A comparison between Expected Utility and Regret Theory models of individuals' propensity to vaccinate

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I. Introduction

Transmission of infectious disease is strongly influenced by how people make choices (both individually and collectively) among the available preventive health care options to maximise their well-being. The recent advancement in 'economic epidemiology' has examined aggregate behaviour on the premise that a rational individual's decision in vaccination is influenced by both economic and epidemiological incentives. Notable papers[1] originating from that perspective argue that the fundamental objective of the rational agent, who evaluates an option on the basis of expected utility of the final value of the outcome, is to find the optimum timing of vaccination. There is obviously a dynamic feedback mechanism between individual choice and aggregate infection rate, but choices regarding vaccination could be argued to more plausibly be represented as a static discrete decision, -to vaccinate or not- rather than deciding an optimum timing. The issue of interest is whether a rational agent's discrete choice behaviour can always be explained by 'Expected Utility' modelling.

Individuals' choices regarding vaccination are important from the perspective of both the social planner and that of the (intended) recipient of vaccination. Even though the objectives of both groups are quite different, the comparison of the social planner's aim to that of recipient will help to identify if there is any gap in the equilibrium level of coverage chosen by individuals and the socially optimum level. The social planner aims to minimise the burden of infectious disease by choosing the optimum level of prevention. Their decision is based on the societal cost-benefit analysis where they can observe the actual risks involved. Individuals, on the other hand, base

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[1] Geoffard and Philipson (1996, 1997), and Francis (1997) have incorporated the economic and epidemiological incentives in rational consumers choice of vaccination timing.

their decision on the basis of their subjective cost-benefit analysis which is based on perceived risks. There are at least two sources of risk involved – risk of infection and risk of vaccine. In general, rational individuals aim to minimise the risk of illness for themselves or for their children, leading them to accept vaccination when the threat of disease is high and that of the vaccine is low. However, there is evidence that individuals refuse to accept vaccination even when it would have been accepted under rational behavioural assumptions. Considerable evidence exists to show that the risk and serious effects of disease are much higher than that of vaccine risks and reactions (for example, Hobson-West, 2003; Prior et al., 2002), but still there is public resistance against vaccination. One of the reasons could be that the individual's rational behaviour is not dependent on the risks, and therefore risks should not be assumed to be the main conceptual tool for understanding resistance to vaccination. Alternatively, there could be a possible disappointment due to non-realisation of expected outcome from a vaccination decision, which is especially relevant to vaccines that provide imperfect immunity or is linked to side effects (or at least perceived risk of side effect). This has raised concerns for analysing the behavioural response to vaccination which, in turn, has important implication for the social planner's effort to control infectious disease since their objectives won't be realised unless individuals decide to accept vaccination.

Individual choice analysis in case of vaccination is crucial to optimal disease control effort. The choice of vaccination is a choice made under conditions of uncertainty, which is usually analysed on the principles of von Neumann and Morgenstern's expected utility (EUT) theory. Under uncertainty, people evaluate alternative choices on the basis of their expected payoffs given their subjective beliefs regarding health outcome and probabilities of the corresponding states. But there is evidence that people's behaviour is not consistent with EU hypothesis[2], which has given rise to alternative explanation of rational choice under uncertainty. One such theory discusses the role of regret in rational choice (Loomes and Sugden, 1982). The paper aims to examine the choice of vaccination under the subjective expected utility theory (EUT) and regret theory (RT) and compares the implications of the theories for individuals' propensity to be vaccinated.

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[2] There is plethora of observed deviations from EUT (e.g., Allais Paradox, preference reversal) in insurance demand models (Braun and Muermann, 2003). Similar evidences are also observed in vaccination where parents are often reluctant to vaccinate their children even when risks (vaccine risk and infection risk) and benefits clearly favour vaccination (Connolly and Reb, 2003). This has questioned the ability of EU hypothesis to explain rational choice.

II. Vaccination decision under uncertainty

Earlier models of vaccination choice have mainly considered two discrete health states – susceptible and infected, and included a cost parameter for adverse health events. This is applicable to vaccines that may have milder side effects, but the negative reaction to vaccination may involve a sustained loss of health status, which for many vaccinations is irreversible. We have considered adverse events to affect both health status and income (loss of income) in the utility function in our framework to allow us to investigate the effect of these factors on vaccination decision-making.

We consider a situation where vaccination is voluntary and an individual makes a choice for herself (this can be extended to the case where the parent act as an agent for the child – the principal). Under this situation the vaccination decision can be modelled as a binary choice under risk. There are risks of infection, risk of severity and duration of illness when infected, and the risk of side effects associated with vaccination decision. Given the actual risks, an individuals' decision depends on the perceived risk. Individuals face a trade-off between the risk of infection and the risk of vaccine, and the decision to choose between two alternatives (vaccinate or remain exposed) is guided by the impact of the above risk on their utility.

Consider a utility function for an individual who derives utility from consumption of a composite material good (x) and from health (h)[3]. The individual has certain monetary income (y). Under certain conditions maximising $u(h,x)$ is equivalent to maximising $u(h,y)$ where y is the full income. The individual faces a risk of contracting an infectious disease, the probability of which is given by $\rho \in (0,1],$ which is exogenous to the individual.[4] The individual faces monetary loss[5] (c) when he is infected, the loss is assumed to depend on income, $c = c(y)$. We assume that these costs are linearly related to income, $c(z) = c_z y$ and $c(i) = c_i y$. It is rational to assume that

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[3] Health is a multidimensional concept, but it can be transformed into a single variable. For example, a widely used single variable is the number of quality adjusted life years (QALYs).

[4] The risk of disease can be endogenous where the individual believes that her preventive action will lower the probability of infection rather than just eliminating the risk of infection.

[5] Infectious state incurs time and pain, all of which can be converted to monetary terms.

$c > 0$ and $c' \in [0,1]$, since illness leads to absence from work for a certain period of time.[6] The intensity of the loss depends on the nature of health state; for example, an adverse health state has much greater monetary loss than that of infectious state.[7] It allows us to incorporate heterogeneity in the model where a high income individual will lose more income than a low income individual.

We assume that for each the utility function is concave in each health state ($u' > 0$, and $u'' < 0$), and for each level of income $u[s, y] > u[i, y]$, and $u'[s, y] > u'[i, y]$.

Case 1: Perfect immunity

Consider a situation where the vaccine provides perfect immunity, but there is probability of adverse side effects with probability $\phi \in (0,1]$. When there is possibility of sustained adverse effects and the corresponding health state is z, then the expected utility of a person who choose to be vaccinated is given by[8]

$$EU_{vaccination} = (1-\phi)u(s, y) + \phi u(z, y - c_z y)$$

The expected utility of a person who decides not to be vaccinated is

$$EU_{exposed} = \rho u(i, y - c_i y) + (1-\rho)u(s, y)$$

The individual is indifferent between the choice if and only if

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[6] This is extended to the case where a parent is acting as an agent for the principal, their child, given that ill health of child will result in lost of earnings for the parent.

[7] Since serious adverse events have longer period of illness than infected state and therefore $c(z) > c(i)$.

[8] The individual is likely to incur some financial cost of vaccination in the current period and expected benefits accrue in the current period and from the subsequent periods. Here we consider a simple case where individual don't have to pay for vaccination and consider a static decision-making setting. A static model ignores the role of time preferences in vaccination which underestimates the cost of disease. We have adjusted that problem by making cost of disease a function of loss of income.

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\begin{aligned}
&(1-\phi)u(s,y)+\phi u(z,y-c_z y)=\rho u(i,y-c_i y)+(1-\rho)u(s,y)\\
&-\phi u(s,y)+\phi u(z,y-c_z y)=\rho u(i,y-c_i y)-\rho u(s,y)\\
&\Rightarrow \rho[u(s,y)-u(i,y-c_i y)]=\phi[u(s,y)-u(z,y-c_z y)]\\
&\Rightarrow \frac{\rho}{\phi}=P_S^{\,*}=\frac{u(s,y)-u(z,y-c_z y)}{u(s,y)-u(i,y-c_i y)}\text{...}(1)
\end{aligned}
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The left hand side of the expression provides a measure of relative risk of morbidity attributable to infection compared to the risk of morbidity attributable to the vaccine. This ratio tells us how many times more dangerous is the natural infection compared to vaccine, and this is the subjective critical probability. An individual will choose to vaccinate when her perceived (expected) relative risk of infection to risk of side effects is above this threshold level.

***Individual decision rule*:** For a given subjective risk of infection relative to risk of side effects (P_S), the individual will decide to be vaccinated, if and only if $P_S > P_S^*$; and will remain unvaccinated otherwise. As P_S^* increases, the propensity of individuals to get vaccinated declines.

Comparative static

Loss in utility due to side effects [$u(s,y)-u(z,y-c_z y)$]: The higher the expected loss in utility from adverse side effects, the higher is the critical subjective probability. A rise in the risk of adverse events reduces an individual's propensity to vaccinate. This also shows that the threshold probability is increasing in income since the losses arising from vaccination side effects are increasing in income. This leads us to infer that higher income groups are more likely to reject vaccination in the face of fear of side effects than lower income individuals.

Loss in utility due to infection [$u(s,y)-u(i,y-c_i y)$]: The higher the expected loss from infection, the lower the threshold level of probability below which individual decides to get vaccinated. This implies that higher income individuals are more likely to get vaccinated in order to avoid the loss resulting from infection.

The net effect of vaccine disutility and infection disutility on threshold probability will be determined by relative income loss due to infection and side effects [($c(i)$ versus $c(z)$], which in turn will be determined by the perceived severity and duration of illness from the corresponding states.

Case 2: Imperfect immunity

In a situation where the vaccine does not provide perfect immunity, it is rational to assume that an individual believes that vaccination reduces the probability of infection rather than completely eliminating the risk i.e., the probability of infection is higher if not vaccinated (ρ_H) than that if vaccinated (ρ). If there are three states of health (susceptible, infected and adverse state), then the expected utilities of two decision alternatives are as follows:

$$EU_{vaccination} = (1-\rho-\phi)u(s,y) + \rho u(i, y-c_i y) + \phi u(z, y-c_z y)$$
$$EU_{exposed} = (1-\rho_H)u(s,y) + \rho_H u(i, y-c_i y)$$

Individuals are indifferent between the choice if and only if

$$\rho u(i, y-c_i y) + (1-\rho-\phi)u(s,y) + \phi u(z, y-c_z y) = \rho_H u(i, y-c_i y) + (1-\rho_H)u(s,y)$$

When vaccine efficacy is less than perfect it can be assumed that $\rho = (1-e)\rho_H$, where e is the expected efficacy of the vaccine. Incorporating this condition in the above expression:

$$\Rightarrow \frac{\rho_H}{\phi} = P_s^{**} = \left[\frac{u(s,y) - u(z, y-c_z y)}{u(s,y) - u(i, y-c_i y)}\right]\frac{1}{e} \quad \text{..(2)}$$

An individual will chose to vaccinate when her perceived (expected) relative risk of infection to risk of side effects is above this threshold level. The only additional term with this threshold probability (P_s^{**}) is the perceived efficacy parameter (e). e has an inverse relationship with the threshold probability. The higher the e, the lower is possibility of infection in vaccination as compared to exposed situation, and therefore the larger the propensity to accept vaccination; and vice versa. Other comparative static results are similar to those found in case of perfect immunity.

III. Regret Theory

Under conditions of uncertainty it cannot be guaranteed that the choice made on the basis of *ex ante* calculations will be optimal *ex post*. *Ex ante* an agent may have inaccurate perceptions of the probabilities of states occurring or may have imperfect information about the efficacy of the vaccination technology, which would affect her payoff, but the information is external to the agent (Besley, 1989). Under this situation *ex ante* optimal choice may diverge from what is *ex post* optimal. Regret theory as proposed by Loomes and Sugden (1982) is relevant in this case where the concerns of rational agents are not limited to their payoffs only. There is potential regret, which plays a role in the choice under uncertainty. The foundation of regret theory is that people experience regrets if their decision turns out to be *ex post* sub optimal even if it appeared optimal with beliefs and information available *ex ante* (Dodonova, 2002). This intuitive assumption implies that an individual's utility function should depend on the factual decision outcome and also on the counter factual outcome that might have occurred had one chosen differently (Braun and Muermann, 2003). There is a large body of evidence[9] to suggest that regret theory can explain deviations from EUT that has been observed in many economic, financial situations and in experimental data.

Regret theory (RT) is arguably particularly relevant for modelling individuals' vaccination choices. With the protection afforded by vaccination, there is a low probability of infection, but there is new risk of adverse health states arising from vaccination side-effects - and in case of the decision not to vaccinate i.e. to remain exposed, most people eventually recover from the infected state even without any protective action. So there is potential source of regret if people end up experiencing adverse health states caused by choosing to take protective action and if the cost of experiencing an infected health state is large in the case of the decision to remain exposed. Regret

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[9] See Loomes and Sugden (1982, 1987), Bell (1982), Kahneman and Tversky (1982), Connolly and Zeelenberg (2002) for evidences that how regret theory helps to explain behaviour that has been represented as irrational behaviour by expected utility hypothesis.

theory enables us to model decision making as an attempt to minimise the regret arising out of health states and the cost associated with health states.

Regret theoretical expected utility function (RTEU): In RT the expected value of a state consists of a baseline utility (equal to that derived by EUT) plus an element of expected regret/rejoice compared with alternative state that could be attained if an alternative choice had been made. The regret theoretical utility function of a representative regret-averse consumer can be expressed as

$$u_c(h, y) = v_c(h, y) - G\left[v(h^{\max}, y^{\max}) - v_c(h, y)\right], \text{ where}$$

$v_c(.)$ is a traditional Bernoulli utility (value) from action c (as represented by subscript c) which is concave ($v' > 0$ and $v'' > 0$) and $G(.)$ is the regret function that depends on the difference between the value of actual level and ex-post optimal level of health status and income(h^{max}, y^{max}).[10] Regret function $G(.)$ is convex ($G' > 0$ and $G'' > 0$) and $G(0) = 0$. This utility function is derived from regret theory as formulated by Loomes and Sugden (1982). The above regret theoretical EU function can be modified as

$$u_c(h, y) = v_c(h, y) - G\left[EO(x) - v_c(h, y)\right]$$

where $EO(x)$ is the expected outcome from alternative action x, which is also *ex-post* optimum. This modified RT utility function allows for differences in the probabilities of each state of the world compared to original formulation of RT where the outcomes differ according to the action chosen, but the probabilities remain the same. This modification of RT makes it more flexible to its application to problems of health care decision making (Richard, 1996). In order to derive the RTEU for an action we have to know the utility of each state, discussed below.

The regret-adjusted expected utility matrix for vaccination and exposed decision are as follows:

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[10] (h^{max}, y^{max}) is the health and income that the individual could have received if he had made the optimal choice with respect to realised state of the nature.

	Susceptible (s)	**Infected (i)**	**Adverse event (z)**
Vaccination	$u(s,y)-G[s,V]$	$u(i,y-c_i y)-G[i,V]$	$u(z,y-c_z y)-G[z,V]$
Exposed	$u(s,y)-G[s,NV]$	$u(i,y-c_i y)-G[i,NV]$	---------

The first argument of $G[,]$ function represents health state (s,i,z) and the second argument is for choice (V for vaccination and NV the choice to remain exxposed). We assume that

(a) $G[s,V]=G[s,NV]=0$ which implies that there is no regret at the susceptible state from either choices,
(b) $G[i,NV]>G[i,V]$ which indicates that regret from exposed decision is higher than that from vaccination decision,
(c) $G[z,V]>G[i,NV]$, which implies that regret from side effect from vaccination choice is larger than the regret from resulting loss from infection due to exposed decision,
(d) From exposed decision there is no possibility of adverse events.

Regrets from other possible states are as follows:

$$G[i,V]=G\left[EO(\exp osed)-u(i,y-c_i y)\right]=G\left[(1-\rho_H)\{u(s,y)-u(i,y-c_i y)\}\right]$$

Regret from experiencing an infected state from vaccination choice (since vaccine is not perfectly effective) depends on utility cost of infection and net increase in risk of experiencing an infected state ($1-\rho_H$) as compared to infected state resulting from an exposed decision.

$$G[z,V]=G\left[EO(\exp osed)-u(z,y-c_z y)\right]=G\left[\{u(s,y)-u(z,y-c_z y)\}-\rho_H\{u(s,y)-u(i,y-c_i y)\}\right]$$

Regret from experiencing an acute (adverse) health state from vaccination choice depends on the difference between utility cost of side effect and expected utility cost of infection from infection resulting from an exposed decision.

$$G[i,NV]=G\left[EO(vaccination)-u(i,y-c_i y)\right]=G\left[(1-\rho)\{u(s,y)-u(i,y-c_i y)\}-\phi\{u(s,y)-u(z,y-c_z y)\}\right]$$

Regret from experiencing infected state from the choice of remaining exposed depends on the net expected increase in the utility cost of infection (as compared to loss of infection from exposed choice) and inversely with the expected utility cost of side effect from a vaccination decision. If it turns out that the expected loss of side effect is higher than the net expected increase in cost of infection, people will rejoice from being in infected state.

Case 3: Perfect immunity (when $\rho = 0$)

$$EU_{vaccination} = (1-\phi)u(s,y) + \phi\{u(z,y-c_z y) - G[\{u(s,y)-u(z,y-c_z y)\} - \rho_H \{u(s,y)-u(i,y-c_i y)\}]\}$$
$$= (1-\phi)u(s,y) + \phi u(z,y-c_z y) - \phi G[z,V]\}$$

$$EU_{exposed} = (1-\rho_H)u(s,y) + \rho_H \{u(i,y-c_i y) - G[\{u(s,y)-u(i,y-c_i y)\} - \phi\{u(s,y)-u(z,y-c_z y)\}]\}$$
$$= (1-\rho_H)u(s,y) + \rho_H u(i,y-c_i y) - \rho_H G[i,NV]$$

An individual is indifferent between the choice if and only if

$$\frac{\rho_H}{\phi} = P_{RS}{}^{*} = \frac{[u(s,y)-u(z,y-c_z y)] + G[z,V]}{[u(s,y)-u(i,y-c_i y)] + G[i,NV]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where the critical probability, $P_{RS}{}^{*}$ depends on both baseline utility and regret element. The critical probability increases with the regret associated with the adverse state (from vaccination) and decreases with regret from infected state associated with the decision to remain exposed.

Individual decision rule: For a given regret-adjusted risk (P_{RS}), the individual will decide to be vaccinated, if and only if $P_{RS} > P_{RS}^{*}$; and will remain unvaccinated otherwise.

Comparative static:

(1) Threshold level of P_{RS}^{*} increases with the utility cost of side effects and decreases with the utility cost of infection.

(2) Threshold level increases with perceived regret from side effect, where the regret from side effect is inversely related with the perceived risk of infection from remaining exposed. Therefore, the higher the risk of infection, the lower is the $G[z,V]$, and therefore the threshold probability is

lower. This implies that higher risk of infection induces an individual to vaccinate through lowering their regret from possible adverse health state that can arise from vaccination decision.

(3) Threshold level increases with perceived regret from infected state, which in turn is inversely related with risk of side effect. Therefore, the higher the risk of side effects (ϕ), the lower the $G[i,NV]$, therefore the higher is the threshold probability.

Case 2: Imperfect immunity

When the vaccine is imperfect, the regret theoretical expected utility for the vaccination and exposed decisions respectively are as follows:

$$\begin{aligned}
&EU_{vaccination} = (1-\rho-\phi)u(s,y) + \rho\big\{u(i,y-c_iy) - G\big[(1-\rho_H)\{u(s,y)-u(i,y-c_iy)\}\big]\big\} \\
&+\phi\big\{u(z,y-c_zy) - G\big[\{u(s,y)-u(z,y-c_zy)\} - \rho_H\{u(s,y)-u(i,y-c_iy)\}\big]\big\} \\
&= (1-\rho-\phi)u(s,y) + \rho u(i,y-c_iy) - \rho G\big[i,V\big] + u\{(z,y-c_zy) - \phi G\big[z,V\big]
\end{aligned}$$

$$\begin{aligned}
&EU_{\exp osed} = (1-\rho_H)u(s,y) + \rho_H\big\{u(i,y-c_iy) - G\big[(1-\rho)\{u(s,y)-u(i,y-c_iy)\} - \phi\{u(s,y)-u(z,y-c_zy)\}\big]\big\} \\
&= (1-\rho_H)u(s,y) + \rho_H\big\{u(i,y-c_iy) - G\big[i,NV\big]\big\}
\end{aligned}$$

An individual is indifferent between the choice if and only if

$$\frac{\rho_H}{\phi} = P_{RS}^{**} = \frac{[u(s,y)-u(z,y-c_zy)] + G[z,V]}{e[u(s,y)-u(i,y-c_iy)] + \{G[i,NV]-(1-e)G[i,V]\}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Individual decision rule: For a given regret-adjusted risk (P_{RS}), the individual will decide to be vaccinated, if and only if $P_{RS} > P_{RS}^{**}$; and will remain unvaccinated otherwise.

Comparative static: This critical probability indicates similar comparative static conclusions to those found in the perfect immunity case with new addition of perceived effectiveness of vaccine. Here, the higher the perceived effectiveness of vaccine, the lower is the threshold point and the larger is the propensity to accept vaccination. If we impose an additional assumption that $G[i,NV] = G[i,V]$, then the threshold probability reduces to

$$\frac{\rho_H}{\phi} = P_{RS}^{**} = \left[\frac{[u(s,y) - u(z, y - c_z y)] + G[z,V]}{[u(s,y) - u(i, y - c_i y)] + G[i, NV]} \right] . \frac{1}{e}$$

IV. Comparison of decisions based on EU and RTEU

Predictions of both EU and RT of consumer behaviour regarding vaccine acceptance have some similarity. In both theories, individuals' propensity to accept vaccination is found to be negatively related to the risk of the vaccine (as threshold prevalence increases) and positively related to the risk of infection (as threshold prevalence decreases). However, although the directions of the relationships are similar, the implications of the theories are dissimilar. In EU theory, threshold probability depends only on relative disutility of infection as compared to vaccination related disutility. But in RTEU, the threshold probability depends on both relative disutility and relative regrets. A comparison of threshold probability under both theories is discussed below.

Other things remaining the same, since $G[z,V] > G[i,NV]$, therefore in both perfect immunity and imperfect immunity case, we find that

(a) Perfect immunity:

$$P_{RS}^{*} = \frac{[u(s,y) - u(z, y - c_z y)] + G[z,V]}{[u(s,y) - u(i, y - c_i y)] + G[i, NV]} > P_S^{*} = \frac{u(s,y) - u(z, y - c_z y)}{u(s,y) - u(i, y - c_i y)}$$

(b) Imperfect immunity:

$$P_{RS}^{**} = \frac{[u(s,y) - u(z, y - c_z y)] + G[z,V]}{e[u(s,y) - u(i, y - c_i y)] + \{G[i, NV] - (1-e)G[i,V]\}} > P_s^{**} = \left[\frac{u(s,y) - u(z, y - c_z y)}{u(s,y) - u(i, y - c_i y)} \right] \frac{1}{e}$$

The higher threshold probability under RT indicates that given a subjective relative risk, an individual has a lower propensity to vaccinate if she considers both actual payoff and counter-factual outcome than the case in EUT where only direct payoffs are considered. These results would be useful in investigating some empirical evidence associated with vaccination decisions where possible regret may arise.

The extent of the effect of these risks on propensity to accept vaccination can be analysed in terms of their effect on welfare. This can be analysed by considering monetary measures of risk in vaccination.

Case 1: Perfect immunity

EUT: An individual (who has preferences for vaccination) aims to maximise

$$EU_{vaccination} = (1-\phi)u(s,y) + \phi u(z, y - c_z y)$$

$$\frac{dy}{d\phi} = \frac{u(s) - u(z)}{(1-\phi)u'[s] + \phi(1-c_z)u'_y[z]} > 0 \text{...}(5)$$

This reveals how much the individual's wealth must increase in order to compensate him for infinitesimal increase in the risk of vaccine to keep utility to the original level. This is known as Hicksian Compensating Variation (CV) (Zweifel , 1997; Johansson, 1995) for a change in risk because welfare change is measured at the original utility. This required compensation is positive because increase of risk has made the consumer worse-off and therefore a positive level of compensation is required to bring the consumer to the original level of utility. The CV expression, as expected, indicates that it is increasing with 'perceived loss in utility from infection' [$u(s,y) - u(z, y - c_z y)$] and increases with marginal utility of income (u'_y).

RTEU: An individual (who has preferences for vaccination) aims to maximise

$$EU_{vaccination} = (1-\phi)u(s,y) + \phi\{u(z, y - c_z y) - G[\{u(s,y) - u(z, y - c_z y)\} - \rho_H \{u(s,y) - u(i, y - c_i y)\}]\}$$

$$\frac{dy}{d\phi} = \frac{\{u(s) - u(z)\} + G[z,V]}{(1-\phi)u'_y[s] + \phi(1-c_z)u'_y[z] - \phi\{\{u'_y[s] - (1-c_z)u'_y[z])]\} - \rho_H \{u'_y[s] - (1-c_i)u'_y[i])]\}G'_y[z,V]} \text{.....................}(6)$$

CV is positive if and only if the denominator of the above expression is positive which leads to the condition that $G_y[z,V] < \frac{1}{\phi}\left[\frac{(1-\phi)u'_y[s] + \phi u'_y[z]}{\{u'_y[s] - u'_y[z]\} - \rho_H \{u'_y[s] - u'_y[i]\}}\right]$.

Comparative static results on the CV provide a number of important results:

- CV is increasing in 'perceived loss of utility from infection' $[u(s,y)-u(z,y-c_z y)]$.
- CV is increasing in regret from vaccination associated with adverse health state $G[z,V]$.

Similarly we find that the CV for a change in expected probability of infection from the decision to remain exposed is as following:

$$\frac{dy}{d\rho_H}=\frac{-\phi R_{\rho_H}[z,V]\{u(s)-u(i)\}}{(1-\phi)u'_y[s]+\phi(1-c_z)u'_y[z]-\phi\{\{u'_y[s]-(1-c_z)u'_y[z]\}-\rho_H\{u'_y[s]-(1-c_i)u'_y[i]\}\}G'_y[z,V]}$$

This indicates that CV is decreasing in the probability of the alternative outcome, which is intuitively interesting because when the risk of infection from exposed decision rises, people would be would be more willing to vaccinate even at lower compensation.

Comparison of CV (risk of vaccine) shows that individuals require more compensation under RT than that under EU if and only if the following condition holds:

$$\frac{u[s]-u[z]+R[z,V]}{(1-\phi)u'_y[s]+\phi(1-c_z)u'_y[z]-\phi\{\{u'_y[s]-(1-c_z)u'_y[z]\}-\rho_H\{u'_y[s]-(1-c_i)u'_y[i]\}\}G'_y[z,V]}>\frac{u[s]-u[z]}{(1-\phi)u'_y[s]+\phi(1-c_z)u'_y[z]}$$

which holds because the numerator of LHS is greater than that of RHS and the denominator of LHS is lower than that of RHS provided that the marginal utility of healthier state is higher than an inferior state. Under this condition it can be concluded that an individual needs to compensated more if his behaviour is regret theoretical compared to that when the individual is an expected utility maximiser. Therefore in a society with continuum of individuals who are heterogeneous in terms of income, RT would predict a lower proportion of individuals as accepting vaccination than the coverage predicted by EU.

Case 2: Imperfect immunity

EUT: An individual (who has preferences for vaccination) aims to maximise

$$EU_{vaccination} = \rho u(i, y - c_i y) + (1 - \rho - \phi)u(s, y) + \phi u(z, y - c_z y)$$

$$(a)\frac{dy}{d\phi} = \frac{u(s) - u(z)}{(1-\rho-\phi)u'_y[s] + \rho(1-c_i)u'_y[i] + \phi(1-c_z)u'_y[z]} > 0 \text{...(7)}$$

since $u(s, y) - u(z, y - c_z y) > 0.$ This reveals how much the individual's wealth must increase in order to compensate him for infinitesimal increase in the risk of adverse events.

$$(b)\frac{dy}{d\rho} = \frac{u(s) - u(i)}{(1-\rho-\phi)u'_y[s] + \rho(1-c_i)u'_y[i + \phi(1-c_z)u'_y[z]} > 0 \text{...(8)}$$

The higher the risk of infection, the higher the CV since $u(s, y) - u(i, y - c_i y) > 0,$ $u'_y[s, y] > 0$, $u'_y[i, y - c_i y] > 0$ and $u'_y[z, y - c_z y] > 0$. This reveals how much the individual's wealth must increase in order to compensate him for infinitesimal increase in the risk of infection.

Comparing (a) and (b) it can be said that CV for risk of vaccine is higher than that of risk of disease since $u(z, y - c_x y)$ < $u(i, y - c_i y)$ because cost associated with adverse health events is larger than that of infected state since adverse health state has larger duration of illness than that of infected state. This is consistent with the adverse effects of vaccination that causes permanent or serious damage (as assumed in our analysis) as compared to that of infection.

RTEU: An individual (who has preferences for vaccination) aims to maximise

$$\begin{aligned} EU_{vaccination} &= (1 - \rho - \phi)u(s, y) + \rho\{u(i, y - c_i y) - G[(1 - \rho_H)\{u(s, y) - u(i, y - c_i y)\}]\} \\ &+ \phi\{u(z, y - c_z y) - G[\{u(s, y) - u(z, y - c_z y)\} - \rho_H\{u(s, y) - u(i, y - c_i y)\}]\} \end{aligned}$$

$$(c)\frac{dy}{d\phi} = \frac{\{u(s) - u(z)\} + G[z, V]}{D} \text{...(9)}$$

$$(c)\,\frac{dy}{d\rho}=\frac{\{u(s)-u(z)\}+G[i,V]}{D}\quad\text{...}(10)$$

where,

$$D=\rho(1-c_i)u'_y[i]+(1-\rho-\phi)u'_y[s]+\phi(1-c_z)u'_y[z]-\rho(1-\rho_H)\left[u'_y[s]-u'_y[i]\right]G'_y[i,V]$$
$$-\phi\left[\{u'_y[s]-u'_y[z]\}-\rho_H\{u'_y[s]-u'_y[i]\right]G'_y[z,V]$$

CV for an infinitesimal changes in both ρ and ϕ will be positive when $D>0$

In case of RT, the magnitude of CV for risk of infection and risk of vaccine depend on the regret from vaccination associated with infected state and adverse health state. Since by assumption $G[z,V]>G[i,V]$, CV for risk of vaccine would be larger than that for risk of infection.

Comparison of *CV (risk of vaccine)* between the utility theories shows that individuals require more compensation under RT than that under EU if and only if the following condition holds:

$$\frac{\{u(s)-u(z)\}+G[z,V]}{D}>\frac{u(s)-u(z)}{(1-\rho-\phi)u'_y[s]+\rho(1-c_i)u'_y[i]+\phi(1-c_z)u'_y[z]}$$

which holds on the basis of assumptions of the analysis. Therefore, under certain restrictions it can be inferred that in the case of vaccines that provide less than perfect immunity, people require more compensation under EU than under RT, leading to lower proportion of individuals predicted to accept vaccination.

V. Conclusion

An individual's decision regarding vaccination is modelled in this paper as being a binary choice under uncertainty – either vaccinate or remain exposed. Optimal level of vaccination of an individual therefore cannot be expressed as an interior solution, but can be expressed as a threshold condition. This paper has examined the vaccination decision making as a binary choice problem with the inclusion of adverse health as a distinct health state. It has been found that an individual evaluates the threshold level with reference to both adverse health state and infected state relative to the susceptible state. An individual benefits from being exposed until the subjective probability is below the critical level, and decides to vaccinate when this subjective probability is above the threshold level. The perceived threshold level is guided by the relative valuation of risk of adverse effects to that of infection. It is generally expected that a rational individual, whose behaviour can be explained by subjective expected utility theory, will decide to accept vaccination when risk of infection is high, and that of a vaccine is low. But the agents base their decision on perceived risk rather than the actual risk. Therefore under uncertainty and imperfect information, there is large possibility of non-realisation of *ex ante* expectation in the *ex post* situation. This implies that there is a potential source of regret associated with the vaccination decision. Further, it is found that a regret-averse individual will have a higher threshold probability that shows their propensity to vaccinate is lower than that suggested by a simple EU model of decision making by regret averse individual. It is also found that a regret-averse individual would require more compensation for a rise in risk of vaccine than that of a traditional expected utility maximiser. If consumers' decisions are better characterised as regret theoretical than traditional EU maximiser, this may provide an explanation for the possible causes of low acceptance of vaccines in the face of increased fear of side effects. It is important to examine consumer behaviour in practice and see which of the theories appears better able to explain and predict empirical evidence about vaccination decisions.

Both EUT and RT, based on perceived risks, have some important findings regarding individuals' propensity to vaccinate with reference to risk of vaccine and risk of disease. It cannot be denied that vaccinations are made only on the basis of risk calculation, but it can be said that the behavioural response to risks under RT provides useful explanation of low vaccine acceptance. Perceived risk of infection (ρ^e) and risk of vaccine (ϕ^e) is an *expectation* about the actual risks (ρ, ϕ). It is often found that public has misperception about risks. Risk communication research has identified that public underestimate the risks from disease ($\rho > \rho^e$) and overestimate the risk of vaccine ($\phi < \phi^e$) (Hobson-West, 2003), leading to a situation where subjective relative risk based on perceived risks is smaller than that of actual risk ($(\rho^e / \phi^e) < (\rho / \phi)$). Therefore when perceived risks do not converge to actual risks, EU theory would lead to a situation where less proportion of individuals will accept vaccination than that would have achieved when individual have known the actual risks. On the other hand the effect of $\rho > \rho^e$ and $\phi < \phi^e$ on critical regret R^* is not unique - this will lead to net higher regrets from being exposed and net lower actual utility from being exposed, the critical R^* will be determined by the relative effect of these two. The net effect will depend on how individuals weight regrets (from counterfactual outcome) relative to factual outcome. It is therefore of immense importance to estimate perceived risks of individuals and see how evaluation of regret and factual outcome varies on the basis of perceived risk across individual.

Risk perception is influenced by many factors which include actual risks parameters, media coverage, herd behaviour and so on: many of which influences cannot explicitly be captured in the theoretical framework discussed in this paper. Moreover, since risks are evolving by nature, it is crucial to know how individuals adjust their perceived risks in response to any new information regarding risk of infection and efficiency of vaccine. The analysis of individual's choice was based on subjective risks, and didn't take any account of risks to the society. If individuals behave as rational agents, it may make sense to 'free ride' and refuse vaccination; the decision to free ride would be influenced by their perceived societal risk. If individuals perceive that everyone will vaccinate and the disease would be eliminated, they would feel regret from their decision to vaccinate. Similarly, if one perceives that infection will not be eliminated, he may experience rejoicing from his protective action. RT can be extended to the case where individual decision is influenced by aggregate societal risk which could provide better analysis of rational decision regarding vaccination. These issues, as well as empirical tests of the theoretical models reported in this paper, are being explored in our ongoing research.

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