and $\sigma^L = 0$, the belief that the vaccine is effective for both variant and non-variant virus when M is observed is not well-defined and an arbitrary probability should be assigned to μ_M in this case. P2's expected payoff of choosing h in I_M is calculated as follows:

$$E\big(R_2^M(\theta; h)\big) = \mu_M R_2^M(H; h) + (1-\mu_M) R_2^M(L; h) = \mu_M a_H^h + (1-\mu_M) a_L^h; \tag{25}$$

while her expected payoff of choosing l is calculated as follows:

$$E\big(R_2^M(\theta; l)\big) = \mu_M R_2^M(H; l) + (1-\mu_M) R_2^M(L; l) = \mu_M a_H^l + (1-\mu_M) a_L^l. \tag{26}$$

h being P2's best response in I_M must satisfy the following:

$$E\big(R_2^M(\theta; h)\big) > E\big(R_2^M(\theta; l)\big) \Leftrightarrow \frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_M}{1-\mu_M}. \tag{27}$$

Let's also consider P2's response in I_V. Since $1 - \sigma^H = 1$ and $1 - \sigma^L = 1$, the belief that the vaccine is effective for both variant and non-variant virus when V is observed is r as obtained in Equation (25). Expected payoffs from choosing h and l in I_V are computed respectively as follows:

$$E\big(R_2^V(\theta; h)\big) = rR_2^V(H; h) + (1-r)rR_2^V(L; h) = ra_H^h + (1-r)a_L^h \tag{28}$$

$$E\big(R_2^V(\theta; l)\big) = rR_2^V(H; l) + (1-r)rR_2^V(L; l) = ra_H^l + (1-r)a_L^l \tag{29}$$

h being P2's best response in I_V must meet the following:

$$E\big(R_2^V(\theta; h)\big) > E\big(R_2^V(\theta; l)\big) \Leftrightarrow \frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}. \tag{30}$$

Figure 17 shows the case of (VV, hh). If Equation (27) and (30) are true, h must be the best response in both I_M and I_V ($s_2^M s_2^V = hh$). P1, whose type is H, has no incentive to deviate from V to M because she will earn greater payoff from choosing $V (\pi_h)$ than from choosing M $(\pi_h - c_H)$; P1, whose type is L, also has no incentive to deviate from V to M because the payoff

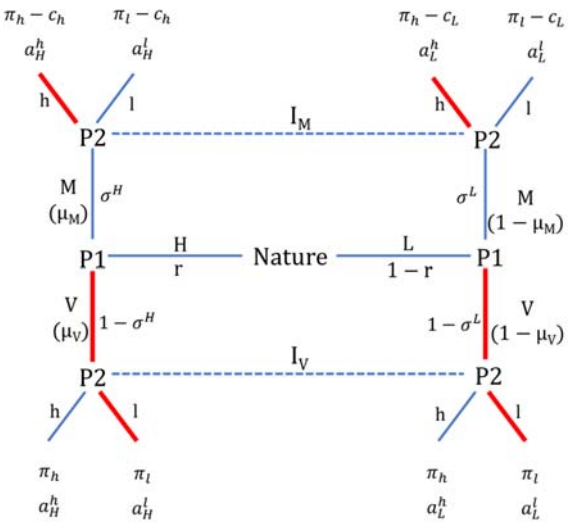


Figure 19. P1's pooling strategy (VV) and P2's response (hl)

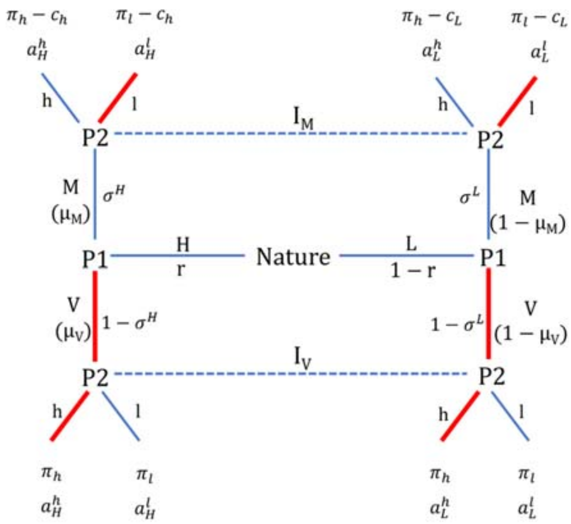


Figure 20. P1's pooling strategy (VV) and P2's response (lh)

from choosing V (π_h) is greater than the payoff from choosing M $(\pi_h - c_L)$. Thus, (VV, hh) will be a pooling equilibrium as long as $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$ are true.

Figure 18 demonstrates the case of (VV, ll). If neither Equation (27) nor (30) is true, then l should be P2's best response in both I_M and I_V $(s_2^M s_2^V = ll)$. P1, whose type is H, has no incentive to deviate from V to M because she will earn greater payoff from choosing $V(\pi_l)$ than

Figure 17. P1's pooling strategy (VV) and P2's response (hh)

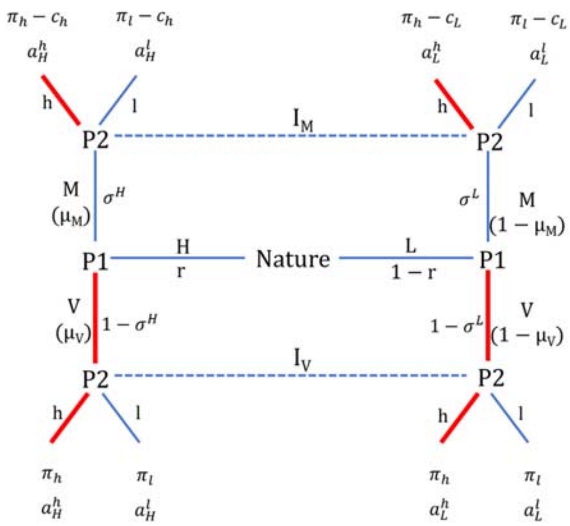
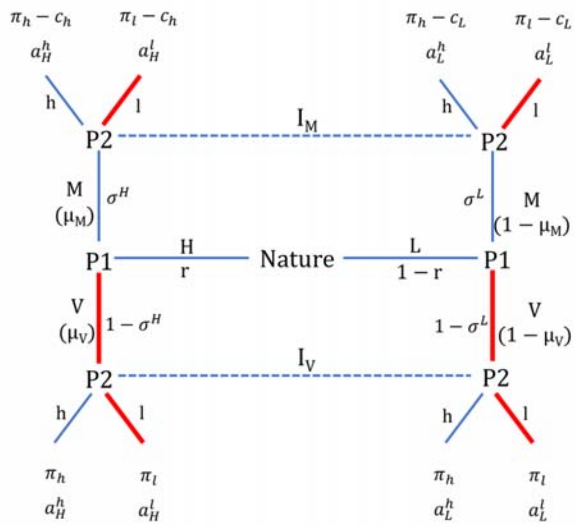


Figure 18. P1's pooling strategy (VV) and P2's response (ll)



from choosing M $(\pi_l - c_H)$; P1, whose type is L, also has no incentive to deviate from V to M

because the payoff from choosing V (π_l) is greater than the payoff from choosing M $(\pi_l - c_L)$. Thus, (VV, ll) will be a pooling equilibrium as long $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r}$ are true.

Figure 19 illustrates the case of (VV, hl). If Equation (27) is true and Equation (30) is untrue, then P2's best response is h in I_M and l in I_V $(s_2^M s_2^V = hl)$. P1, whose type is H, has no incentive to switch from to V to M if the payoff from choosing V (π_l) is greater than the payoff from choosing M $(\pi_h - c_H)$; P1, whose type is L, also has no incentive to switch from V to M if she will earn greater payoff from choosing $V(\pi_l)$ than from choosing M $(\pi_h - c_L)$. Thus, (VV, hl) will be a pooling equilibrium if $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_M}{1-\mu_M}$, $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r}$ and $\pi_h - \pi_l < c_H$.

Figure 20 describes the case of (VV, lh). If Equation (27) is untrue and Equation (30) is true, then P2's best response is l in I_M and h in I_V $(s_2^M s_2^V = lh)$. P1, whose type is H, has no incentive to switch from to V to M because the payoff from choosing $V(\pi_h)$ is greater than the payoff from choosing M $(\pi_l - c_H)$; P1, whose type is L, also has no incentive to switch from V to M because she will earn greater payoff from choosing $V(\pi_h)$ than from choosing M $(\pi_l - c_L)$. Thus, (VV, lh) will be a pooling equilibrium as long as $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$ are met.

Overall, with each of the following conditions met, P1's pooling strategy $s_1^H s_1^L = VV$ will lead to each condition's corresponding equilibrium:

ii) $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r} \Longrightarrow (VV, hh)$;

iii) $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r} \Longrightarrow (VV, ll)$;

iv) $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{r}{1-r}$ and $\pi_h - \pi_l < c_H \Longrightarrow (VV, hl)$; and

v) $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} > \frac{\mu_M}{1-\mu_M}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r} \Longrightarrow (VV, lh)$.

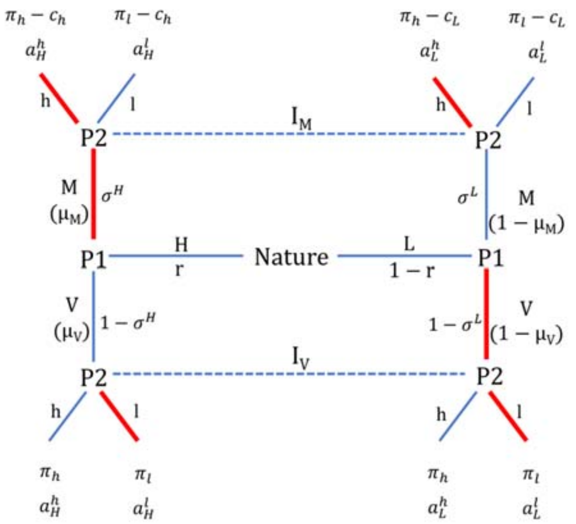


Figure 21. P1's separating strategy (MV) and P2's response (hl)

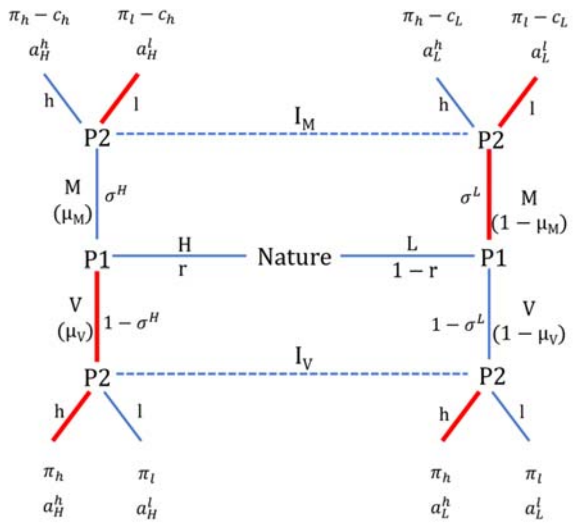


Figure 22. P1's separating strategy (MV) and P2's response (lh)

c) $\boldsymbol{s_1^H s_1^L = MV}$

Figure 21 demonstrates the case of (MV, hl). Suppose that P1 chooses M if her type is H and V if her type is L. It suggests $\sigma^H = 1$ and $\sigma^L = 0$. It turns out $\mu_M = 1$ and $\mu_V = 0$. In other words, P2 is confident that P1's type is H if M is observed while P1's type is L if $V$is observed. P2's best responses will be h if M is observed and l if V is observed. P1, whose type is H, has no incentive to deviate from M to V if the payoff from choosing M $(\pi_h - c_H)$ is greater than the payoff from choosing V (π_l); and P1, whose type is L, has no incentive to deviate from V to M if the payoff from choosing V (π_l) is greater than the payoff from choosing M $(\pi_h - c_L)$. Thus, with the following condition met, P1's separating strategy $s_1^H s_1^L = MV$ will lead to a PBE:

vi) $c_H < \pi_h - \pi_l < c_L \Rightarrow (MV, hl)$.

d) $\boldsymbol{s_1^H s_1^L = VM}$

Figure 22 describes the case of (VM, lh)Suppose that P1 chooses V if her type is H and M if her type is L. It suggests $\sigma^H = 0$ and $\sigma^L = 1$. It turns out $\mu_M = 0$ and $\mu_V = 1$. In other words, P2 is confident that P1's type is H if V is observed while P1's type is L if $M$is observed. P2's best responses will be h if V is observed and l if M is observed. P1, whose type is H, has no incentive to deviate from V to M because the payoff from choosing V (π_h) is greater than the payoff from choosing M $(\pi_l - c_H)$; and P1, whose type is L, has incentive to deviate from M to V because the payoff from choosing M $(\pi_l - c_L)$ is smaller than the payoff from choosing V (π_h). Thus, the separating strategy $s_1^H s_1^L = VM$ will not lead to any equilibrium.

IV. Discussions

A. Penalty, Reward and Nudge

It is demonstrated in III.A. that an individual is required to purchase a fully effective vaccine $(A = L)$ to completely mitigate the loss due to the infectious disease. It also shows that degrees of actuarial fairness of the vaccine and individual differences in preference for risk may complicate one's choice. For example, as demonstrated in III.A., a risk-loving individual will not purchase the vaccine at all when the vaccine is actuarially fair or disadvantageous; even if the vaccine is actuarially advantageous, a risk-loving individual with the relatively strong preference for risk will not buy the vaccine, as well. Even a risk-neutral or risk-averse individual may not buy the vaccine, either, in case the vaccine is actuarially disadvantageous or their risk aversion is relatively weak.

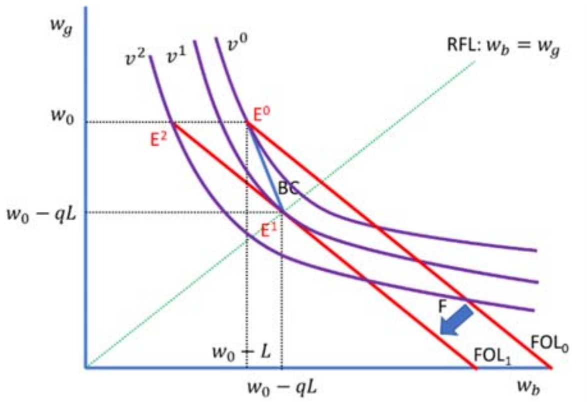


Figure 23. A weakly risk-averse agent may switch to getting vaccinated if penalized for not being vaccinated although the vaccine is actuarially disadvantageous.

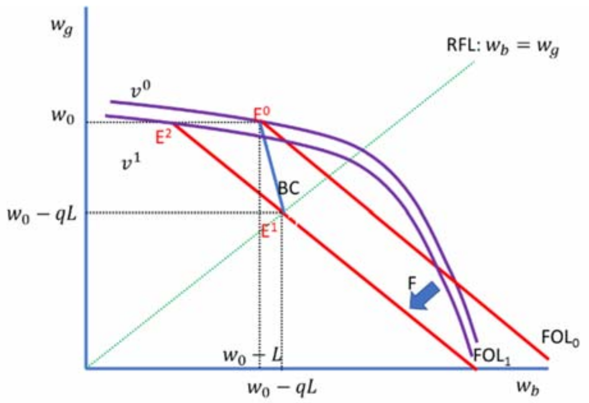


Figure 24. A risk-loving agent may remain unvaccinated even if penalized for not being vaccinated when the vaccine is actuarially advantageous.

It may not be always undesirable that an individual takes a risk of her own as long as the risk is not contagious through society. For example, the damage of an uninsured robbery is typically isolated to the victim and harmless to a third party. However, in this case, an individual who is not vaccinated may not only allow herself to be infected but also carry and transmit the disease to someone else, eventually harming the rest of society. Especially if the probability to get infected is very large, it may be too risky to leave even a small fraction of the population unvaccinated. Thus, vaccination of those who would not vaccinate themselves will be necessary in order to maintain public health from the disease.

Generally, financial means are used to provide individuals with incentives to get vaccinated. One way to lead unvaccinated individuals to vaccination is to penalize them. Various methods can be designed as penalties from taxes or fines imposed by the government to health insurance surcharges or increase in premia charged by private parties. In the context of this thesis, these actions will add loss to the existing loss from the disease and reduce one's expected wealth if that person decides to remain unvaccinated. The expected wealth with the penalty is calculated in application of Equation (9):

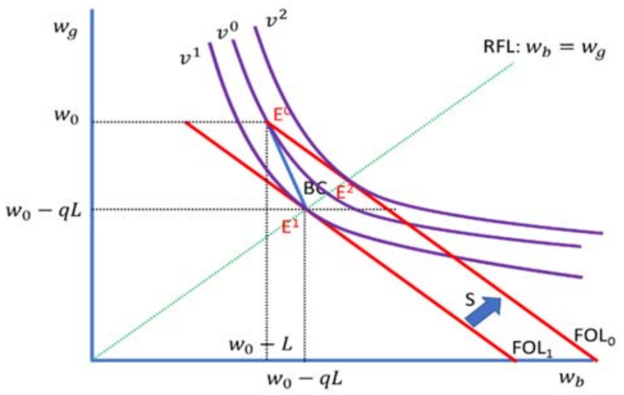


Figure 25. A weakly risk-averse agent may switch to getting vaccinated if rewarded for being vaccinated although the vaccine is actuarially disadvantageous.

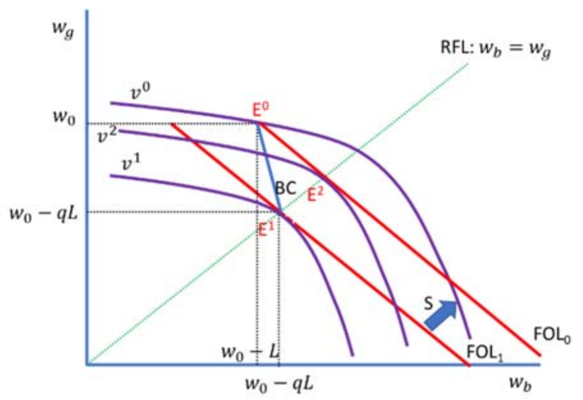


Figure 26. A risk-loving agent may remain unvaccinated even if rewarded for being vaccinated when the vaccine is actuarially advantageous.

$$E(w^0) = pw_b^0 + (1-p)w_g^0 = w_0 - pL - F, \quad (31)$$

where F refers to the penalty imposed to reduce an unvaccinated individual's expected wealth. This penalty is supposed to bring down the expected wealth of an unvaccinated individual and to induce herself to be vaccinated. However, depending on the degree of actuarial fairness of the vaccine and the extent of one's preference for risk, the effectiveness of the penalty may have significant difference.

Let us assume that the vaccine is actuarially disadvantageous. Figure 23 suggests that a risk-averse individual with relatively weak risk aversion might inoculate herself if she were properly penalized for not being vaccinated. The penalty will reduce the expected wealth without vaccination. If she remains unvaccinated, her expected utility will be reduced from v_0 to v_2. However, if she is vaccinated, she will be guaranteed to receive v_1. Thus, for her, it is not worth maintaining the position to remain unvaccinated.

On the other hand, Figure 24 suggests that a risk-loving individual might remain unvaccinated even if the penalty reduces the expected wealth. If she remains unvaccinated, she can yield lower expected utility than otherwise. However, the expected utility from remaining unvaccinated still exceed that from getting vaccinated. Thus, for her, it is still worth taking a risk getting infected. In this case, the penalty for a risk-loving individual must be much more severe so that she will be forced to be vaccinated.

Another way to encourage those unvaccinated to vaccinate themselves is to provide them with financial incentives. It can be done with subsidies from government or bonus from employers. In this context, these actions will increase individual's expected wealth as follows:

$$E(w^1) = pw_b^1 + (1-p)w_g^1 = w_0 - pL + (p-q)A + S \quad (32)$$

where S refers to the reward for getting vaccinated. Figure 25 implies that a risk-averse individual with relatively weak risk aversion might get vaccinated if she is properly rewarded for getting vaccinated. Not only the reward will increase her expected wealth, but also she will have a certain amount of wealth . The utility (v_2) generated at E^2 by getting vaccinated is greater than the expected utility from remaining unvaccinated.

On the other hand, a risk-loving individual will remain unvaccinated if the subsidy is large enough to induce her to get vaccinated as illustrated in Figure 26. Even though the increase in her expected wealth by the reward for getting vaccinated, she may still believe that she can eventually obtain greater wealth that will generate greater utility in case she is not infected. Thus, despite a certain amount of wealth earned which would be greater because of the reward for getting vaccinated, she may decide not to get vaccinated.

Financial means, i.e., penalty and rewards, described above may have other related weaknesses. Even if a penalty or a reward is properly assessed for an individual, this amount may be too large for other to afford or not be enough to induce others to get vaccinated. However, imposing different penalties or providing different rewards depending on the individual's preference for risk will result in administrative difficulties involving backlog costs. In addition, collecting penalties and giving out rewards will require both individuals and corresponding authorities (e.g., government, employer, etc.) to be able to afford these financial means. If these requirements are not fulfilled, the effectiveness of financial means may be highly limited.

Other than financial means, ‘nudging’ can be an effective tool to lead individuals to get vaccinated. According to Thaler & Sustein (2009, p. 6), a “nudge…is any aspect of the choice architecture that alters people’s behaviror in a predictable way without forbidding any options or significantly changing their economic incentives.” For example, instead of penalizing or rewarding, a simple text reminder of a physician appointment that includes “a shot is reserved for you at the clinic” may help individuals get the idea that the vaccine is already available (Brewer, 2021). This message actually can be interpreted that it costs less to get vaccinated than they have thought. In other words, individuals may realize that q, the premium on the vaccine effectiveness mentioned in Equation (3), is lower and that the vaccine is actuarially more advantageous than perceived, encouraging them to get vaccinated.

Of course, the effectiveness of this “nudge” is limited. One who really dislikes getting vaccinated will unlikely change her mind and get vaccinated after receiving this message; one who really wants to get vaccinated will get vaccinated anyway whether or not she receives this message. However, for those who are not sure whether vaccination will improve their welfare, the “nudge” can be a very powerful instrument to encourage vaccination.

B. Interplay between the Signal and the ‘Type’

It is assumed in III.B. that the signal sent by P2, i.e., technology, is not correlated with the type of P2, i.e., the level of skillfulness of the producer which determines the quality of the

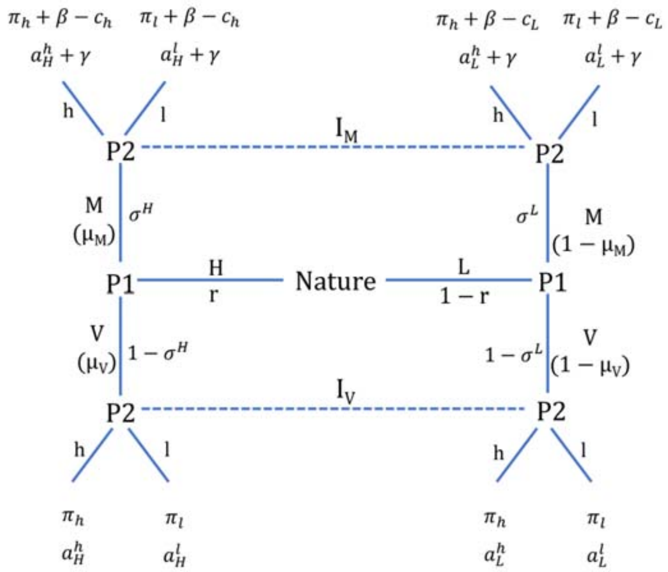


Figure 27. P1's payoffs increase because the vaccine produced with a higher level of technology is believed to be more effective.

vaccine. However, such an assumption is unrealistic because P2, the vaccine producer, would not adopt a new technology unless it helped the productivity or quality of the product improved to eventually enhance its profitability. Thus, it will be worth examining how the adoption of a new technology will influence the outcome of the game.

In Figure 27, two players' payoffs are revised as a relatively new 'mRNA' technology (M) raises the quality of the vaccine. Not only P2's but also P1's payoff should increase because P2 is willing to pay more for the vaccine produced using M. Additionally, P1 earns β and P2 earns γ.

Let us consider P1 plays a pooling strategy MM, which previously had only one case of perfect Bayesian equilibrium with very restrictive conditions. Simply adding γ to P2's payoff will not alter P2's belief because the extra payoff will cancel out when the expected payoff of P2 is calculated. Thus, P2's belief that P1's type is H conditional on observing M and P2's belief that P1's type is H conditional on observing V remain not altered and must meet as $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$

and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_V}{1-\mu_V}$, respectively. If $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{r}{1-r}$ and $\frac{a_L^l - a_L^h}{a_H^h - a_H^l} < \frac{\mu_V}{1-\mu_V}$ are correct, then h should be P2's best response in both I_M and I_V ($s_2^M s_2^V = hh$). P1, whose type is H, may have no incentive to deviate from M to V if she earns greater payoff from choosing M ($\pi_h - c_H + \beta$) than from choosing $V(\pi_h)$; P1, whose type is L, may also have no incentive to deviate from M to V if the payoff from choosing M ($\pi_h - c_L + \beta$) is greater than from choosing V (π_h). Thus, (MM, hh) can be a pooling equilibrium if $\beta - c_L > 0$.

To sum up, the assumption that the signal and the sender's type are uncorrelated may not be realistic. Taking into account the interplay between the signal and the sender's type may significantly alter the outcome of the game. If it is true that the type of technology applied to vaccine production has deep influence on the effectiveness of vaccination, the buyer needs to take it into consideration.

V. Concluding Remarks

Two models for individual decisions on vaccination under incomplete information, which poses uncertainty and information asymmetry, have been presented in this thesis.

In the state-preference model, the vaccine plays a role of insurance against the disease. It suggests that the agent's vaccine purchase is determined by interaction between actuarial fairness of the vaccine and risk aversion of the agent. The more actuarially advantageous the vaccine is and the more risk-averse the agent's personality is, the more likely the agent will purchase the vaccine.

It is also important to note that an individual normally acts upon her own interest, which may not coincide with collective goals of society, i.e., herd immunity achieved by universal vaccination in this thesis. Penalty, reward and 'nudge' are discussed as instruments to implement universal vaccination. Financial incentives provided by penalty and reward may not be as effective as intended if the agent's preference for risk is strong. A 'nudge' may be a powerful tool to encourage individuals, who is at the border between those who like vaccines and those who dislike vaccines, to engage in universal vaccination.

The signaling game model shows that an individual buyer of the vaccine builds up her belief of the vaccine's quality by observing the signal sent by the producer, in this case, the type of technology. The producer's pooling and separating strategies may result in perfect Bayesian equilibria with conditions that bound the buyer's belief and the producer's incentive to deviate from the initial strategy.

These conditions may be altered if the initial assumption that the signal sent by the producer, i.e., the type of technology used by the producer, is not correlated with the information that the buyer actually pursues, i.e., the quality of the vaccine does not hold. It is concerned with the effectiveness of vaccination, and the buyer may need to take it into account.

Finally, it is important to note that this thesis mainly focuses on individual behaviour, not on collective actions of group or society regarding vaccination. Especially, it assumes that the purchase of a vaccine is individually financed, which is usually not the case in real life. A publicly-financed vaccination program may have other consequences than predicted by this research because individuals will likely face uncertainty and incentives altered by the program.

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