Department of Economics
School of Social Sciences

Understanding individuals' decisions about vaccination: a comparison between Expected Utility and Regret Theory models

Sadique, Z.[1], Edmunds, W. J. [1,2], Devlin, N.[1], Parkin, D.[1]

1. City Health Economics Centre, Economics Department, City University, London.
2. Health Protection Agency Centre for Infections, London.

Address for correspondence: Zia Sadique, Economics Department, City University, Northampton Square, London EC1 V OHB.

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1. Introduction

The transmission and control of infectious disease is strongly influenced by how people make choices, both individually and collectively, when presented with opportunities to engage in preventive actions or to utilise preventive health care services. Researchers in the emerging field of 'economic epidemiology' analyse these choices by modelling aggregate behaviour on the premise that a rational individual's decision with respect to vaccination is influenced by both economic and epidemiological incentives. Notable papers originating from that perspective, including Geoffard and Philipson (1996; 1997) and Francis (1997), argue that the fundamental objective of a rational agent, evaluating an option on the basis of the expected utility of the final outcome, is to find the optimum *timing* of vaccination. An important contribution of these models is that they clearly demonstrate the importance of dynamic feedback between individual choices regarding prevention and the aggregate infection rate.

This paper builds on that literature, and seeks to extend it in three ways.

First, it could be argued that choices regarding vaccination are more (or at least equally) plausibly represented as a static discrete decision – to vaccinate or not to vaccinate – rather than as a decision about optimum timing. In many countries, vaccination programmes are delivered as packages of public health services offered at specific points in time – for example, in post-natal care, at 18 months, at 6 years, and so on. On each occasion, an opportunity to receive vaccination is offered, and is either accepted or declined. Modelling these decisions as discrete choices made in response to each invitation may generate new insights into the determinants of individuals' choices, and yield results in a form more compatible with predicting or explaining the achievement of stated public policy goals regarding vaccination coverage rates among birth cohorts.

Second, although the prevalence of disease is important to individuals' assessments of the risks of infection, the information individuals possess about aggregate level risks may be far from perfect. It is the individuals' *perception* of risks that will influence their decisions. This becomes particularly important given individuals' decisions are based not just on perceived benefits of vaccination, but also the perceived risks of vaccination, such as those arising from adverse side-effects. Understanding how individuals weigh up these various risks is crucial – for example, the spurious link between the Measles Mumps and Rubella (MMR) vaccine and autism made by Wakefield (1998), although scientifically lacking any credibility[1], resulted in heightened anxiety among parents reflected in a sharp and sustained reduction in vaccine uptake in the UK (British Medical Association, 2003). This suggests that the perception of vaccine risk can undermine public health strategies, with serious implications for the ability to prevent epidemics. Modelling decisions as a product both of the risk of disease and of side-effects may allow us better to understand these influences.

Third, decisions about vaccination are made under conditions of uncertainty, and the existing literature analyses these choices using the principles of von Neumann and Morgenstern's expected utility (EUT) theory. In EUT, individuals are assumed to evaluate alternative vaccination choices on the basis of their expected payoffs, given their subjective beliefs regarding health outcome and probabilities of the corresponding states. However, there is ample evidence that individual behaviour is often not consistent with EUT[2], which has given rise to alternative explanations of rational choice under uncertainty, including the role of regret in rational choice (Loomes and Sugden, 1982). Regret theory (RT) arguably has intuitive appeal as an approach modelling vaccination decisions. A characteristic of these choices is that the risks of vaccine side effects is statistically small, but the side effects are (or are perceived to be) severe and permanent. Furthermore, many (although not all) of the public health issues which we might wish to analyse using these models concern childhood immunisation – where the decision to vaccinate is made by an agent (the parent) for the principal (the child). The potential for imperfect agency, combined with potentially substantial caring externalities between the principal and the agent (i.e., any adverse effects experienced by the principal may cause greater disutility to the agent than to the

[1] Since Wakefield's report, epidemiological studies carried out to verify this association found no causal link between temporal trends in MMR uptake and the incidence of autism. See Taylor *et al* (1999; 2002); Farrington *et al* (2001) and Kaye *et al* (2001) for empirical evidence.

[2] There is plethora of observed deviations from EUT (e.g., the Allais Paradox; preference reversal) in insurance demand models (Braun and Muermann, 2003). Similar evidence is 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 gives rise to questions about the ability of EUT to explain rational choice.

principal) suggest grounds for exploring the role of regret in modelling. Although we do not formally incorporate agency or interdependent utility functions here, we do examine the choice of vaccination under both EUT and RT and compare the implications of the theories for predictions about decisions to receive vaccination.

The aims of this paper are, therefore, to propose new theoretical models for examining individual decision making regarding vaccination where (i) decisions are modelled as discrete choices which are (ii) a product both of the perceived risk of the preventable disease and of the risk of adverse side effects of the vaccine; and (iii) where individuals' behaviour is modelled both as regret minimising and as expected utility maximising, and the results compared. The following sections describe our models and their implications for individuals' decisions regarding vaccination. We conclude by highlighting the hypotheses that emerge and suggesting further research to test these.

2. Vaccination decision under uncertainty

The economic epidemiology models of vaccination choices referred to above have generally 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 readily be extended to the case where the parent acts 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 and h represents discrete health states. h can take three values, $h \in [s,i,z]$ where s represents susceptible, i represents infected and z represents adversely affected health state. 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, and this 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 $c > 0$ 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 an infectious state.[7] This 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 the individual's utility function is concave in each health state ($u'_y > 0$, and $u''_y < 0$), and for each level of income $u[s,y] > u[i,y]$, and $u'_y[s,y] > u'_y[i,y]$.

The model assumes that vaccination is 'free at the point of demand' i.e. that there is no price charged for receiving the vaccine, either because of full subsidisation or complete insurance coverage.

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

Case 1: Perfect immunity threshold probability

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

$$\begin{aligned}
&(1-\phi)u(s,y) + \phi u(z, y - c_z y) = \rho u(i, y - c_i y) + (1-\rho)u(s,y) \\
&-\phi u(s,y) + \phi u(z, y - c_z y) = \rho u(i, y - c_i y) - \rho u(s,y) \\
&\Rightarrow \rho[u(s,y) - u(i, y - c_i y)] = \phi[u(s,y) - u(z, y - c_z y)] \\
&\Rightarrow \frac{\rho}{\phi} = P_S^{\ *} = \frac{u(s,y) - u(z, y - c_z y)}{u(s,y) - u(i, y - c_i y)} \quad \text{..........(1)}
\end{aligned}$$

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, which is termed as 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.

[8] In some health care systems the individual may incur some financial cost of vaccination in the current period, while the expected benefits accrue in the current period and from the subsequent periods. Here we consider a simple case where individuals 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.

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 for case 1

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.

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 above which individual decides to get vaccinated.

Case 2: Imperfect immunity threshold probability

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.

3. 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 counterfactual 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

[9] See Loomes and Sugden (1982; 1987), Bell (1982), Kahneman and Tversky (1982) and Connolly and Zeelenberg (2002) for evidence on instances where regret theory can help to explain behaviour that has been represented as irrational behaviour by expected utility theory.

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 the 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 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

[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.

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

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 (Smith, 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 the decision to seek vaccination and the decisions to remain exposed (not to vaccinate) are as follows:

	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 exposed). 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:

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

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 $\rho = 0$) threshold probability

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

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

An individual is indifferent between the choice if and only if

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

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 4: Imperfect immunity threshold probability

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

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

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

An individual is indifferent between the choice if and only if

$$\frac{\rho_H}{\phi} = P_{RS}^{**} = \frac{[u(s,y) - u(z, y - c_z y)] + G[z,V]}{e[u(s,y) - u(i, y - c_i y)] + \{G[i,NV] - (1-e)G[i,V]\}} \quad \text{...(4)}$$

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

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

4. Comparison of decisions based on EUT and RTEU

The predictions of both EUT 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 5: Perfect immunity CV

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

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

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

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 the Hicksian Compensating Variation (CV) (Zweifel , 1997; Johansson, 1995) for a change in risk because welfare change is measured at the original utility level. This required compensation is positive because the increase in risk has made the consumer worse off and therefore a positive level of compensation is required to return 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). But, the higher the marginal utility, the smaller is the CV, which implies that higher income groups are more likely to vaccinate their child (as low required compensation is equivalent to more willing to vaccinate) compared to lower income groups.

The cost (anticipated cost) of side effect has important implication on CV. CV increases with anticipated cost of side effect ($\frac{\partial(CV)}{\partial c_z}=\frac{1}{\phi c_z^2}>0$). This perceived cost of side effect is assumed here to depend on income. Knowledge about the severity of vaccine related side effect has great influence in determining this perceived cost, and may explain vaccination choice varies across and within socioeconomic groups.

RT: 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 $G_y[z,V]<\frac{1}{\phi}\left[\frac{(1-\phi)u'_y[s]+\phi u'_y[z]}{\{u'_y[s]-u'_y[z]\}-\rho_H\{u'_y[s]-u'_y[i]\}}\right]$. This condition implies that the expected utility of vaccination relative to marginal utility cost of vaccination (over and above marginal utility cost of infection) must be larger than the regret from side effects.

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 probability of infection is as following:

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

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

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

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

This result arises 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 a 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 6: Imperfect immunity CV

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

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

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

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.

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

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 (7) and (8) it is evident that the 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 the cost associated with adverse health events is larger than that of infected state, since the adverse health state has a longer duration 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.

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

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

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

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

where,

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

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

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

5. Conclusion

An individual's decision regarding vaccination is modelled in this paper as being a binary choice under uncertainty – either to vaccinate or to remain exposed to the disease. The 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. Individual decisions to vaccinate are made with reference to a threshold level, where 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 valuation of the risk of adverse effects relative to that of infection from the disease. It is generally expected that a rational individual, whose behaviour can be explained by expected utility theory, will decide to accept vaccination when risk of infection is high, and that of the 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 nonrealisation 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 – this suggests that their propensity to vaccinate is lower than that suggested by a simple EU model of decision making by a 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. It needs to be mentioned here that the findings of this analysis rest on the assumption that individuals makes decision on a target level of accepted risks and that threshold level depends on individuals perceived utility of different health states. This analysis is a very simplified version of the actual situation where individuals' valuation of health state depends on individuals' heterogeneity in their ability and knowledge to process the information (regarding risks) to calculate their perceived risks. Nevertheless, the findings are useful and can be extended in numerous possible ways. Now, if this theory is applied to analyse vaccination choice then we need estimates of utility values across individual groups. Lastly, higher threshold risk under regret theory is based on some assumption which needs to be tested. Particularly, the assumption that the side effects of the vaccine are more severe/long-lasting than those of the disease is crucial and therefore estimates of regrets associated with different health states needs to known in verifying the theoretical findings.

Both EU and RT, based on perceived risks, have some important implications regarding individuals' propensity to vaccinate with reference to risk of vaccine and risk of disease. The behavioural response to risks under RT may provide a 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 the public has misperception about risks – for example, 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 their regrets (from the 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 doesn'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 perception of 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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